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WHAT IS THE EVIDENCE SUPPORTING THE TECHNOLOGY SELECTION FOR LOW-VOLUME, RURAL ROADS IN LOW-INCOME COUNTRIES AND WHAT EVIDENCE IS THERE TO SUPPORT THE SUSTAINABILITY OF DIFFERENT RURAL ROAD TECHNOLOGIES?

A SYSTEMATIC REVIEW, JULY 2016

The authors of this report are:

Dr Michael Burrow (University of Birmingham)

Mr Robert Petts (Intech Associates)

Professor Martin Snaith (University of Birmingham)

Dr Gurmel Ghataora (University of Birmingham

Dr Harry Evdorides (University of Birmingham)

Funding

This is an independent report commissioned and funded by the Research and Evidence Division in the Department for International Development. This material has been funded by UK aid from the UK Government, however, the views expressed do not necessarily reflect the UK Government’s official policies.

Acknowledgments

The authors are very grateful to a team from the EPPI-Centre, overseen by Professor Sandy Oliver, for their assistance throughout the review process. In particular they are extremely grateful for the continual guidance and invaluable comment provided by Ms Kelly Dickson throughout the review stage and in helping to draft this report. The patient assistance of Mr Jeff Brunton in helping the review team to make best use of the EPPI-Reviewer software is also gratefully acknowledged. The review team are also grateful for the guidance and advice provided by the project’s Advisory Group. The three researchers who assisted greatly with the searching process, namely Mehran Eskandari Torbaghan, Danielle Fintleman and Fiona Raje, are thanked for their patience and thorough endeavours. We would also like to thank the peer reviewers for their input. The systematic review has been funded by the DFID. The advice provided by DFID’s Ms Liz Jones and Mr Suman Baidya in addressing the research question is also noted with gratitude. Finally, the review team would like to acknowledge the work of the authors of studies included in this review and those who participated in them, without which the review would have had no data.

Conflicts of interest

Where a paper written or co-authored by a member of the Review Team was considered for or included in the review, the author was not involved in decisions relating to its selection or quality assessment.

Contributions

The opinions expressed in this publication are not necessarily those of the EPPI-Centre/3IE or the funders. Responsibility for the views expressed remains solely with the authors.

Citation

This report should be cited as: Burrow MPN, Petts RC, Snaith MS, Ghataora GS, Evdorides H (2016). *What is the evidence supporting the technology selection for low-volume, rural roads in low-income countries and what evidence is there to support the sustainability of different rural road technologies? A systematic review.* London: EPPI-Centre, Social Science Research Unit, UCL Institute of Education, University College London.

Picture

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SUMMARY

INTRODUCTION

This systematic review sought to identify technologies appropriate for low-volume rural roads (LVRR) which enable improved and sustainable low-volume rural access in low-and-lower middle-income countries (LLMICs). It is funded by DFID and conducted by the University of Birmingham. The hypothesis is that, if technologies can be found which have enabled the provision of LVRR infrastructure sustainably, the resulting improved access for rural communities will: (i) reduce poverty by facilitating economic activity; (ii) reduce the costs associated with transporting goods to and from internal and export markets; and (iii) increase social wellbeing by providing access to a variety of facilities and services. To this end this review addresses the following questions:

1. What is the evidence supporting the use of technology in low-income countries?
2. What is the evidence on which of these technologies have proved to be sustainable?

This brief is designed to provide an overview of the key evidence identified in the systematic review and to assist policy makers and researchers in assessing that evidence. As the evidence is deeply contextual and this brief provides an overview, it is not designed to provide advice on which interventions are more or less appropriate in any given particular context.

SUMMARY CONCLUSIONS

This systematic review has identified a sound evidence base that engineering-based technologies can be used to improve the functional and structural performance of earth or gravel rural roads in LLMCs. Studies measured sustainability in terms of the performance of technologies (see Table 1). These technologies may be considered to be sustainable in physical terms in specific environments. Earth and gravel roads may also be considered to be sustainable in particular environments. Claims that these technologies are financially, operationally, environmentally or socially sustainable cannot be made strictly from the evidence of this review alone. However, the evidence from the review 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.

The selection of a sustainable technology also needs to take into consideration the geo-socio-political environments in which the technology is implemented. This includes considering the sustainability needs of roads managed and financed by:

(i) **District councils**: where there is an acute shortage of qualified technical staff; design, supervision, and the provision of regular maintenance funds is problematic. **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.

(i) **Central government roads department**: these organisations typically employ technically qualified staff or use private-sector contractors, have reasonable but not always adequate or timely budgets. **Sustainable technology in this context**: could use cutting edge engineering technology; should not require close supervision of construction and maintenance; be robust enough to perform adequately under irregular maintenance.

(ii) **Contracted out management and maintenance of roads**. In this case, funds typically come from a national road fund, but could also come through the ministry of local government. All road works are strictly audited. **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.

Table 1: Trial technologies against some key markers

		Measure of sustainability													
	Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak sub-grades**	**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
	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

		Measure of sustainability													
	Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak sub-grades**	**Small contractor suitability**	**Local economy advantages**	**Resistance to axle overloading**	**Initial cost**	**Possible whole life cost advantage**	**Environmental impact**	**Achieved road serviceability**	**AVERAGE SCORE**
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
	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.

SYSTEMATIC REVIEW APPROACH

A systematic search of the international literature was conducted and involved searching thirteen electronic bibliographic databases and nine websites relevant to low-volume rural roads, as well as three search engines. Members of the Review Team and the review's three-member Advisory Group also contributed material unavailable in the public domain. The titles and abstracts of 16,893 potentially relevant studies were screened and full reports of 1,143 citations were retrieved for further consideration. A total of 15 studies, of sufficient quality, describing technologies to improve rural roads in LICs and LMICs, were critically appraised and analysed in depth. The data from the studies were synthesised, using narrative methods, to demonstrate the sustainability of the technology as a function of parameters which affect road pavement performance.

SUMMARY MAP OF EVIDENCE

Twenty-three studies, published between 1975 and 2010, were included and described in the map of evidence.

GEOGRAPHICAL LOCATION

The majority studies were carried out were in Africa: Kenya (n=6), Botswana (n=2), Malawi (n=2), Mozambique (n=2), Ethiopia (n=1), Lao PDR (n=1), Tanzania (n=1), Uganda (n=1) and Zimbabwe (n=1) followed by Asia: India (n=4), Bangladesh (n=1), Cambodia (n=2), Vietnam (n=2).

FOCUS OF THE STUDIES

The 23 studies broadly focused on the effect on road performance (n=22), and all but three were associated with the materials used for LVRR construction (n= 20). Two studies were associated with maintenance of LVRRs and another on the costs of different road surfacing technologies on the operation of bicycles. Studies describing the use of materials for the construction of LVRR focused on: the performance of block surfaces of a LVRR (n=3); concrete road surfaces (n=3); sealed (n=11) or unsealed surfaces (n=11); sealed (n=10) or unsealed (n=1) bases and/or sub-bases or with the use of geotextiles (n=1). Concerning LVRR maintenance, one study reported on methods used to carry out the maintenance and their effectiveness in relation to gravel roads, whilst another considered the use of a novel material for maintenance. In all cases, the suitability of the technology was assessed in terms of road condition.

Fourteen studies concerned the use of different materials and standards for road construction with just one study comparing the effect on road condition of maintenance by motor grader, towed grader, mechanical drags and labour-intensive methods. Of the 14 studies on road pavement construction, ten focused on the use of alternative, low-cost and marginal materials and one study monitored the performance of sealed LVRRs constructed to new Indian design standards. Despite the vast majority of LVRR are gravel or earth roads, only three studies focused on the performance of existing in-service gravel or engineered earth roads (EERs). Six of the studies reported the performance of specially constructed sections of road built to trial particular technologies.

All of the studies reported on the durability of the designs and materials using measures of the functional and structural condition of the roads, and discussed the sustainability of these technologies in terms of their deterioration over time, their cost, availability and maintainability. The performance of five broad categories of road surfaces were explored, engineered earth roads, unsealed gravel roads, flexible pavement seals, concrete surfaces and block surfaces respectively.

Outcomes measured across the studies included both functional (n=15) and structural (n=15) measures of road condition.

OUTLINE OF THE EVIDENCE

QUALITY OF THE EVIDENCE

The weight of evidence of studies was assessed according to the study's soundness, appropriateness of design and relevance. Fifteen studies were judged to be high quality and were included in the synthesis. The findings were organised according to the type of technology used: (i) road pavement construction (n=14) and (ii) means of carrying out maintenance (labour and equipment) (n=1).

ROAD PAVEMENT CONSTRUCTION

BLOCK SURFACES

Block surfaces were shown to be a sustainable option for an LVRR and particularly suited to environments where the rainfall is high (>2,000 mm/year), and the subgrade is weak (CBR ≤5%). The most sustainable surface was dressed stone/cobble, particularly when locally sourced and manufactured using labour-intensive methods. Fired clay and concrete bricks was marginally less sustainable since energy sources are required to produce them. A disadvantage of dressed stone/cobble surfaces is their much rougher surface than clay and concrete bricks, and therefore may not provide a suitable solution for LVRRs where it is important to minimise road-user costs. The extent to which block pavements are a viable option for LVRR surfacing is influenced by:

- the quality of construction of the surface material
- the compliance with specifications
- timely and regular maintenance to ensure that good performance can be retained for a long time (particularly with respect to joints and seals).
- tensile strength: to ensure that the base is strong enough to sustain the loading environment so that joints do not break down under repetitive wheel loads.

CONCRETE ROAD SURFACES

The evidence suggests that four types of concrete road surface (concrete slabs, geocells and bamboo- and steel-reinforced concrete) perform satisfactorily in all environments provided they are constructed to appropriate standards and their joints are maintained adequately. In terms of:

i) **Riding quality** concrete road surfaces 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.

Therefore, LVRRs constructed from concrete may be considered most appropriate when the major requirements are to provide all-season access and to ensure that road-user costs are minimised.

ii) **Structural dimensions**, concrete reinforced with steel was found to perform marginally better on weak sub-grades than non-reinforced options. Steel, however, needs to be imported and is relatively expensive. It is questionable whether reinforcement is necessary on LVRRs, since they are designed to carry light traffic loads, although can be subject to significant overload. Road sections made from concrete reinforced with bamboo were shown to have performed at least as well as those without reinforcement. However bamboo-reinforced slabs were found to be more expensive to manufacture. Inter-slab joints could be prone to early deterioration; a significant feature when considering the life-cycle cost of concrete slabs with respect to other surfacing options.

Overall, the maintenance costs of the cement concrete sections are low in the environments considered; however, concrete road sections have a high initial construction cost, are likely to require the use of imported material, and require precise construction.

SEALED SURFACES

Many of the sealed LVRRs examined were found to be performing adequately after the expected lifetime of the seal (5-10 years), despite little or no maintenance, overloading in a number of cases and the use of materials below the recommended standards (see table 2). In general the extra thickness of surfacing material provided by double and Cape seals enables them to perform best, in a range of environments, particularly where gradients are steep. Thus, double or Cape seals could be used for steep gradients with single seals used for other parts of a sealed LVRR. In low-rainfall environments (rainfall ≥ 2,000 mm/year), where low road roughness is an important consideration, an emulsion sand seal was found to be an appropriate solution as it provides a good running surface, and can be produced and maintained using locally available resources at lower 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 are a more appropriate choice.

Table 2: Selection criteria for different sealed surfacings (Gourley et al, 1999)

Surfacing type	Situations of use			
	Requiring little maintenance	Steep gradients (>10%)	Wet climate or poor drainage	Turning trucks
Single seal (conventional)	No	No	Yes	No
Double seal (conventional)	Yes	Yes	Yes	Yes
Single graded seal (e.g. Otta)	Yes	No	Yes	No
Double graded seal (e.g. double Otta)	Yes	Yes	Yes	Yes
Slurry seal	Yes	No	Yes	Yes
Cape seal	Yes	Yes	Yes	Yes
Sand seal	No	No	No	No

Poor construction quality was found to be an issue with many seals, affecting their performance and that of the road pavement structure. Given that seals deteriorate over time, routine maintenance is required. The early maintenance of such defects prevents water ingress into the road pavement structure, and the softening of the sub-grade and possible premature failure of the road. In addition, periodic maintenance resealing was found to be required after approximately five years (for single seals) to ten years (for double seals). Some studies demonstrated the benefit of sealing the shoulders of LVRRs, thus enabling a drier environment to be maintained under the road pavement.

BASES AND SUB-BASES

The studies found in general that the LVRRs constructed with the majority of base and sub-base materials investigated performed satisfactorily from a functional and structural point of view, provided that the road was sealed, designed appropriately and well-constructed. The majority of the roads considered showed signs of significant deterioration after 5–10 years which would require a periodic maintenance treatment to readdress (i.e. resealing). All studies showed that marginal materials (including all gravels considered) can be used as bases and/or sub-bases, with lower than conventionally accepted strengths (CBR values) provided that these layers are protected from moisture ingress via an impervious seal and through appropriate drainage, and the road structure has been designed adequately.

UNCONVENTIONAL PAVEMENT DESIGNS

Two studies found that two-layered sealed LVRRs, built on relatively strong sub-grades (i.e. CBR ≥30%), performed well from a structural point of view for many years in excess of their design life. Such strategies may reduce the construction costs of conventional thicker designs, which incorporate three layers, by 166-233%.

STABILISATION

The performance of marginal materials used in road bases was shown to be improved via chemical stabilisation (with lime and/or cement) and the performance of some marginal materials with inappropriate grading characteristics could be enhanced via mechanical stabilisation with fines.

ENGINEERED EARTH ROADS

Only one report on the performance of EERs was identified, finding that a wide range of soils can be used to provide an adequate surface for motorised traffic of up to 50 vehicles per day (vpd) and higher in climates with rainfall up to 2,000 mm/year. EERs have an advantage over all other types of LVRRs considered in this review since they only require the use of local materials. Such roads, however, must include the provision of adequate drainage and cross fall. Overall, their sustainable use is very much reliant on the prevention of overloading, and of regular maintenance.

GRAVEL ROADS

The sustainability of natural gravel surfacing was shown to be dependent on a range of factors: setting and achieving the application of appropriate specifications relating to particle grading, plasticity and particle strength; restricting application to roads carrying traffic of up to 200 vpd, rainfall of less than 2,000 mm/year and gradients of less than 6% (for manageable maintenance and sustainable gravel loss); ensuring appropriate design, including the provision and maintenance of adequate camber and run-off arrangements through side drains, turnout (mitre) drains and cross drainage; and timely resourcing and provision of regravelling to replace material losses.

ROAD MAINTENANCE APPROACHES

Less-expensive road maintenance approaches in terms of capital expenditure and more labour-intensive technologies were found to be at least as effective and sustainable as the more capital-expensive options. However, to achieve the same effectiveness, less-expensive technologies require frequent maintenance cycles and labour-intensive technology requires high levels of supervision.

RESEARCH GAPS

There is a lack of robust data supporting an analysis of the aspects of sustainability associated with the materials. Such as the capacity and performance of the construction and maintenance regimes to achieve cost-effective asset management, environmental issues, including the impact on global and local environments in which the materials are used, and the sustainability of the supply of scarce resources.

CONTENTS (BOOKMARKS SHOULD BE ADDED ONCE STYLE GUIDE HAS BEEN DELETED)

1 BACKGROUND

1.1 AIMS AND RATIONALE FOR REVIEW

It is acknowledged that rural road access in low-income countries (LICs) is critical for economic and social wellbeing. In many LICs, agriculture offers a tremendous opportunity, as growth in demand for food continues to rise with increasing population growth. Much of this food requirement can be met by local or regional producers; however, in many LICs, food imports are increasing because local production cannot meet rising demands. In addition to these opportunities, international prices for traditional export crops are high and export volumes could increase (Knox et al., 2013; Akpan, 2014). However, these commercial opportunities can only be realised if products can reach internal and export markets in a timely fashion, undamaged and with acceptable vehicle operating costs. Further, the movement of both human resources to the farm and products to support agriculture also requires adequate transport infrastructure and associated services. Poor transport infrastructure and associated high costs of transport services from poor route conditions, or intermittent seasonal access, necessarily impact adversely on agricultural costs. Further, rural communities in LICs with inadequate access are also often restricted from the pursuit of social interaction, and from schools, health facilities and basic needs such as clean water and firewood.

Despite huge investment programmes, the road networks in LICs are characterised by low density of network and underdevelopment (Gwilliam and Bofinger, 2011). Typically, less than 20% of classified networks are to a paved standard in many countries (World Bank, 2008). Low-volume rural roads (LVRRs) in LICs also suffer from under-resourced and under-achieved maintenance, resulting in their poor condition and associated high road-user costs. Routes can also be impassable after periods of rain. As a consequence, it is estimated that around a billion of the world’s population do not have reliable year-round road access and their social and economic development is thereby substantially constrained (Lebo and Schelling, 2001). There are concerns that the predicted change in the climate will exacerbate the situation, with the result that many regions in LICs and LMICs are expected to experience more extreme weather events, with a consequential effect of increasing the frequency and length of time during which routes to rural communities are impassable.

There is, therefore, a need to identify low-cost, proven sustainable solutions for rural road access in LICs that maximise the use of local resources (labour, skills, materials, enterprise, manufacture and ingenuity) and reduce the impact on the environment.

Rural road access can be considered to be composed of the provision of:

1. transport services: the investment, planning, design, economics, safety modes and frequency of transportation
2. infrastructure: the financing, appraisal, planning, design, construction, maintenance and management of the rural road infrastructure.

This review focuses on solutions for transport infrastructure and aims to identify technologies appropriate for LVRRs which enable improved and sustainable low-volume rural access in low-income countries. It addresses the following questions: (i) What is the evidence supporting the use of technology in low-income countries? and (ii) What is the evidence on which of these technologies have proved to be sustainable?

1.2 DEFINITIONAL AND CONCEPTUAL ISSUES

The main hypothesis is that if technologies can be found which have enabled the provision of LVRR infrastructure sustainably, the resulting improved access for rural communities will: (i) reduce poverty by facilitating economic activity; (ii) reduce the costs associated with transporting goods to and from both internal and export markets; and (iii) increase social wellbeing by providing access to a variety of facilities and services.[1]

This review uses the literature to report on: (i) the types of technologies currently being adopted and reported; (ii) the outcomes of these technologies reported in the evidence base; and (iii) the sustainability of these interventions.

LOW-VOLUME RURAL ROADS

There are no universally accepted definitions of LVRRs; the normally accepted definition can be found in Table 1.1. The great majority of roads in rural areas in LICs are LVRRs, and are most often constructed of earth or gravel; their accessibility is therefore greatly influenced by seasonal rainfall and maintenance regimes.

TECHNOLOGY

Improvements to access can be associated with building new roads, providing all-season access through upgrading existing earth or gravel roads, and implementing more appropriate maintenance practices. Such improvements, if carried out appropriately, require economic appraisal, planning and the use and management of appropriate resources (materials, labour, skills, equipment, enterprises, credit/capital) in a sustainable context. Roads are structural systems and deteriorate over time due to the combined effects of traffic and the environment and therefore may require both routine and periodic maintenance as a function of their construction type (e.g. earth, gravel, sealed), traffic utilisation, construction quality and environment (topography, climate, road geometry, sub-grade). Routine maintenance is associated with scheduled works, and the requirement for it depends primarily on the effect of the environment on road deterioration and drainage and earthwork performance, and to a lesser degree on the effect of traffic. Typical examples of routine maintenance include the maintenance of road drainage, vegetation control and slope management. Periodic maintenance, on the other hand, is condition-based and planned to be undertaken at intervals of several years, is generally more resource-intensive and based on the need to restore as-

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[1] This hypothesis is being addressed in a separate review; see Hine et al. (in press).

constructed attributes such as running surface characteristics (e.g. regravelling or resealing). Maintenance requires the use of appropriate resources and also management tools. LVRRs may be expected to experience low levels of vehicular traffic. Therefore, the predominant mode of deterioration may be expected to be associated with the environment. However, this is not necessarily always the case, since engineered or earth LVRRs may often be used injudiciously during the rainy season and subjected at other times to (illegal) overloading resulting in the road experiencing loading conditions for which it may not have been designed.

For the purposes of this review, the definitions of terminology given in Table 1.1: Definitions are used.

Table 1.1: Definitions

Term	Definition
Low-income countries (LICs/LMICs)	The World Bank defines countries by income group. Economies are divided according to GNI per capita, calculated using the World Bank Atlas method. The groups are: low-income, \$1,035 or less; lower-middle-income, \$1,036-4,085; upper-middle-income, \$4,086-12,615; and high-income, \$12,616 or more (World Bank, 2015).[2]
Low -volume rural roads (LVRR)	They are normally considered to be roads with an annual average daily traffic (AADT) of less than 300 motor vehicles per day (mvpd), a design cumulative total traffic loading to be carried in service of less than 0.5 million ESAs, with design speeds typically of less than 80 km/h (50 mph), and corresponding geometry. Most roads in rural areas in LICs are LVRRs.
Technology	Technology includes, but is not limited to: resources (local/imported, materials, labour, equipment, credit/capital); management tools (e.g. economic appraisal, planning tools, computer tools); and design, construction and maintenance methods.
Sustainability	Capable of being maintained and performing to the planned, designed and constructed standards with the available financial and physical resources and the local operational arrangements, in the local

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[2] This list is based on the World Bank classifications for 2014; however, this is no longer available online, so for the convenience of readers, a reference has been given to the current listing, which is slightly different. On the World Bank web page, countries which have changed classification since 2014 are indicated in bold.

	environment.

GEOGRAPHICAL LOCATION

This review focuses on low-income countries as defined by the World Bank (2015). The main criterion for classifying countries is based on gross national income (GNI) per capita. A full list of the countries that meet the World Bank criteria was compiled and used to screen studies for inclusion (see Appendix 3).

DFID, the sponsor of this review, has recently funded related research in lower-middle-income countries, and is funding a new research and capacity building programme (AFCAP2/ASCAP) which includes some lower-middle-income countries. Therefore studies identified in the literature from lower-middle-income countries were also included in this systematic review (DFID, 2014b).

OUTCOMES

This review focuses on studies reporting a range of outcomes associated with the implementation of rural road technology. A technology is considered to be sustainable if it has ensured that the road on which it has been applied has: at least maintained or enhanced the capability of the road 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.

1.3 POLICY AND PRACTICE BACKGROUND

Over the last 50 years, there have been a number of initiatives funded by central and local governments, road funds, donor agencies and development banks to address the issues associated with poor access of rural communities in LICs. These have included changes in policy as well as small-scale pilots of technologies that have aimed to test the suitability of a variety of technologies to improve LVRR infrastructure. Several key examples are provided below to illustrate the variety of approaches undertaken.

LABOUR-BASED CONSTRUCTION AND MAINTENANCE TECHNOLOGIES

In the 1960s and early 1970s, rural transport research and the poverty-focused agenda promoted labour-based road work methods in countries that had previously moved towards more equipment-intensive methods. Large national labour-based road construction and maintenance programmes were initiated with development agency assistance in countries such as Kenya, where local community labour was employed on new and rehabilitated road networks extending to about 11,000 km through the Rural Access Roads Programme, Minor Roads Programme and Roads 2000. Ensuing studies found that benefits related to domestic and subsistence activities were more dominant than the road-focused economic issues traditionally considered. Village-level travel and transport surveys quantified household travel demand in relation to livelihoods. Pilots were effected in a number of sub-Saharan African (SSA) countries, such as Ethiopia, Malawi, Nigeria and Tanzania. Labour-intensive techniques were also successfully utilised in post-crisis emergency programmes.

Initially, most projects concerned force account or direct labour arrangements (i.e. managed by a public body rather than contracted out). However, the focus moved to private sector approaches through initiatives to develop small-scale labour-based contractors. There was already a long-established culture of labour-based road works in China, India and some other Asian countries. The use of labour-based technology formed therefore an important part of the LVRR strategy for both the World Bank (WB) and the International Labour Organisation (ILO), which commissioned additional field studies of road construction technologies.

Further projects in the early 1990s reported mixed success in SSA countries such as Benin, Burundi, Ethiopia, Ghana, Kenya, Madagascar, Mozambique, Namibia, South Africa, Tanzania, Uganda and Zambia. More recently, various technologies, via WB and the UK Department for International Development (DFID) funding amongst others, have been introduced in several Asian countries, including Bangladesh, Cambodia, Laos, Nepal, the Philippines, Sri Lanka and Vietnam.

INTERMEDIATE-EQUIPMENT TECHNOLOGIES FOR CONSTRUCTION AND MAINTENANCE

Since the 1990s, the investigation of LVRR technology has developed beyond the previous focus on unskilled labour versus heavy plant technology, to consider the wider perspective of better use of local resources (e.g. materials, skilled and unskilled labour, local enterprises, manufacturing processes). There has also been increased interest in the use of intermediate equipment, with its potential for low-capital investment and flexibility.

MATERIALS USED IN THE CONSTRUCTION AND MAINTENANCE OF LVRR

Recent research programmes driven by donor organisations and development banks have supported the investigation of various means of utilising local resources and marginal materials for road surfacing, road pavement construction and maintenance. Two recent DFID-funded initiatives, the African Community Access Programme (AFCAP, 2008-2014) and the South East Asia Community Access Programme (SEACAP, 2004-2009) facilitated the provision of safe, reliable and sustainable all-season access to markets, healthcare and education for rural communities across Africa and South East Asia through strengthening and promoting research to influence policy and practice for the construction and maintenance of rural roads (DFID, 2014a). The programmes worked closely with national governments and other bilateral and multilateral donors to build on investments in low-volume road construction, maintenance and transport services.

CURRENT DFID INITIATIVE

As part of DFID's longstanding poverty reduction development objectives, it is funding a new Rural Roads and Transport Services Research Programme (RRTSRP) (DFID, 2014b). The programme is founded on the AFCAP and SEACAP research initiatives and will consist of two components: phase 2 of AFCAP (AFCAP2) and a new Asia Community Access Programme (ASCAP). AFCAP2 and ASCAP are poverty-targeted low-volume rural transport research programmes. The new RRTSRP will continue the earlier approaches, identifying and supporting the uptake of low-cost, proven solutions for rural transport that maximise the use of local resources (labour, materials, enterprise and ingenuity). AFCAP2 and ASCAP will fund applied research to address rural transport issues, communicate the research outcomes to stakeholders, support the uptake of the research results into practice and build research capacity in Africa and Asia. AFCAP2 will build on the existing country partnerships developed in AFCAP (i.e. Democratic Republic of the Congo, Ethiopia, Kenya, Malawi, Mozambique, South Sudan and Tanzania) and will seek to enlarge the programme to 14 countries by including those in West Africa. ASCAP will focus on approximately six Asian countries; these are yet to be defined, but are likely to include Bangladesh, Burma, India, Nepal, Pakistan and Vietnam (DFID, 2014b).

DFID's new RRTSRP will commission research projects which are associated with the development and use of rural road technologies in the LICs and LMICs mentioned above. Therefore, an assessment of evidence, as provided by this systematic review, concerning technologies which have, or have not, proven to be sustainable in such countries is important in helping to identify suitable projects for DFID to support under the new research initiative and provides a basis for future policy.

1.4 RESEARCH BACKGROUND

The use of various technologies for rural roads has been studied since the early 1970s, in particular, labour-based methods; however, relatively few studies have been carried out which can demonstrate the sustainability of the technology using an evidence-based approach. Further, whilst the available literature on economic appraisal techniques discusses the issue of benefit distribution, operational applications are often restricted by ideological considerations. A large amount of the evidence given in these studies to support the use of technologies is either subjective and based on argument or, where objective analysis has been carried out, is based on the creation of indices. Further whilst there is growing international evidence on rural roads-poverty-agriculture-investment returns, there is a lack of evidence on the performance and sustainability of technology choices. This review seeks to address these issues by providing an informed, evidence-based systematic review of the literature. Since developments in rural road technologies have taken place concurrently with other initiatives, such as the development of low-cost transport solutions and other rural sector initiatives, it may be difficult to assess direct evidence of the contribution of rural road technologies to socio-economic benefits.

1.5 REVIEW QUESTIONS AND APPROACH

This systematic review has been guided by the conceptual framework (see Section 1.2) and the review questions. The conceptual framework and questions posed in the review have informed all aspects of the review methodology, including the search strategy, the inclusion and exclusion criteria, data extraction and the approach to synthesis. The review has been conducted in two stages. The aim of the first stage was to provide a brief, descriptive overview of the type and scope of studies being conducted in this area. The aim of the second stage was to appraise and synthesise evidence on the sustainability of technology for LVRRs.

Following a discussion with the project's funders (DFID), the question was decomposed into two parts, with an emphasis on the second aspect, as follows:

a. Evidence of technologies (i.e. methods, materials, equipment and tools) which have been, or are used in the investment appraisal, investment, design, construction and maintenance of LVRR in low-income countries.
b. Evidence on which of these technologies have proved to be sustainable (financially, economically, physically, environmentally).

1.6 AUTHORS, FUNDERS, AND OTHER USERS OF THE REVIEW

The review was undertaken by an academic team from the University of Birmingham, consisting of Dr Michael Burrow (MPNB), Dr Harry Evdorides (HE), Dr Gurmel Ghataora (GSG) and Professor Martin Snaith (MSS). Professor Snaith's role was to act as a quality assurance person with the remit to engage with an independent advisory group (see Section 0). The team was supported by Mr Robert Petts (RP), who is an independent consultant with over 30 years' experience in rural road technology and management in developing and emerging countries.

The review has been commissioned by the DFID, and seeks to inform policy on rural access provision in general, and in particular on supporting sustainable technologies for LVRR in LICs. The review is registered with the EPPI-Centre, which supports the conduct of systematic reviews, including those focused on low- and lower-middle-income countries.

2 METHODS

The systematic review protocol was drafted, revised and finalised in autumn 2014 (Burrow et al., 2014). Thereafter, a scoping study was undertaken to test the search strategy and gauge the scale of available literature based on the agreed search terms. The full systematic review (SR) commenced in October 2014 and was completed in March 2015. Following peer review, the SR was then updated and finalised in July 2015.

2.1 USER INVOLVEMENT: APPROACH AND METHODS USED

The review has been informed by the commissioners and relevant policy makers at DFID and supported by a three-member Advisory Group. The latter consisted of topic specialists with substantial experience in the rural roads sector in LICs, with specialism associated with economics, transport services, maintenance and sustainability. They played an important role in informing the review process at three stages:

(i) Protocol: feedback was provided by members on the scope of the review, including the conceptual framework, search strategy, draft inclusion and exclusion criteria and the approach for assessing the quality of studies and weight of evidence for the review question.

(ii) Searching: Advisory Group members were asked to identify any published material, research or ongoing projects that could be considered relevant to answering the review question.

(iii) Interim findings:

  a. Whether the conceptual framework has been developed and applied appropriately to answer the review question(s)
  b. Whether the findings have been presented usefully to those who are considering investing in sustainable technologies or in the associated research, for rural roads in LICs
  c. Whether the policy and practice implications have been addressed sufficiently
  d. Whether the recommendations for future research are relevant and appropriate.

Feedback and recommendations from the Advisory Group associated with the above have been incorporated herein.

2.2 IDENTIFYING AND DEFINING RELEVANT STUDIES

(i) To be included in the scope identified studies must:

(ii) Language: be in the English language only.

(iii) Geographical location: be conducted in low- or lower-middle-income countries.

(iv) Roads: low-volume and rural roads only (see definitions above).

(v) Technologies: methods, materials, human resources, equipment and tools used in the appraisal, investment, design, construction and maintenance.

(vi) Study design: be empirical research

(vii) Reporting data: measures of road condition obtained by objective means. These should be reported before and periodically after the application of the proposed technology

(viii) Date: be published after 1950

Further details on what constitutes a LIC or LMIC and the inclusion criteria, transformed into exclusion criteria to facilitate the identification of relevant studies using EPPI-Reviewer, can be found in Appendix 2.

2.3 STUDY DESIGN AND COMPARATORS

As stated above, the work sought to identify studies which have been carried out over the entire life cycle of a low-volume road. Ideally, each should address a different type of technology and demonstrate the sustainability of the technology. Other studies to be considered should compare the outcomes before and after the implementation of the technology (e.g., the effect of a new construction or maintenance technique on maintenance needs). These studies need not necessarily be from the same geographical location, provided that they demonstrate a similar climate, road and sub-grade composition and historical levels of traffic and maintenance. Studies have also been considered which may disprove the sustainability of a technology.

2.4 IDENTIFICATION OF POTENTIAL STUDIES: SEARCH STRATEGY

SEARCH APPROACH

The initial search identified the available technology choices. The review question lends itself to an unbiased aggregation approach where the aim of the study is to identify a sufficient number of studies which demonstrate the sustainable use of technology in different contexts (Gough et al., 2013). Given unlimited resources, such an approach would ideally seek to identify all relevant literature. However, given the resource constraints of the study, this was not possible, and therefore careful consideration was given to locating an unbiased sample of studies most pertinent to addressing the research question. The strategy thus aims to identify longitudinal studies which have been carried out over a significant part of the life cycle of a low-volume road, each demonstrating the sustainability of the technology. This required consideration of the search strategy, including the methods, sources and resources available.

SEARCH TERMS

Key search terms were developed from consideration of the review question and the inclusion and inclusion criteria, and were used to identify relevant studies**.** The search strategy involved developing strings of terms and synonyms to denote two key aspects of the review, namely:

1. Low-volume roads.

2. Technologies used in the appraisal, investment, design, construction and maintenance of low-volume rural roads in LICs or LMICs.

These are described further in **Error! Reference source not found.**.

Table 2.1: Concepts underlying the study search terms

Subject	Proxies	Technology	Comparators	Measures of sustainability
Low-volume roads	Single carriageway roads, usually with a maximum running surface width of <7m	Materials (local/imported) Labour/labor Equipment (heavy/ intermediate)	Life-cycle studies	Economic, environmental, political, physical, social**
Rural roads	Surfaced or unsurfaced Access roads Rural roads Social roads Low value and road* Rural and road* Unpaved and road* Unsurfaced and road*	Finance (credit/capital) Management tools (economic appraisal, planning tools, design methods, computer tools) Design, construction and maintenance methods	Comparisons of technologies with similar climate, traffic, construction type/materials, maintenance history	Net present value/cost Cost–benefit ratio (Costs may not necessarily be monetary) Rural Access Index Road condition Local contractors Locally sourced materials Appropriate technology
Low-income countries				

*: Truncation symbol

** Note the reduction of aid dependence can be considered to be associated with economic and political sustainability.

SOURCES

The study utilised websites of organisations involved in the road sector, bibliographic databases, subject-specific databases, internet search engines, hand searching of books and journals, scanning reference lists and professional contacts.

A number of organisations have commissioned projects using different technologies, and follow-up studies have analysed the effectiveness of the implemented technology. The majority of these studies are available via the organisations’ web sites (i.e. organisation-specific databases). Consequently, a large part of the source identification process was to search these databases. However, it is recognised that the results of these studies reported by some organisations may not always be objective, and the information retrieved was used with care. A number of studies have also been reported in the academic literature, and therefore the study was complemented by searching relevant bibliographic and subject-specific databases. A forward reference list checking exercise was also carried out using Google Scholar, Web of Science and the University of Birmingham’s citation database, FindIT.bham.ac.uk. These identified research reports, dissertations and journal papers not already identified from the search of the bibliographic databases. The searches were complemented by hand searches of reference lists contained in hard copies of publications which were not held electronically, and included theses, books and technical reports identified by the search team and steering group. Further details of the search strategy can be found in Appendix 3.

2.5 SCREENING STUDIES: APPLYING INCLUSION AND EXCLUSION CRITERIA

Inclusion and exclusion criteria were applied successively to (i) titles and abstracts and (ii) full reports. Because of the timeline of the review, text-mining methods were applied to rank all articles found in terms of likelihood for inclusion. Text mining has been offered as a potential solution for identifying relevant studies in an unbiased way for inclusion in systematic reviews through automating some of the screening process (Alison et al., 2015). This meant that the most potentially relevant studies were screened first, thus reducing the likelihood of missing key studies at a later stage (Alison et al., 2015).

Thereafter, full reports of those articles that appeared to meet the criteria, or where there was insufficient information to decide, were obtained in electronic format for further screening. This involved using the previously defined inclusion and exclusion criteria together with a set of additional criteria to identify sub-sets of articles for synthesis.

A specialised systematic review software application, EPPI-Reviewer 4 (Thomas et al., 2010) was used to facilitate the management of the systematic review. The software was used for screening, text mining, coding, analysing and storing retrieved documents, providing a single web location to house the documents and monitor progress of the review. It allows a number of users to access, input, remove and review studies without compromising the integrity of the system. Table 2.2: Systematic review functions lists the functions which could be assisted by this software.

Table 2.2: Systematic review functions

Function	Tasks
Reference management	Importing references from the electronic and other media Managing references obtained from the literature on LVRR (see Section 0) Duplicate checking Storing original documents in an electronic format
Study classification and data extraction (see Section 2.7)	Coding schemes for classifying relevant studies on the use of rural road technology, including: • inclusion, exclusion and eligibility criteria • descriptive codes • capturing detailed information about an identified study Text mining Calculation of common measures of effect (i.e. carrying out standard statistical summaries)
Synthesis (see Section 2.8)	Running meta-analyses Searching of information contained within the EPPI-Reviewer database Producing reports Searching full-text documents (see Section 0) Diagrams of summaries
Review management	Allocation of tasks to reviewers Work progress reporting Setting permissions amongst reviewers Summary flow charts to gauge progress

Source: Gough et al. (2013)

2.6 DETAILED DESCRIPTION OF STUDIES IN THE SYNTHESIS

Studies meeting the selection criteria were analysed in depth by two of the reviewers, using a coding tool developed specifically for this review (see Appendix 4). The tool was designed to extract and record descriptive information which enabled the two reviewers to make a judgement on the quality of each study. This included the study aim/research questions and focus, its geographical location and design, the technology type (e.g. investment, appraisal, construction, maintenance) and the research methods (i.e. outcomes measured, sampling, data collection, data analysis and results).

2.7 WEIGHT OF EVIDENCE: ASSESSING THE QUALITY OF STUDIES

A weight of evidence framework was used to assess the quality and relevance of a study (Gough et al., 2013). The critical appraisal tool assessed the methodological quality of each study in three key areas (see **Error! Reference source not found.**): (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 tasks identified in **Error! Reference source not found.** were used to assess the degree to which a study met each of these criteria. For a study to receive an overall rating of high, and therefore be used in the review stage, it needed to achieve a rating of high in at least two categories and medium in the third.

Table 2.3: Weight of evidence (WoE)

WoE	Tasks
A. Soundness of studies	**High:** There were explicit and detailed methods and results sections for data collection and analysis; the interpretation was soundly based on findings. There were critical comparison with other similar work. **Medium:** There were satisfactory methods and results sections for data collection and analysis; the interpretation was partially warranted by the findings. **Low:** The methods and results sections were unsatisfactory; there was no interpretation of findings or interpretation was not warranted by the findings.
B. Appropriateness of study design for answering the review	**High:** Road pavement trials covered the life cycle of the road pavement, from construction through at least two periodic maintenance cycles following construction (approximately 7-10 years). Road condition data had to be collected at least yearly over this period and the frequency

question	and type of routine and periodic maintenance carried out also had to be 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 had to be assessed at the end of the dry and wet seasons. **Medium:** Trials lasting at least one periodic maintenance cycle after construction (2-5 years). Road condition data had to be collected periodically during this time. Slice-in-time studies should 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 to the Review	**High:** More than 10 sections of at least 100 m of an LVRR in a LIC or LMIC. **Medium:** Between 1 and 10 sections of at least 100 m of a rural road in a LIC. **Low:** One section of at least 100 m of a rural road in a LIC.

Source: after Gough et al. (2013)

2.8 SYNTHESIS OF EVIDENCE

The search aimed to identify a number of longitudinal studies which described the use of a technology over the life cycle of a rural road (typically 12–20 years, depending on a variety of factors), demonstrating its sustainability (or otherwise). Subsequently, the data from these studies were synthesised, using narrative methods, to indicate the sustainability of the technology as a function of the parameters which affect road pavement performance: road geometry, structural design, maintenance history, traffic (speed and load) and environment. An important objective for the review was also to identify technology options which do not have robust evidence of sustainable use (despite perhaps being practised), so that future sector research initiatives may be guided by this knowledge.

2.9 QUALITY ASSURANCE PROCESS

The systematic review followed standard EPPI-Centre procedures for maintaining quality (Harden and Gough, 2012). At the scoping review stage, consistency in application of the selection criteria was ensured by members of the Review Team undertaking double screening on a sample of papers to pilot the inclusion/exclusion criteria. The remainder of the screening was carried out by individual reviewers. Uncertainty in allocation was dealt with through discussion with a subject specialist in association with the reviewer. Thereafter, all reports selected for inclusion were interrogated by a third reviewer with subject specialism to confirm their relevance or otherwise. The process of assessing quality assessment for the in-depth review was undertaken by two members of the review team with appropriate subject specialisms, who considered each report individually and together. The reports so assessed were thereafter scrutinised by the review team's quality assurance person. The data extraction and synthesis components of the review were carried out by a member of the review team with a relevant subject specialism. The results were reviewed by another member of the team to ensure consistency in interpretation.

3 RESULTS

3.1 STUDIES INCLUDED FROM SEARCHING AND SCREENING

The database and website searches identified a total of 21,501 articles for further screening. The titles and abstracts of these were imported into EPPI-Reviewer 4 for further processing. Following the removal of duplicates, the title and abstracts of 16,893 (79%) articles remained. Thereafter the priority screening tool available within EPPI Reviewer-4 was used to process these articles (text mining). This process was stopped when the rate of included articles tended towards zero, at which point 8,516 articles had been screened. Of these, 8,490 (99.69%) were excluded from the review as they were not found to meet the inclusion criteria. A large majority of these articles were excluded because they were not related to rural roads (n=2,787, 33%) or the studies which they reported were not associated with low-income countries (n=3,080, 36%). A smaller proportion of studies were excluded because they described technology which was outside the scope of the review (n=636, 7%), or because they were not empirical studies (n=505, 6%), were found to be duplicates (n=197; 2%), had outputs not related to road serviceability (n=24, 0.28%), did not report data (n=11, 0.13%), or were not longitudinal studies (n=162, 1.9%); 63 (0.74%) articles were excluded because they were carried out before 1950. Seven articles could not be obtained within the timescale of the review (the cut-off date for retrieval was 28 February 2015). Consequently, 26 articles were considered further, and of these, three were found to be linked to others, i.e. they described different aspects or stages of the same study. Thus 23 studies were taken forward for analysis and three articles were consequently coded as linked (secondary) reports (i.e. Cook et al., 2008 was linked to TRL, 2009; Rolt and Cook, 2009 was linked to TRL 2009; Sahoo and Reddy, 2011 was linked to Sahoo et al., 2014).

Figure 3.1 provides a summary of the process described above.

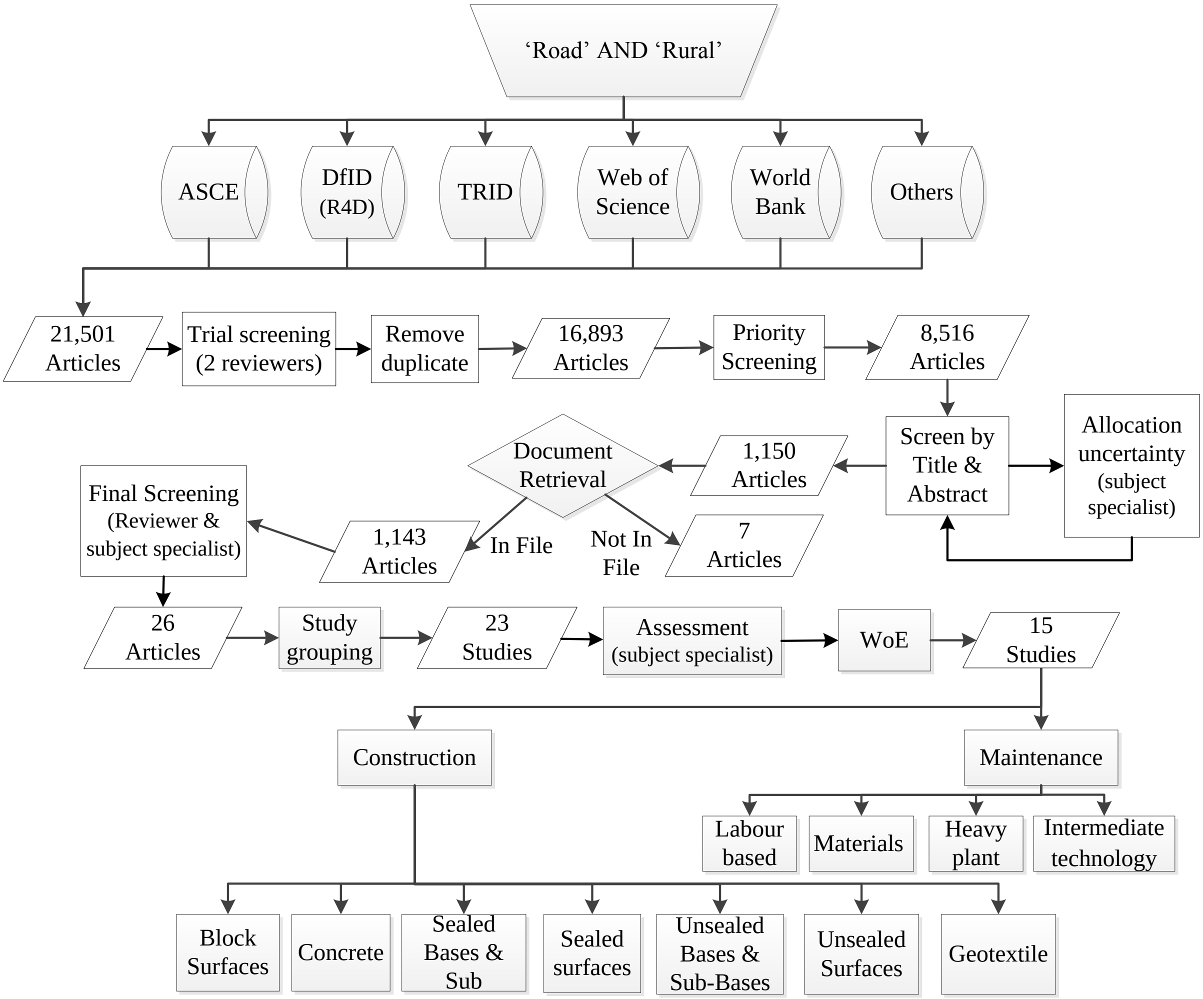

Figure 3.1: Schematic overview of the individual stages in the systematic review

3.2 BROAD CHARACTERISTICS OF THE INCLUDED STUDIES

The studies were coded in EPPI-Reviewer 4 with a set of keywords (see Appendix 4). The descriptive information which follows is based on the information obtained using the coding tool from EPPI-Reviewer 4 and provides an illustration of selected pertinent aspects of the studies.

PUBLICATION SOURCE

Figure 0.1 summarises the number of relevant studies by journal or organisation. The most significant data sources were the series of studies carried out under the AFCAP and SEACAP research programmes which each provided five relevant reports that fitted the SR selection criteria. The TRL also provided five relevant studies.

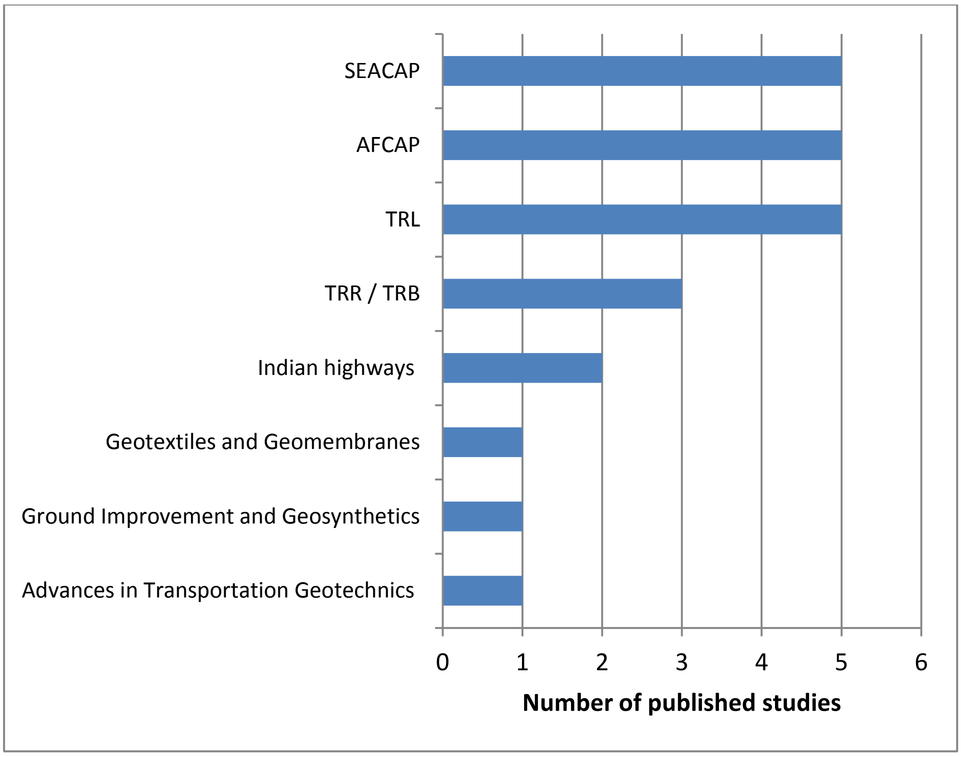

Figure 0.1: Number of relevant studies per journal or project

PUBLICATION DATE

In terms of the date of the publication of the study, the highest number was observed for the period 2008-2014, with 11 studies (Figure 0.2). This partly reflects the results emanating from the SEACAP and AFCAP research programmes.

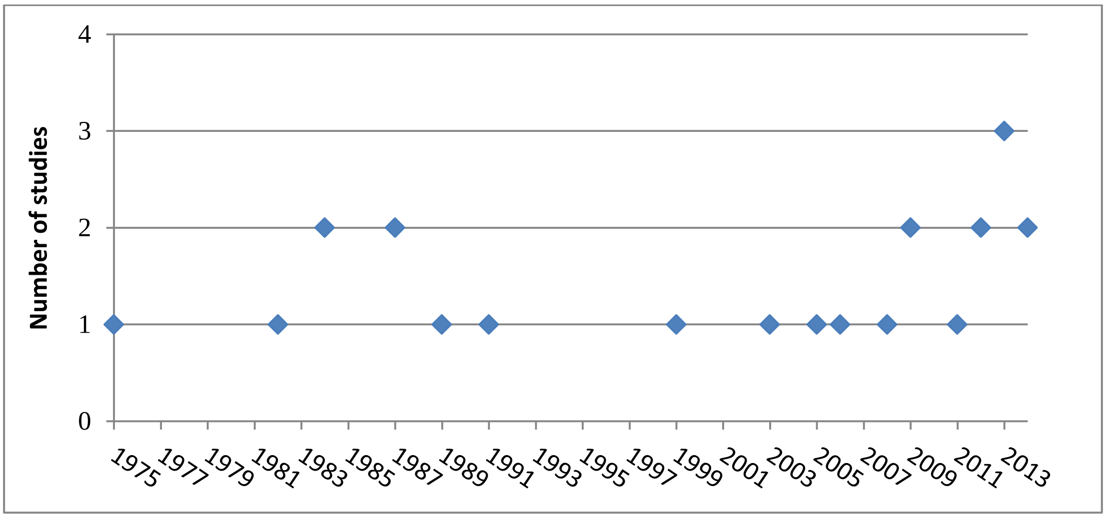

Figure 0.2: Number of studies used in the SR, based on year of publication

GEOGRAPHICAL LOCATION

The countries represented in the evidence base (see Figure 0.3) were Kenya (n=6), India (n=4), Botswana (n=2), Cambodia (n=2), Malawi (n=2), Mozambique (n=2), Vietnam (n=2), Bangladesh (n=1), Ethiopia (n=1), Lao PDR (n=1), Tanzania (n=1), Uganda (n=1) and Zimbabwe (n=1) (note a number of studies considered more than one country).

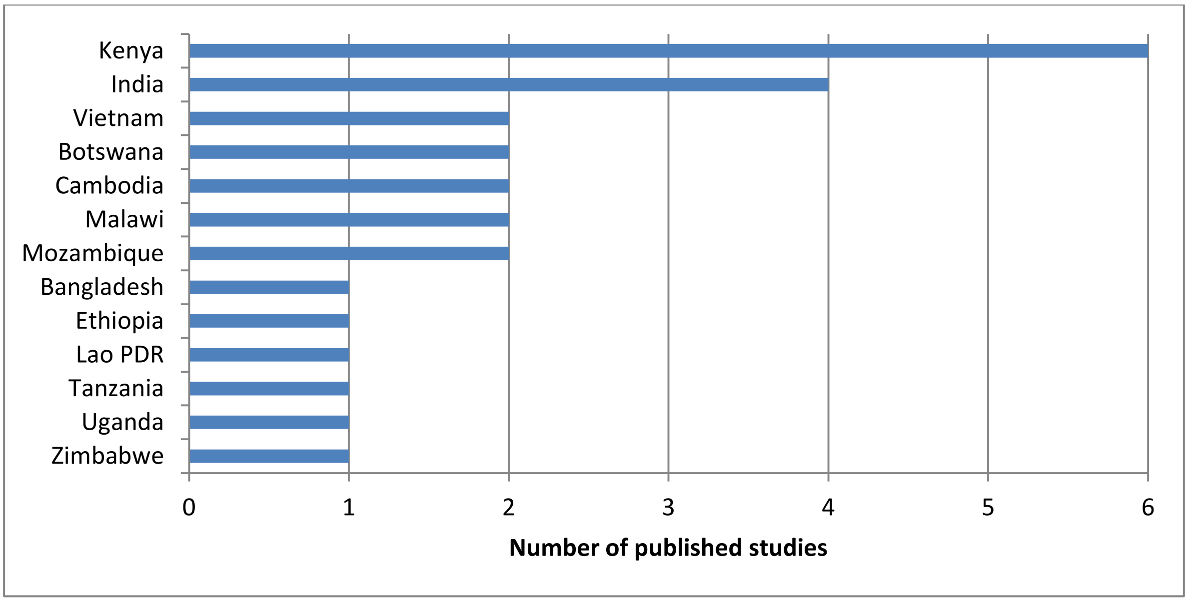

Figure 0.3: Number of relevant published studies, by country

STUDY DESIGN AND METHODS OF EVALUATION

The purpose of all but one study was to evaluate the effectiveness of at least one technology for rural roads in terms of their physical performance.

Generally there are two methods which can be used to study the performance of roads (Hodges et al., 1975). In one such method, which can be considered to be a before-and-after longitudinal study, the changing condition of a sample of road test sections is obtained by monitoring the performance of road sections over their design lifetime, from their initial construction to when they reach a condition of failure (however that condition may be defined). A major issue concerning this approach is that the design life of a road carrying low volumes of traffic may be 20 years or more and therefore condition monitoring needs to be conducted over a long period if a complete history of performance is to be obtained. A second approach involves sampling road performance over time whilst ensuring that the sample contains a representative selection of roads at different stages of their lives. A disadvantage of this slice-in-time method is that the data obtained tends to follow a statistical distribution because of the different standards achieved during initial construction and subsequent maintenance and different (unknown) traffic and environmental loadings to which the roads may have been subjected.

Of the 22 studies which focused on the performance of technology, 16 used a controlled before-and-after longitudinal study whereby the performance of newly implemented technologies were assessed over a given period from their inception (ranging in time from 18 months to 16 years) and compared to a non-matched control group. Six studies adopted the second approach, utilising data collected 12 months to 25 years after the technology had been implemented, devising comparison groups based on homogeneous levels of traffic and similar operational environments. One study used a combination of the controlled study design approach with secondary data analysis. The time periods of the studies, other than the slice-in-time studies, are shown in Figure 0.4. The longest study is by Wason and Oli (1982), from 1964–1980, but data were only collected four times over this period. One-off slice-in-time studies were carried out by Gichaga (1991), Gourley and Greening (1999), Rolt et al. (2008), Cook and Petts (2005), Rolt et al. (2013) and Pinard (2011).

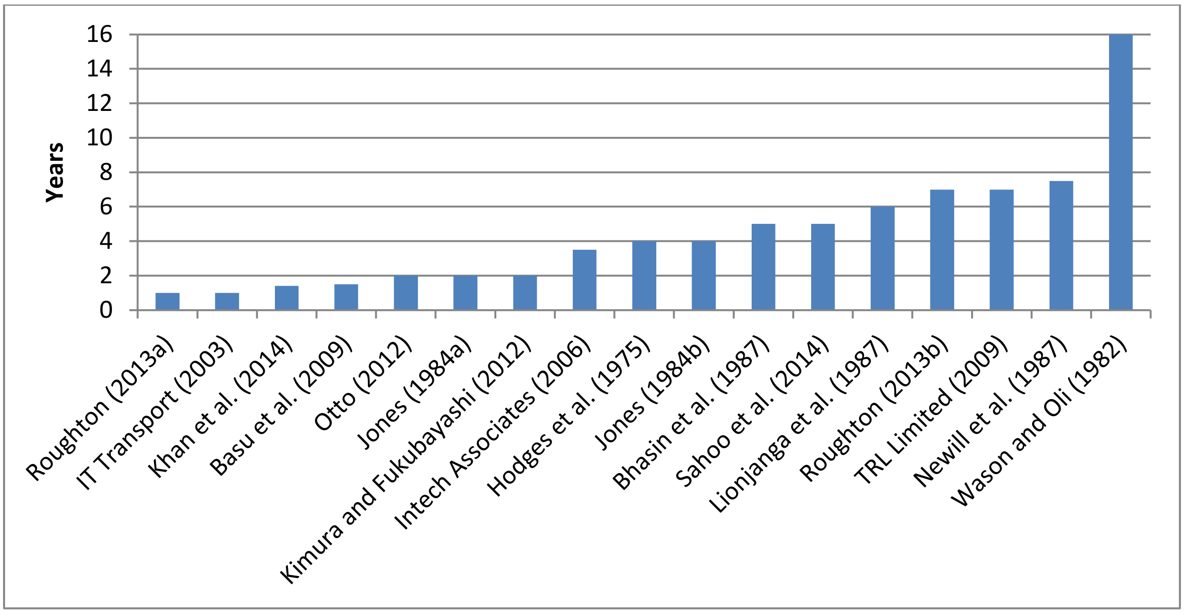

Figure 0.4: Length of studies (Slice-in-time studies are not included)

The studies broadly focused on the effect on road performance (n=22), and but two were associated with the materials used for LVRR construction (n= 20). Two studies were associated with maintenance of LVRRs and another on the costs of different road surfacing technologies on the operation of bicycles.

TECHNOLOGIES

Of those studies describing the use of materials for the construction of LVRRs, three focused on the performance of block surfaces of a LVRR, three were concerned with concrete road surfaces, eleven with sealed surfaces, eleven with unsealed surfaces, ten with sealed bases and/or sub-bases, one with unsealed bases and/or sub-bases and two with the use of geotextiles. Concerning LVRR maintenance, one study reported on methods used to carry out the maintenance and their effectiveness in relation to gravel roads, whilst another considered the use of a novel material for maintenance. These aspects are summarised in Table 0.1.

Table 0.1: Considered studies categories

Activity	Type of surface/road base	Study
Construction	Block surfaces	1, 2, 3
Construction	Concrete	1, 2, 3
Construction	Sealed bases and sub-bases	2, 3, 4, 5, 6, 7, 8, 9, 10,11
Construction	Sealed surfaces	1, 2, 3, 5, 6, 7, 10, 12, 13, 14, 15
Construction	Unsealed bases and sub-bases	9
Construction	Unsealed surfaces	1, 2, 3, 6, 9, 10, 11, 13, 16, 17, 18, 21
Construction	Geotextile	19, 20
Maintenance frequency	Unsealed surfaces	22
Maintenance material	Geotextile	23

[1]Roughton (2013a), [2]TRL (2009), [3]Roughton (2013b), [4]Gichaga (1991), [5]Wason and Oli (1982), [6]Otto (2012), [7]Gourley and Greening (1999), [8]Lionjanga et al. (1987), [9]Bhasin et al. (1987), [10]Hodges et al. (1975), [11]Newill et al. (1987), [12]Rolt et al. (2013), [13]IT Transport (2003), [14]Sahoo et al. (2014), [15]Pinard (2011), [16]Cook and Petts (2005), [17]Rolt et al. (2008), [18]Intech Associates (2006), [19]Basu et al. (2009), [20]Khan et al. (2014), [21]Jones (1984a), [22]Jones (1984b), [23]Kimura and Fukubayashi (2012)

In terms of outputs, all studies reported at least one measure of road condition. All of the before-and-after longitudinal studies reported road condition immediately after construction or maintenance (and often at time intervals in between).

The technologies uptake timeline is presented in Figure 3.6, which also presents the countries where the research on technologies was carried out.

The numbers of studies that covered the various types of road surfaces are shown in Figure 0.6. Although a large number considered sealed LVRRs, an analysis of the performance of sealed surfaces was the predominant focus of two studies (TRL, 2009; Roughton International, 2013b).

A variety of techniques and methods were used to assess the technologies. These are summarised in Figure 3.8. In most cases, two or more methods were used for measuring the condition of roads.

Most studies used visual assessment techniques (to determine cracking) allied to the measurement of road roughness to assess the functional performance of road sections. Structural performance was assessed in many cases using rutting and measures of deflection and CBR.

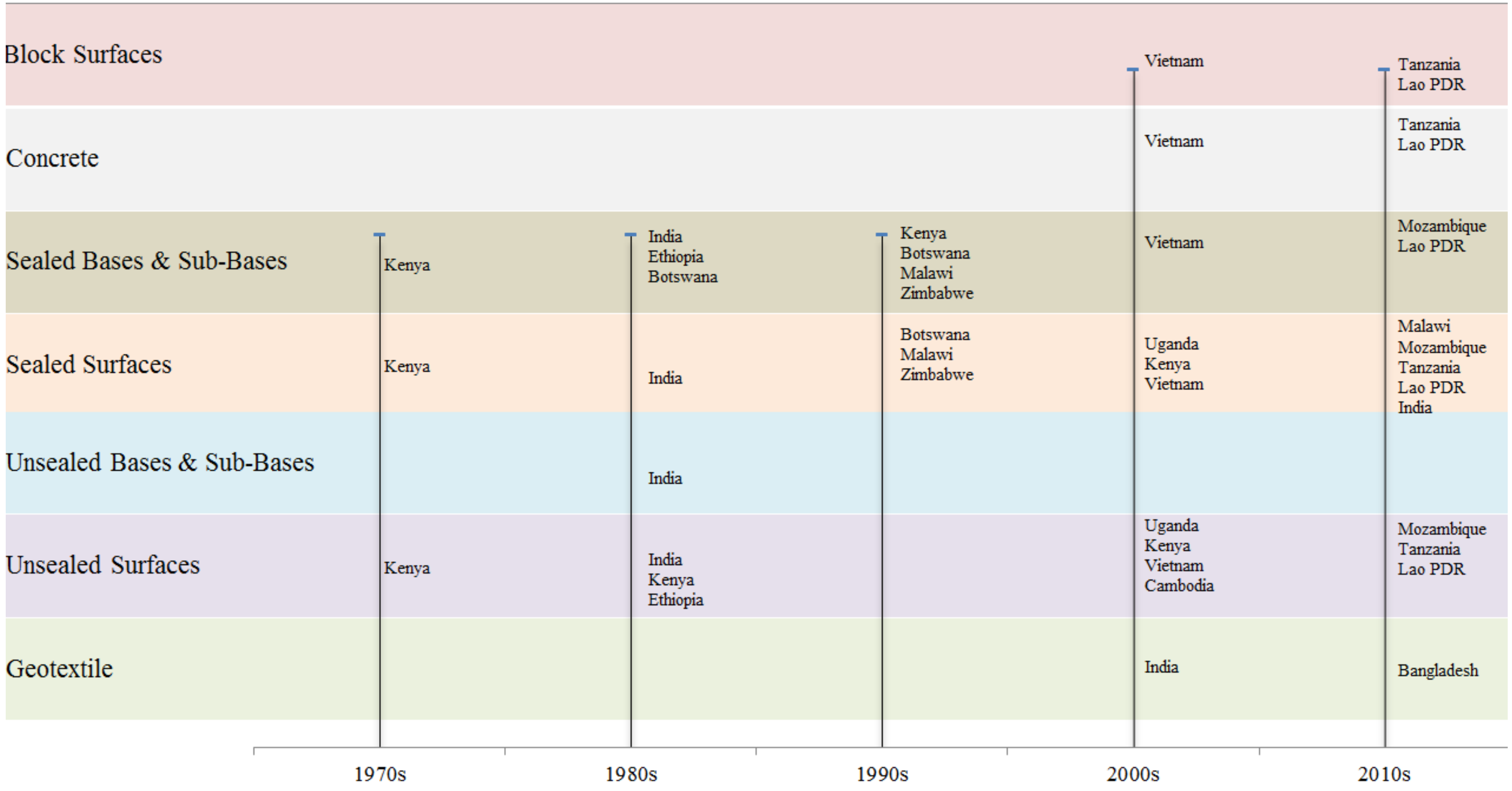

Figure 0.5: Technology uptake timeline

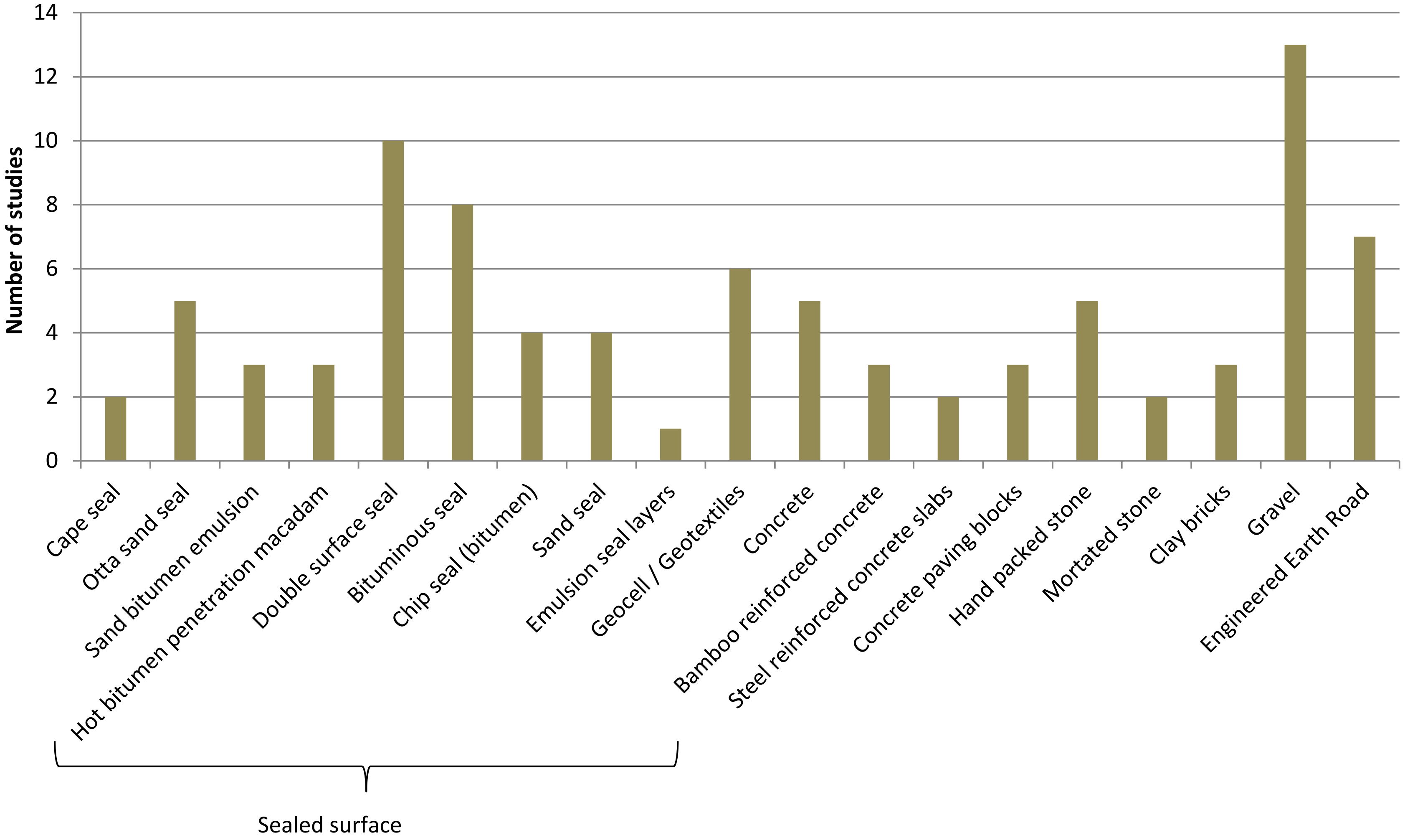

Figure 0.6: Road surface finishes considered in the studies examined

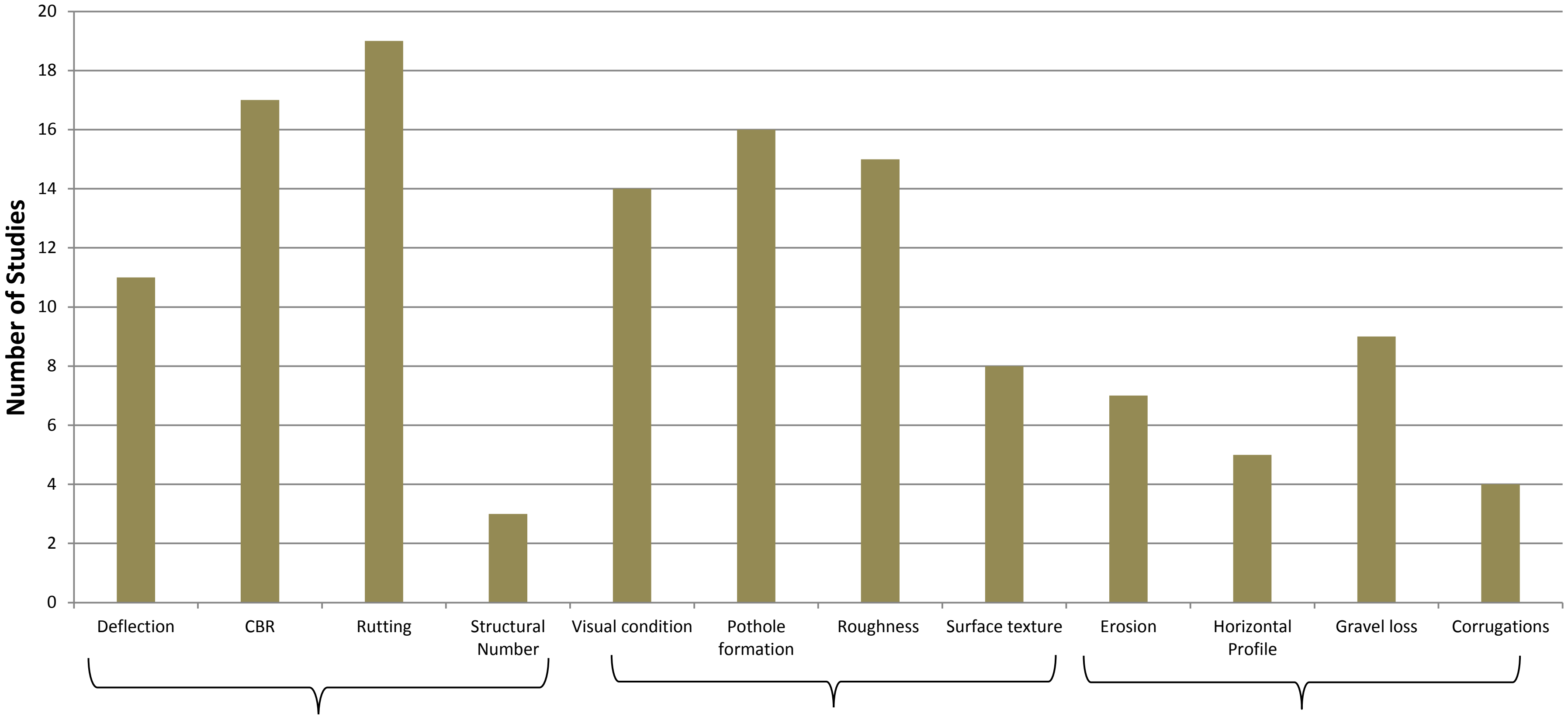

Figure 0.7: Methods used for monitoring the condition of LVRRs

4 DISCUSSION AND CONCLUSIONS

4.1 MOVING FROM IDENTIFYING STUDIES TO IN-DEPTH REVIEW

The findings of the first stage of the review process have been described in Chapter 3 together with a short description of the 23 studies (and three linked articles) included in the review. The second stage of the review process is described in this chapter, which presents the quality and findings of studies that could be synthesised to answer the review questions. From the 23 relevant studies, 15 provided quantitative data which could be synthesised to answer the primary review question:

> What is the evidence of the sustainability of technologies used in the appraisal, investment, design, construction and maintenance of LVRR in low-income countries?

Section 4.2 presents an overview of the quality and relevance of the studies for answering the review questions using a weight of evidence (WoE) approach. In Section 4.3, the 15 studies included in the synthesis are described in more detail. Information is given about the types of technologies found together with a breakdown of the study design, and the outcomes measured by each study. Section 0 explores briefly the technologies used, identifying any moderating considerations.

4.2 QUALITY AND RELEVANCE OF STUDIES

Following the logic described in Section 2.7, two reviewers extracted data from individual studies by answering questions about the aims of the study, the sampling strategy, its internal and external validity and the results, and made judgements about the trustworthiness of the findings. The coding tool used to extract data from each study and can be found in Appendix 4.

The WoE of each study, summarised in Table 0.1, was assessed through careful assessment of the study using the criteria given in Section 2.7. Three studies were considered to be high in terms of the soundness of the study (WoE A), appropriateness of study design (WoE B) and relevance (WoE C) (Wason and Oli, 1982; Gourley and Greening, 1999; Rolt et al., 2008). Twelve studies were considered to be high in terms of the soundness of the study (WoE A) and its relevance (WoE C) (Hodges et al., 1975; Jones, 1984a, b; Bhasin et al., 1987; Lionjanga et al., 1987; Newill et al., 1987; Cook and Petts, 2005; TRL Limited, 2009; Pinard, 2011; Rolt et al., 2013; Roughton International, 2013b; Sahoo et al., 2014).

The eight remaining studies were considered not to meet the criteria described in Section 2.7. Four, although rated highly in terms of relevance, were rated as medium in both the soundness of studies and appropriateness of study design for answering the review question (IT Transport, 2003; Intech Associates, 2006; Otto, 2012; Roughton International, 2013a). Two of these studies (Otto, 2012; Roughton International, 2013b) are interim reports of on-going studies and therefore suitable findings should be available in the future and they could therefore be included in any future systematic review. Three others were assessed as medium in terms of soundness, and low for appropriateness of study design for answering the review question (Gichaga, 1991; Basu et al., 2009; Khan et al., 2014).

Table 0.1: Summary of study assessment by weight of evidence

Study	WoE A (soundness)	WoE B (appropriate design)	WoE C (relevance)	Included in synthesis
Gourley and Greening (1999)	High	High	High	Included
Rolt et al. (2008)	High	High	High	Included
Wason and Oli (1982)	High	High	High	Included
Bhasin et al. (1987)	High	Medium	High	Included
Cook and Petts (2005)	High	Medium	High	Included
Hodges et al. (1975)	High	Medium	High	Included
Jones (1984a)	High	Medium	High	Included
Jones (1984b)	High	Medium	High	Included
Lionjanga et al. (1987)	High	Medium	High	Included
Newill et al. (1987)	High	Medium	High	Included
Pinard (2011)	High	Medium	High	Included
Rolt et al. (2013)	High	Medium	High	Included
Roughton (2013b)	High	Medium	High	Included
Sahoo et al. (2014)	High	Medium	High	Included
TRL Limited (2009)	High	Medium	High	Included
Intech Associates (2006)	Medium	Medium	High	Excluded
IT Transport (2003)	Medium	Medium	High	Excluded

Study	WoE A (soundness)	WoE B (appropriate design)	WoE C (relevance)	Included in synthesis
Otto (2012)	Medium	Medium	High	Excluded
Roughton (2013a)	Medium	Medium	High	Excluded
Basu et al.(2009)	Medium	Low	High	Excluded
Gichaga (1991)	Medium	Low	High	Excluded
Khan et al. (2014)	Medium	Low	High	Excluded
Kimura and Fukubayashi (2012)	Low	Low	High	Excluded

4.3 THE SUSTAINABILITY OF TECHNOLOGY INTERVENTIONS

The synthesis examines the impact of technologies used in the construction and maintenance of LVRRs in LICs/LMICs. The findings were organised according to the type of technology used, and are reported in the following order: (i) Road pavement construction (n=14) and (ii) Means of carrying out maintenance (labour and equipment) (n=1).

ROAD PAVEMENT CONSTRUCTION

Traditionally, rural roads in LICs were engineered earth roads (constructed of the in situ soil material), or roads provided with a natural gravel surface. The latter were ideally designed to a specification designed to protect the underlying sub-grade (foundation) from the environment in which they operated, namely the climate, surface and sub-surface hydrology, terrain, properties of the materials, sub-grade, traffic, construction and maintenance regimes. However, earth surfaces are often unable to provide year-round all-season surfaces in many regions and require regular routine maintenance (camber shape and drainage), particularly during and after any wet season. Gravel surfaces also require regular routine maintenance, and gravel material loss from road surfaces due to traffic and weather can be extreme in many environments, and replacing an often scare resource can be unsustainable. Consequently, alternative road constructions are being used in many LICs/LMICs. These comprise a variety of layered pavement constructions, including sealing the existing gravel, or constructing concrete, block/stone or flexible pavements. Many such roads are designed according to a particular standard, most often not using a rational analytical approach, which specifies the types of materials and their thicknesses to be used within the constituent layers of the road pavement. Increasingly however, it is recognised that these approaches are often unsuitable for the environment in which they are being applied, and consequently research is being conducted into alternative rational designs which incorporate different materials and thicknesses.

This review found 14 studies associated with the use of different materials and standards for road construction. Ten were associated with the use of alternative, low-cost and marginal materials (Hodges et al., 1975; Wason and Oli, 1982; Bhasin et al., 1987; Lionjanga et al., 1987; Newill et al., 1987; Gourley and Greening, 1999; TRL Limited, 2009; Pinard, 2011; Rolt et al., 2013; Roughton International, 2013a). One study (Sahoo et al., 2014) monitored the performance of sealed LVRRs constructed to new Indian design standards. Surprisingly, given that the vast majority of LVRR are gravel or earth roads, only four studies (Hodges et al., 1975; Jones, 1984b; Cook and Petts, 2005; Rolt et al., 2008) focused on the performance of existing in-service gravel and earth roads.

All of the studies report the durability of the designs and materials in terms of measures of functional and structural condition of the roads and discuss the sustainability of these technologies in terms of their deterioration over time, and their cost, availability and maintainability.

Twelve studies (Hodges et al., 1975; Wason and Oli, 1982; Bhasin et al., 1987; Lionjanga et al., 1987; Newill et al., 1987; Gourley and Greening, 1999; Cook and Petts, 2005; Rolt et al., 2008; TRL Limited, 2009; Pinard, 2011; Roughton International, 2013b; Sahoo et al., 2014) reported the impact of different types of road surfaces on road performance.

The performance of 5 broad categories of road surfaces were explored: (i) engineered earth roads (n=5), (ii) unsealed gravel roads (n=7), (iii) block surfaces (n=2), (iv) concrete surfaces (n=2) and (v) flexible pavement seals (n=10). Outcomes measured across the studies included both functional (n=15) and structural (n=15) measures of road condition. Six studies compared the performance of road sections of the trialled technology with control sections built without the trialled technology, but otherwise designed to the same standards (Wason and Oli, 1982; Bhasin et al., 1987; Lionjanga et al., 1987; Newill et al., 1987; TRL Limited, 2009; Roughton International, 2013b).

ENGINEERED EARTH ROADS (EER)

Engineered earth roads utilise the in situ soil material as the running surface and are shaped to form a camber to shed rainwater. Such roads are provided with a system of side drains, turn-out (mitre) drains and cross drainage to manage the dispersal of rain water. This is the most basic (and lowest cost) form of road engineering, and EER roads are in significant contrast to earth ‘tracks’ which have no engineered attributes. Although the majority of rural routes in developing regions are EER, there has been very little research into the performance of this surface type. Two relevant studies were identified in the review and are summarised in Table 0.2. Both studies formed a minor component of the reported programmes, which focused on other issues. A few projects have successfully applied EER (for example, Intech Associates, 1993) to LVRRs; however these were not pursued in the SR framework approach because of a lack of associated performance monitoring data. A summary of the indicators of sustainability from the two studies is given in Table 0.3.

Table 0.2: Earth road studies

Study	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Hodges et al. (1975)	Engineered earth roads	8 existing in-service earth roads in Kenya monitored over 2-4 years	Rainfall: 400–2,000 mm/yr AADT: 25–200 mvpd Gradient: 0-5.5%	Road condition (roughness, pothole depth, rut depth, looseness of surface material) Gravel loss Maintenance	(+-) Sustainability related to a number of factors; see Table 0.3
Rolt et al. (2008).	Engineered earth roads	Back analysis, 91 roads in Cambodia	Rainfall: 1,030-2,307 mm/yr AADT: <50 mvpd Gradient: 0–27%	Road condition (rut depth, visual condition, corrugation, erosion, CBR) All-season access	(+-) Sustainability related to a number of factors see Table 0.3

Note: +, -, +- symbols indicate that the technology is (+), is not (-) or is marginally (+-) sustainable in the physical and social environment in which the technology was trialled

The performance of 91 existing earth LVRRs in Cambodia was carried out by Rolt et al. (2008) using a slice-in-time method of study, where road performance was assessed according to functional (surface condition and ability to provide all-season access) and structural condition (CBR). The sites surveyed represented a range of road conditions and factors which might affect performance, including traffic, environment, topography and soil type. Data were collected via in situ field surveys and from laboratory analysis of field samples. Nearly half (45%) of the roads were reported as providing satisfactory all-year access, but 32% were reported as being too slippery when wet. Of these, approximately 25% were reported as providing only limited or no access in the wet season. The study tried to collate performance with a number of measurable engineering, geophysical and metrological parameters. However, it was difficult to establish rigorous relationships because of the high natural variability of performance and the large number of contributory factors (and their interactions) that determine the behaviour of EER LVRRs. A summary of the salient sustainability features of EER identified by the study is given in Table 0.3.

A smaller study of existing in-service earth roads (n=8) monitored over two years was carried in out in Kenya by Hodges et al. (1975). The study was part of a larger one associated with the performance of sealed and gravel LVRRs. The performance of the earth roads was monitored using field measures of road condition (roughness, pothole development, rutting, surface looseness of material) and via laboratory measurements of soil properties. The study was not able to find generally applicable relationships between measured parameters and performance or sustainability because of the small sample size and the large number of contributory factors and their associated interrelationships.

Table 0.3: Engineered earth road sustainability indicators matrix

Criterion[1]	A	B	C	D	E	F	G	H
Study	**Material strength**	**Grading coefficient[2]**	**Plasticity**	**Age/traffic**	**Rainfall <2,000 mm/year?**	**Longitudinal gradient <6%?**	**Camber and drainage arrangements provided**	**Routine maintenance applied (camber and drainage)**
Hodges et al. (1975)	5 of the 8 sites measured with soaked CBR of 14-27%	Assessed to be approx. 0–32 for the earth road trial sections	PI (Plasticity Index): ≤27. 23-88% passed the 0.06 mm sieve	ADDT approximately 50 mvpd	All sites <2,000 mm/year	All but one section <3%	Maintenance grading requirements depend on material properties. It is likely to be beneficial every 5,000–10,000 vehicle passes	Full and zero maintenance applied. The results were highly variable. Roughness was dependent on the grading regime
Rolt et al. (2008)	Range of existing roads analysed. Materials	Minimum of 10–45 recommended depending on rainfall, gradient	Plasticity Product (PP)[3] ideally <1,000. However,	95% of sites AADT <50 mvpd. Deterioration was time related. Traffic was found	Rainfall at sites up to 2,300mm/ year	Can be steeper than 6%, but material properties are	Camber, longitudinal slope, ease of run-off, crown height, good side drains	Assessed as critical to sustainability

	<26.5 mm Min. CBR of 15% at 95% of Proctor compaction recommended	and maintenance regime	higher values can perform but may be slippery when wet	not to be very influential. However, it should be noted that few sites were subjected to heavy trucks		important and maintenance is essential	and adequate cross drainage were all assessed as critical interrelated factors	

Notes: 1. The sustainability criteria are not ranked since their relative importance depends on the road's operating environment.

2. Defined by the product of the gravel component of the material (the percentage retained between the 26.5 and 2 mm sieves) and the percentage passing the 4.75 mm sieve/100. It indicates the degree of mechanical stability.

3. Plasticity Product (PP) is defined as the product of plasticity index (PI) and the percentage of fines smaller than 75 µm sieve. It indicates likely surface performance.

GRAVEL ROAD SURFACING

Naturally occurring gravel is widely used in emerging and developing economies as a road surfacing material. The surfacing gravel layer is placed on the previously shaped and compacted in situ soil formation or an intermediate layer of gravel material. A perceived attraction is that gravel surfacing is often of relatively low initial cost, and usually requires little processing. It merely needs to be excavated, (stockpiled/mixed if necessary), loaded, hauled, dumped, spread, (watered if necessary), shaped and compacted to form the road surface. Mechanical mixing or 'stabilisation' is sometimes practised to improve the particle grading properties. Despite generally low initial construction costs, regular and expensive maintenance may affect the whole life cycle cost considerations compared to other LVRR surface types. By the diverse nature of its geological formation, natural gravel is infinitely variable in its physical and engineering properties. From experience, most road authorities specify a range of characteristics required for use of the material as a gravel surfacing layer in view of its material loss and 'wearing' nature in use, due to the action of traffic and weather. These criteria usually relate to material soundness, particle grading and plasticity.

Seven studies were identified which considered the performance (and sustainability) of gravel surfaced roads. Three of these studies (Cook and Petts, 2005; Jones, 1984b; Hodges et al., 1975) analysed the performance of existing in-service gravel roads. An experiment described by Newill et al. (1987) compared the performance of a number of specially built trial sections of gravel roads. The three other studies (Bhasin et al., 1987; Roughton International, 2013b; TRL, 2009) utilised constructed gravel sections primarily as control sections to be compared with the performance of sealed road surfaces. These are described below in Section 05. All studies show that whilst there is no reasonable constraint to the use of gravel as a surfacing material in temporary or long-term situations, assuming that its material properties are superior to the in situ material being overlaid, there are a number of criteria that need to be met for a sustainable surfacing application as identified in the studies. These are summarised in Table 4.4.

Table 0.4: Summary of gravel road studies

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Bhasin et al. (1987)	Soil-gravel mix (Kankar[1]) bases and sub-bases within sealed and unsealed roads	5-year monitoring programme of trial sections in India	Average annual rainfall: <1,000 mm/yr. AADT: <300 AADT Terrain: unknown	Visual road condition Use of locally available low-grade material	(+-) Sustainable within a sealed road pavement only (see Table 4.8) Maintenance requirements greatly reduced where depth of construction >200 mm
Cook and Petts (2005)	Gravel roads	Back analysis of in-service gravel roads in Vietnam	Rainfall: 800-4,000 mm/yr AADT: <200 AADT Gradient: >6%	Road condition % gravel loss Maintenance Regravelling	(-) Gravel roads unsustainable
Hodges et al. (1975)	Gravel (lateritic, quartzitic, volcanic and coral) road surfaces	2-year monitoring of 38 existing gravel roads in Kenya for 2 years	Rainfall: 400–2,000 mm/yr AADT: 25–200 AADT Gradient: 0-5.5% on unpaved roads	Road condition (roughness, rut depth, looseness of surface material) Gravel loss Maintenance	(-) See Table 0.3

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Jones (1984b)	Gravel (lateritic, quartzitic, volcanic and coral) road surfaces	2-4 year monitoring of existing gravel roads in Kenya (99 sections in 11 roads)	Rainfall: 500-2,000 mm/yr Annual traffic: 1,533-81,760	Road condition (roughness, rut depth, looseness of surface material) Gravel loss Maintenance	(-) Sustainable for roads with less than 50–200 vpd depending on gravel type
Newill et al. (1987)	Volcanic cinder gravel surfaces, unstabilised and mechanically stabilised	2-year monitoring programme of 6 trial road sections in Ethiopia	Rainfall: ~750 mm/yr AADT: 150–200 vpd Terrain: unknown	Road condition % gravel loss Maintenance Regravelling	(-) Unsealed gravel roads unsustainable (although gravel loss can be reduced through mechanical stabilisation)
Roughton (2013b)	Gravel trials used as control sections in a wider study on alternative surfacing.	5-year monitoring programme of trial road sections. Lao PDR	Average annual rainfall: 1,300-1,500 mm/yr. Traffic: 126,000 ESALs over the monitoring period (67 vpd; 10% HGV). Gradients: flat (0–3%) to steep (10-15%)	Road condition (roughness, rut depth, texture depth, CBR) NPV	(+-) Sustainable only when sealed, and providing that maintenance can be applied on a routine basis and resealing can take place periodically (5 years for single seal, 10 years for double seal)

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
TRL (2009)	Gravel trials used as control sections in a wider study on alternative surfacing.	24-37 month monitoring of trial sections built to DCP design method. Vietnam and Cambodia	Rainfall : 1,400–3,000 mm/yr Traffic 1,000-330,000 ESALS over the monitoring period Gradient: flat (0–3%) to steep (10-15%)	Road condition (roughness, rut depth, texture depth, CBR, visual condition) Cost	(+-) Only when sealed

1. An impure concretionary carbonate of lime, usually occurring in nodules in alluvial deposits, and especially in the older of these formations.

An extensive study of 38 in-service engineered gravel roads (lateritic, quartzitic, volcanic and coral), in a variety of environments in Kenya, was carried out by Hodges et al. (1975) over two years. The test sections were selected to enable the performance of the roads to be related to the characteristics of the gravel (including strength and material grading), and additionally the frequency of road maintenance, the traffic flow and the characteristics of the natural environment (rainfall and gradient). The performance of the surface of the roads was quantified in terms of surface irregularities (roughness, corrugations), the rut depth in the wheel-tracks, the looseness of the surface material and gravel loss. The results showed that roughness, rut-depth development and surface looseness were functions of cumulative traffic loading, rainfall, gravel type and the particle size distribution of the gravel. It was also shown that the surface condition of the road was very dependent on the quality of the maintenance grading operation and that the frequency of grading could be as low as one grading for every 50,000 vehicles provided that the gravel road in question was not prone to corrugations. The performance of gravel roads, other than for gravel loss, was not found to depend on rainfall in the range of annual rainfall included in the study (400-2000 mm).

Jones (1984b) carried out a similar analysis in Kenya to that of Hodges et al. (1975), which assessed the performance of 99 sections of 11 gravel roads over two years. In addition to the Hodges et al. study, Jones included sandstone gravel roads but excluded coral gravels. The performance of the test sections was found to be strongly related to cumulative traffic, original design standards and construction, maintenance strategy and climate. He also found that rainfall increased the annual surface roughness by 970–1,100 mm per year for sandstone and quartzitic gravels. Of additional significance, the rate of gravel loss found in the study was higher than that predicted by Hodges et al. (1975). Jones (1984b) noted that total gravel loss in LICs/LMICs would increase annually because of additions to the road network and that the problem of sourcing suitable replacement gravel would therefore become exacerbated as road networks expanded and the sources of good road-making gravel continued to dwindle.

An assessment of gravel loss from 766 road sites on 269 roads (representing approximately 1,000 km) in Vietnam was carried out by Cook and Petts (2005). Gravel loss figures from their study indicated that around 58% of the surveyed sites were suffering unsustainable deterioration (20mm/yr), while 28% were losing material at twice the sustainable rate. Factors which affected gravel loss were found to be related to gravel type and quality, availability of gravel for replacement, climate, terrain, drainage provision and maintenance. In terms of unsustainable gravel losses the following percentages of sites were found with respect to gravel types: 82% (of 115 sites) with laterite gravels, 34% (of 35 sites) with laterite and rock, 71% (of 110 sites) of hill gravels, 42% (of 74 sites) of hill gravel and rock; 79% (out of 126 sites) of graded crushed stone, 24% (of 90 sites) of non-graded crushed stone, and 62% (of 60 sites) of alluvial gravels.

Newill et al. (1987) carried out an experiment to determine the suitability of four different types of marginal volcanic cinder gravels for use in LVRRs in Ethiopia. The use of these materials was assessed, since although they are widespread in Ethiopia, they were generally considered to be deficient in fine material and therefore not to conform to the generally accepted grading specifications for use in gravel roads. Part of the experiment involved the assessment of the use of gravels for unsurfaced roads using field trials of six specially constructed sections of road built on a standard sub-base and sub-grade (specified according to Road Note 31 – TRRL, 1997), monitored over two years. Two sections were mechanically stabilised via the addition of fines. The sections were assessed in terms of rutting, roughness, corrugation and gravel loss. All of the mechanically stabilised sections showed better performance in terms of lower rates of gravel loss and roughness and development of corrugations. Gravel loss for the stabilised sections was found to be marginally sustainable at 14-45 mm/year (compared to a value of 20 mm/year, which was considered to be sustainable) whilst for unstabilised sections, gravel loss was considered to be unsustainable (50–60 mm/year). All sections were surface dressed after two years.

Table 0.5: Surfacing gravel sustainability indicators matrix

Criterion	A	B	C	D	E	F	G	H
Study / country	**Material Specification set and applied?**	**AADT <200 mvpd**	**Rainfall <2,000 mm/yr?**	**Longitudinal gradient <6%?**	**Camber and drainage arrangements provided**	**Manageable rate of annual gravel loss (<20 mm/year assumed)[1]**	**Routine maintenance applied (camber and drainage)**	**Periodic regravelling applied to replace material losses**
Bhasin et al. (1987) India	7.5–10 cm surface layers of Kankar[3] over various bases	AADT ~300 mvpd (10% heavy vehicles)	Not reported but believed to be <600 mm/year	Not reported	Not reported	Not reported	Not reported	Had to be reconstructed after 3 years
Cook and Petts (2005) Vietnam	A relaxed specification, and 57% of the sites' materials were outside the accepted criteria for good surfacing gravel	All sites were believed to comply	55% of sites where rain was >2,000 mm/yr had gravel loss higher than sustainable. All authorities with rainfall of more than 3,000 mm/year had sealed	74% of sites with gradients of more than 6% exhibited significant erosion	60% of road sites experienced impeded run-off conditions. 48% of sites did not have side drainage where	58% of roads were losing gravel higher than a sustainable rate. 28% of roads were losing gravel at more than twice the sustainable rate	19–23% of the requirements achieved	2–11% of the requirements achieved

Criterion	A	B	C	D	E	F	G	H
Study / country	**Material Specification set and applied?**	**AADT <200 mvpd**	**Rainfall <2,000 mm/yr?**	**Longitudinal gradient <6%?**	**Camber and drainage arrangements provided**	**Manageable rate of annual gravel loss (<20 mm/year assumed)[1]**	**Routine maintenance applied (camber and drainage)**	**Periodic regravelling applied to replace material losses**
			their gravel roads		required			
Hodges et al. (1975) Kenya	Complied with Ministry of Transport specifications	AADT range 42-415 mvpd	Range: 400–2,000 mm/year	Maximum gradient 5.5%	Constructed with camber and drainage provided	Gravel loss 2-35 mm/year per 100 vpd depending on rainfall and gradient	Road condition very dependent on grading achievement	None achieved
Jones (1984b) Kenya	Constructed to national specifications	AADT <200 mvpd Some trucks, but few overloaded	Recorded rainfall <1,000 mm/year	All test sections ≤3%	Crossfall constructed at 4–6% and maintained at >3%	13-27 mm/ year; 100 vpd	Grading with compaction achieved on most trial sections[2]	Not relevant
Newill et al. (1987)	Cinder gravel, natural and	Approx. 170	<1,000	Not reported	Constructed with 2.5%	Gravel loss 15-45 mm/year	Some sections were graded and	Half of the sections were

Criterion	A	B	C	D	E	F	G	H
Study / country	**Material Specification set and applied?**	**AADT <200 mvpd**	**Rainfall <2,000 mm/yr?**	**Longitudinal gradient <6%?**	**Camber and drainage arrangements provided**	**Manageable rate of annual gravel loss (<20 mm/year assumed)[1]**	**Routine maintenance applied (camber and drainage)**	**Periodic regravelling applied to replace material losses**
Ethiopia	blended	mvpd	mm/year		camber	mechanically stabilised, 50-60 mm/year unstabilised	recompacted. However, roughness increased, ranging from 3 to 14 m/km in one year	reconstructed after 1 year
Roughton (2013b) Lao PDR	Constructed to national specs: CBR ≥25. However, monitoring of sources found only 27% of sources rated as good quality	2012 AADT of 20–107 mvpd (5 years after construction)	Trials area rainfall 1,500-2,000 mm/year	Sections >6% exhibited substantially higher gravel loss rates and erosion.	Provided originally, but not maintained	Gravel loss on all sections more than 200 mm in 5 years: unsustainable	2 of the 7 gravel road sections had reduced roughness. However, the average increased from 8.2-10.7 IRI	None achieved

Criterion	A	B	C	D	E	F	G	H
Study / country	**Material Specification set and applied?**	**AADT <200 mvpd**	**Rainfall <2,000 mm/yr?**	**Longitudinal gradient <6%?**	**Camber and drainage arrangements provided**	**Manageable rate of annual gravel loss (<20 mm/year assumed)[1]**	**Routine maintenance applied (camber and drainage)**	**Periodic regravelling applied to replace material losses**
TRL Limited (2009) Vietnam	Common poor compliance to specifications	All sites were believed to comply	Rainfall 1,500-3,000 mm/year	0–4.6%	Provided initially but not maintained	Gravel loss 12–59 mm/year	None apparent	Some sections had to be reconstructed to sealed standard after 15 months

Notes:

1. Will depend on a range of local factors, resources and capability. Assessed as a ‘benchmark’ value.

2. Note that routine grading is normally not accompanied by watering and compaction, so this represents a non-typical situation.

3. An impure concretionary carbonate of lime, usually occurring in nodules in alluvial deposits, and especially in the older of these formations.

BLOCK SURFACES

The trials of four different types of block surfaces, constructed over a variety of sub-bases, are reported in two studies (Roughton International, 2013b; TRL, 2009); these are summarised in Table 4.6. The four different block surfaces trialled were those constructed from fired clay bricks (TRL, 2009), concrete bricks (TRL, 2009; Roughton International, 2013b), dressed stone (TRL, 2009) and cobble stones (TRL, 2009; Roughton International, 2013b).

The study by Roughton International (2013b) found that after five, years all three of the trial road sections were performing adequately from an engineering perspective and their conditions were rated as either moderate or good. All surfaces were able to provide all-season access, but they showed significant shoulder wear. This was attributed to motorcyclists, who because of the high roughness associated with the surfaces, tended to avoid the main carriageway and use the hard shoulder.

TRL (2009) reported on the trial of 11 sections of different block surfaces made with fired clay bricks (n=6), concrete blocks (n=3), dressed stone (n=1) and cobble stones (n=1). The block layers were constructed over a variety of sub-bases. A statistically significant proportion (64%; $p < 0.05$) of the sections trialled were found to be in an unsatisfactory condition at the end of the monitoring period (24 to 37 months). Further, in all 11 cases the joints were found to be in a poor condition. Half of the clay brick sections performed satisfactorily and the other half unsatisfactorily, although the difference in performance cannot be explained by traffic or environmental factors, which were similar for all clay brick trials. Similarly, the two concrete block sections founded on dry-bound macadam performed unsatisfactorily whereas that on gravel performed adequately, despite the sections experiencing similar traffic and environmental loading. Both the stone sections were found to be in an unsatisfactory state. All of the sections with concrete blocks and all but one of the brick sections were sealed with sand. The seals on all eight of these sections were found to be in very poor condition at the end of the trial.

Table 0.6: Summary of block surfacing studies

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Roughton (2013b)	Non-mortared hand-packed stone on 50 mm sand / 125 mm gravel (25% CBR) Mortared stone (100mm) on 50 mm sand / 125 mm gravel (25% CBR) Concrete blocks (65mm bricks/ 20 mm sand / 125 mm gravel (25% CBR)	5-year monitoring programme of trial road sections. Lao PDR	Average annual rainfall: 1,300-1,500 mm/yr Traffic: 126,000 ESALs over monitoring period (67 vpd; 10% HGV) Gradients: flat (0–3%) to steep (10-15%)	Road condition (roughness, cracking, rut depth, CBR) NPV	(+) Integrity of all surfaces was good. Poor roughness performance of stone surfaces
TRL (2009)	Mortared clay bricks on cement-stabilised sand base Sand-sealed clay bricks on cement-stabilised sand or dry-bound macadam base Sand-sealed concrete bricks (100 mm) on natural gravel or dry-bound macadam Mortared dressed stones (200 mm) on natural gravel Cobble stones (100-150 mm) on dry-bound macadam	24–37 month monitoring of trial road sections built to DCP design method standards. Vietnam and Cambodia	Annual rainfall : 1,400–3000 mm/yr Traffic 1,000-330,000 ESALS over monitoring period Flat to steep gradients	Road condition (roughness, cracking, rut depth, CBR) NPV	Condition of 64% was unsatisfactory (-) Sand seals performed very poorly (+-) Mortared bricks (joint maintenance was critical)

CONCRETE ROAD SURFACES

Table 0.7 summarises the findings of the two studies which reported the outcomes of trials of rigid concrete road pavements constructed on a variety of sub-bases (TRL 2009; Roughton International, 2013b). Both studies reported the trials of both bamboo- and non-reinforced concrete slabs. In addition, Roughton International (2013b) described the outcome of trials using concrete geocell, whilst the TRL (2009) study also described the outcome of trials using steel-reinforced concrete. The studies found that the majority of concrete road pavements performed satisfactorily or better for the period of the trial. For the trials where a similarly designed control gravel road was also present, subject to comparable traffic and environmental loading, the performance of the trial section was better than that of the gravel control section.

The study by TRL (2009) found that a statistically significant number ($p < 0.05$; 16 out of 24; 67%) of concrete pavements were in at least a fair overall condition and showed little or no deterioration after 24 to 37 months of service in the form of cracking of the slabs, the primary mode of failure of concrete slabs. A statistically significant number (44%, $p < 0.05$) however showed considerable joint deterioration and a statistically significant number (49%, $p < 0.05$) exhibited shoulder erosion. Nine sections (38%) were rated as performing inadequately in terms of cracking. Further investigation reported by TRL (2009) found that the reason these sections performed poorly was always due to inappropriate construction in terms of poor-quality concrete used for the section and inadequate support for the concrete slabs. This was exacerbated in 6 of the 9 sections (67%) which experienced higher traffic loading compared to the average of the 24 sections. Six of the sections (25%) could be compared to control sections of gravel surfacing, and in all cases, their performance was rated as superior. After 24 months all gravel sections were rated as being in a very poor condition. The relative performance, in terms of the area of cracking present, of bamboo-reinforced (4.5% cracked area), steel-reinforced (3.6%) and non-reinforced (5%) trial sections for those sections which performed at least satisfactorily was found to be similar. However, 33% (3 out of 9) bamboo-reinforced sections, 25% (1 out of 4) steel-reinforced sections and 45% (5 out of 11) non-reinforced concrete sections performed unsatisfactorily. This suggests that statistically, steel-reinforced concrete sections perform less poorly than bamboo-reinforced sections or non-reinforced concrete sections ($p < 0.05$), and that bamboo sections perform less poorly than unreinforced concrete sections ($p < 0.05$).

In contrast the study by Roughton International (2013b) of seven sites (three of bamboo-reinforced concrete and four of concrete geocell) trialled over five years found that all of the sections were performing at least satisfactorily, while the gravel control sections adjacent to these sites were considered to have performed very poorly and had mostly lost their gravel surfaces. However, a detailed supporting analysis carried out as part of this study suggested that the bamboo did not contribute to the structural integrity of the pavement due to its disintegration and was therefore considered to be unnecessary.

Table 0.7: Summary of concrete surfacing studies

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Roughton (2013b)	Geocell reinforced concrete (75–150 mm thick) Bamboo-reinforced concrete slabs (125–150 mm thick)	5-year monitoring programme of trial road sections. Lao PDR	Average annual rainfall: 1,300-1,500 mm/yr. Traffic: 126,000 ESALs over monitoring period (67 vpd; 10% HGV). Gradients: flat (0–3%) to steep (10%-15%)	Road condition (roughness, cracking, rut depth, CBR) NPV	(+) Geocells: the majority of trial sites showed improved all-season performance. There was less requirement for maintenance (+-) The benefit of bamboo reinforcement was questionable
TRL (2009)	Bamboo- (150 mm thick) and steel-reinforced (150 mm thick) concrete slabs Non-reinforced concrete slabs (200 mm thick)	24–37 month monitoring of trial road sections built to DCP design method standards. Vietnam and Cambodia	Annual rainfall: 1,400–3,000 mm/yr Traffic 1,000-330,000 ESALS over the monitoring period Flat to steep gradients	Road condition (roughness, cracking, rut depth, CBR) NPV	(+) two-thirds of the trial studies with bamboo showed improved all-season performance (+) three-quarters of the steel-reinforced sections performed well with less requirement for maintenance (+-) slightly more than half

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
					of the non-reinforced concrete slabs performed adequately

SEALED SURFACES

Two different types of experiments were reported in ten studies which assessed the performance of sealed gravel roads. One type of experiment consisted of comparing the performance of specially built trial sections of roads, surfaced with a variety of seals, with control sections over a number of years (n=7). Four of these studies were primarily associated with the performance of marginal base and sub-base materials and they are therefore dealt with in Section 4.3.1.6. Sahoo et al. (2014) concerned the overall performance of the entire road section and is discussed in Section 4.3.1.7.

A second type of experiment consisted of slice-in-time studies of in service LVRRs sealed with a number of materials and of various ages (n=3) (Gourley and Greening, 1999; Pinard; 2011; Rolt et al., 2013). All of these are concerned with the overall performance of the entire road section and therefore are discussed in Section 4.3.1.7. Table 4.8 summarises the reported studies.

It should be noted that the task of seals in LVRRs is to provide a reasonable quality riding surface and to prevent moisture ingress into the lower layers of the road pavement. They contribute little to the strength of the pavement. Therefore, in an assessment of the performance of sealed LVRRs, it is necessary to distinguish between surface (seal) deterioration and structural failure of the base, sub-base or sub-grade (which may also manifest at the surface, primarily as certain forms of cracking or rutting).

Two high-quality studies considered explicitly a number of different seals in road trials (TRL, 2009; Roughton International, 2013b). In both sets of trials, seal performance was associated with its surface condition, as determined from visual surveys of cracking and potholes, and the measure of roughness and rutting. The largest of the two trials was reported by TRL (2009); it took place in Vietnam and Cambodia over 24–37 months and involved the monitoring of 55 road trial sections with a variety of flexible seals. Seven sections were sealed with penetration macadam hot bitumen, 15 with hot bitumen, nine with bitumen emulsion sand seal over SBST emulsion seal and 24 with bitumen DBST emulsion. A total of 86% of the penetration macadam sections and 58% of the bitumen DBST emulsion-sealed trial sections were performing satisfactorily after 24–37 months. However, only 40% of the sections with hot bitumen seals and 22% of those with bitumen emulsion sand seal over SBST emulsion seals were found to be performing adequately.

Table 0.8: Studies of seals

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Bhasin et al. (1987)	Soil-gravel mix (Kankar) bases and sub-bases within sealed and unsealed roads	5-year monitoring programme of trial sections in India	Rainfall: <1,000 mm/yr. AADT <300 mvpd Terrain: unknown	Visual road condition Use of locally available low-grade material	(+) Seals make the use of local gravel (Kankar) suitable as base/sub-base
Gourley and Greening (1999)	Quartzitic gravel weathered rock, lateritic gravel, calcareous gravel and sand road bases and sub-bases in sealed LVRRs	Back-analysis of 59 sections of in-service roads in Botswana, Malawi and Zimbabwe	Climate: Weinert N-values of ~2 <N <5 Design traffic: 0.05-0.8 million ESA Sub-grade CBR 15-30%	Road condition: roughness, rut depth, visual condition, cracking, CBR, deflection, structural number Base/sub-base performance: CBR, moisture content	(+) Seals enable natural gravel road base materials to be used successfully
Lionjanga et al. (1987)	Low-cost locally available calcretes in bases and sub-bases Lower-quality calcretes stabilised with cement,	7-year study of 9 different consecutive road sections each of 100 m length. Botswana	Rainfall: ranging between 200 mm and 800 mm, during the life of the experiment AADT: ranging between 180 and 260 mvpd, during	Local availability of materials Road condition (deformation, rutting, cracking, roughness, and	(+) Calcretes were sustainable as road bases and sub-bases (-) Stabilised materials were shown to be unsustainable on grounds

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
	lime or sand		the life of the experiment Gradient: I in 6	deflection)	of performance
Newill et al. (1987)	Volcanic cinder gravel bases and sub-bases in sealed and unsealed LVRRs	7½ year monitoring programme of trial road sections in Ethiopia	Rainfall: ~750 mm/yr AADT: 150–200 mvpd Terrain: unknown	Road condition % gravel loss Maintenance Regravelling	(+) Surfaced dressed sections sustainable (-) Unsealed gravel roads unsustainable
Pinard (2011)	2-layered sealed, upgraded gravel LVRRs	Back analysis of six existing roads constructed in a 2-layer system and four 3-layer roads constructed using unconventional specifications. Malawi	Annual rainfall: 600-1200 mm/yr Traffic: ~300 mvpd, 0.5 million ESA to date.	Road condition (visual condition, structural condition via DCP and rut depth) Construction costs	(+) 2-layer pavement system for upgrading gravel roads is effective
Rolt et al. (2013)	Performance of LVSR in Mozambique constructed	Back analysis of LVSR up to 10 years old	Rainfall: 532–1288 mm	Road condition (visual condition in terms of	(+-) From a structural point of view, roads are

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
	with marginal materials and/or not according to design standards		AADT: 166–993 mvpd	cracking, potholes; structural condition in terms of SN, rutting, deflection, CBR)	performing sustainably. Some issues from a functional point of view
Roughton (2013b)	Double Otta seal, single Otta seal with sand, sand seal	5-year monitoring programme of trial road sections. Lao PDR	Average annual rainfall: 1,300-1,500 mm/yr Traffic: 126,000 ESALs over monitoring period (67 vpd; 10% HGV) Gradients: Flat (0–3%) to steep (10%-15%)	Road condition (roughness, rut depth, texture depth, CBR) NPV	(+) Otta seals are sustainable provided maintenance can be applied on a routine basis and resealing can take place periodically (5 years for single seal, 10 years for double seal)
Sahoo et al. (2014)	Thin (20 mm) bituminous surfacing of LVRRs	6½ year monitoring programme of 19 road sections, each of 100 m, designed according to the Indian Road Congress standards	Annual rainfall: 1,435-2,252 mm/yr Daily traffic (initial) 68-281 cvpd Sub-grade modulus values: 41-119 MPa	Road condition (rutting >25 mm and roughness >850 mm/km)	(+) Assuming maintenance after 5 years, 84% of the trial sections could be considered to be performing satisfactorily

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
TRL (2009)	Thin flexible surfacing including: • Sand bitumen emulsions • Double stone chip bitumen emulsion • Double stone chip hot bitumen • Triple bitumen surface treatment (hot bitumen) • Penetration macadam • Otta Seal • Sealed dry-bound macadam • Sealed water-bound macadam • S and DBST with emulsion • Sealed armoured gravel	24–37 month monitoring of trial road sections built to DCP design method standards. Vietnam and Cambodia	Annual rainfall : 1,400–3000 mm/yr Traffic 1,000-330,000 ESALS over monitoring period Flat to steep gradients	Road condition (roughness, rut depth, texture depth, CBR, visual condition) Cost	(+) Penetration macadam and bitumen DBST emulsion seals appeared to be the most durable options
Wason and Oli (1982)	Use of moorum for road bases/sub-bases in sealed roads	Twenty 200 m consecutive trial sections monitored 4 times over a 16 year period. India	Annual rainfall: <1,000 mm/yr Traffic: 100-150 carts and 10-15 heavy vehicles per	Road condition (visual assessments of potholes, cracking, surface deformation; rut depth) Local availability of	(+) Sealed surfacing enable use of local gravel soil mix (moorum) as base or sub-base material

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
			day	materials Cost of materials	

The experiment described by Roughton International (2013b) trialled three seals (double Otta seal, single Otta seal with sand seal and sand seal) on road sections in Lao PDR over five years. The study found that all of the sections where Otta seals were used were performing satisfactorily, albeit some routine maintenance was required to address edge breaks and pothole formation. In contrast, the gravel control sections adjacent to these sites were considered to have performed very poorly, having lost completely their gravel surfaces. The double Otta seal section was in the best condition, exhibiting the lowest roughness and deflection values. The double Otta seal and the single Otta seal with sand seal were found to have similar NPV discounted over a 20-year analysis period (using discount rates of both 6% and 10%). The sand seal was found to have almost completely disintegrated after five years (although it should be noted that it is standard practice to add a second layer of sand seal within six months of construction).

A full-scale experiment carried out in Ethiopia to examine the performance of volcanic cinder gravels as the road base under bituminous surfaced roads was reported by Newill et al. (1987). Whilst the main aim of the experiment was to assess the performance of cinder gravels as road bases (see below), two different types of seals were trialled, a bituminous double surface dressing and a 50 mm roadmixed asphalt. Eleven consecutive 60 m sections of road surfaced with a double surface dressing and designed according to Road Note 31 (TRRL, 1997) were trialled. Three additional sections, also designed according to RN 31, one of 60 m and two of 120 m but surfaced with the roadmixed asphalt, were also built. The sections had a variety of materials as their bases and sub-bases, although at least one section with the surface dressing used the same materials (with the same thicknesses and properties) as the each of the three sections surfaced with roadmixed asphalt. All sections were subjected to 440,000 ESAL during a 7.5 year monitoring period and during this time their performance was assessed periodically in terms of functional measures of condition (roughness and cracking) and structurally (deflection and rutting). The 11 surfaced dressed sections performed well over the monitoring period in relation to both functional and structural measures of performance. However, those surfaced with roadmixed asphalt experienced top-down cracking which had initiated in the third year of the study for two of the three sections. By the sixth year all three premix sections had unacceptable amounts of cracking. These three sections also experienced unsatisfactory deflections which increased with surface cracking. Roadmixed asphalt was therefore considered not a suitable surfacing for cinder gravels.

BASES AND/OR SUB-BASES

Thirteen studies (listed in Table 4.9) reported on the performance of LVRRs constructed with a variety of road-base and sub-base materials and thicknesses. Botswana and India were the subject of two studies each and Cambodia, Ethiopia, Kenya, Lao PDR, Malawi, Mozambique, Uganda, Vietnam and Zimbabwe were each the subject of one study. The main objective of two of the studies, Roughton International (2013b) and TRL (2009), was to assess the performance of road surfaces, albeit with different base and sub-base materials within pavements designed to specifications. These studies have been described above. The study by Cook and Petts (2005) is primarily associated with gravel and earth roads and has therefore been discussed in Section 0. This section discusses the ten studies where the main focus is on bases and/or sub-bases.

Outcomes were reported in terms of the functional road condition and structural condition. Functional condition was assessed in terms of roughness (n=8), rutting (n=10) and cracking (n=10). Structural condition was reported in terms of road deflection (n=6) and CBR values (n= 7). Table 4.9 shows the performance of the road sections considered in the trials in terms of these outcomes.

Table 0.9: Studies of Bases and/or sub-bases

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Bhasin et al. (1987)	Soil-gravel mix (Kankar) bases and sub-bases within sealed and unsealed roads	5-year monitoring programme of trial sections in India	Average annual rainfall: <1000 mm/yr AADT <300 mvpd Terrain: unknown	Visual road condition Use of locally available low-grade material	(+) Sustainable within a sealed road pavement Maintenance requirements were greatly reduced where the depth of construction was >200 mm
Cook and Petts (2005)	Gravel and earth roads	Slice-in-time back analysis of in-service gravel and earth roads in Vietnam	Rainfall: 800-4,000 mm/yr AADT <200 mvpd Gradient: >6%	Road condition % gravel loss Maintenance Regravelling	(-) Gravel and earth roads were unsustainable
Gourley and Greening (1999)	Quartzitic gravel weathered rock, lateritic gravel, calcareous gravel and sand road bases and sub-bases in sealed LVRRs	Slice-in-time back-analysis of 59 sections of in-service roads in Botswana, Malawi and Zimbabwe	Climate: Weinert N-values of ~2 <N <5 Design traffic (ESA million): 0.05-0.8 Sub-grade CBR	Road condition: roughness, rut depth, visual condition, cracking, CBR, deflection, structural number	(+) The natural gravel roadbase materials can be successfully used in the upper pavement layers of LVRRs

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
			generally 15-30%	Base/sub-base performance: CBR; moisture content	
Hodges et al. (1975)	Engineered earth roads Gravel (lateritic, quartzitic, volcanic and coral) road surfaces	2-4 year monitoring period of in-service roads in Kenya: 8 earth roads, 38 gravel roads	Rainfall: 400–2,000 mm/yr Gradient 0-9% on paved; 0-5.5% on unpaved Traffic: 25–200 mvpd	Paved roads: roughness, rut depth, cracking, patching, deflection, CBR, moisture content Unpaved roads: road condition (roughness, rut depth, looseness of surface material) Gravel loss Maintenance	See Table 4.3
Lionjanga et al. (1987)	Low-cost locally available calcretes in bases and sub-bases Lower-quality calcretes stabilised with cement,	7-year study of 9 different consecutive road sections of 100 m length. Botswana	Rainfall: between 200 mm/yr - 800 mm/yr over the period of the experiment	Local availability of materials Road condition (deformation, rutting, cracking, roughness and	(+) Calcretes were sustainable as road bases and sub-bases (-) Stabilised materials were shown to be unsustainable on grounds of performance

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
	lime or sand		AADT: 180 to 260 mvpd over the period of the experiment Gradient: 1 in 6	deflection)	
Newill et al. (1987)	Volcanic cinder gravels bases and sub-bases (stabilised and un-stabilised) in sealed and unsealed LVRR	7½ year monitoring programme of trial road sections in Ethiopia	Rainfall: ~750 mm/yr AADT: 150–200 mvpd Terrain: unknown	Road condition % gravel loss Maintenance Regravelling	(+) Surfaced-dressed sections were sustainable (-) Unsealed gravel roads were unsustainable
Pinard (2011)	2-layered sealed, upgraded gravel LVRRs	Back analysis of six existing roads constructed in a 2-layer system and four 3-layer roads constructed using unconventional specifications. Malawi	Annual rainfall: 600-1,200 mm/yr Traffic: ~300 mvpd, 0.5 million ESA to date	Road condition (visual condition, structural condition via DCP and rut depth) Construction costs	(+) 2-layer pavement system for upgrading gravel roads is sustainable

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Rolt et al. (2008)	Effectiveness of engineered earth roads.	Slice-in-time back analysis. Cambodia	Rainfall: 1,030-2,307 mm/yr Traffic: 20-120 mvpd Longitudinal gradient: 0–27%	Road condition (rut depth, visual condition, corrugation, erosion) (potholes)	See Table 4.3
Rolt et al. (2013)	Performance of LVSR constructed with marginal materials and/or not according to design standards	Slice-in-time back analysis of LVSR up to 10 years old. Mozambique	Annual rainfall: 532–1,288 mm/yr Traffic: 166–993 vpd	Road condition (visual condition in terms of cracking, potholes; structural condition in terms of SN, rutting, deflection, CBR)	(+) From a structural point of view, the roads are performing sustainably. Some issues from a functional point of view.
Roughton (2013b)	Double Otta seal, single Otta seal with sand, sand seal	5-year monitoring programme of trial road sections. Lao PDR	Average annual rainfall: 1,300-1,500 mm/yr Traffic: 126,000 ESALs over monitoring period	Road condition (roughness, rut depth, texture depth, CBR) NPV	(+) Otta seals are sustainable provided maintenance can be applied on a routine basis and resealing can take place periodically (5 years for single seal, 10 years for double seal).

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
			(67 vpd; 10% HGV). Gradients: flat (0-3%) to steep (10-15%)		
Sahoo et al. (2014)	Thin (20 mm) bituminous surfacing of LVRR	6½ yr monitoring programme of 19 road sections each of 100 m designed according to the Indian Road Congress Standards	Annual rainfall: 1,435-2,252 mm/yr Daily traffic (initial) 68-281 cvpd Sub-grade modulus values: 41-119 MPa	Road condition (rutting >25 mm and roughness >850 mm/km)	(+) Assuming maintenance after 5 years, 84% of the trial sections could be considered to be performing satisfactorily
TRL (2009)	Sand bitumen emulsions Double stone chip bitumen emulsion Double stone chip hot bitumen Triple bitumen surface	24–37 month monitoring of trial road sections built to DCP design method standards. Vietnam and Cambodia	Annual rainfall: 1,400–3,000 mm/yr Traffic 1,000-330,000 ESALS over monitoring period Flat to steep gradients	Road condition (roughness, rut depth, texture depth, CBR, visual condition) Cost	(+) Penetration macadam and bitumen DBST emulsion seals appeared to be the most durable options

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
	treatment (hot bitumen) Penetration macadam Otta seal Sealed dry-bound macadam Sealed water-bound macadam S and DBST with emulsion Sealed armoured gravel				
Wason and Oli (1982)	Locally available moorum for road bases/sub-bases founded on black cotton soils. Lime-stabilised black-cotton sub-bases	20 x 200 m consecutive trial sections monitored 4 times over 16 years. India	Annual rainfall: <1,000 mm/yr Traffic: 100-150 carts and 10-15 heavy vehicles per day	Road condition (visual assessments of potholes, cracking, surface deformation and the measurement of rut depth) Local availability of materials	(+) Moorum soils can be sustainable as base and sub-base materials in sealed LVRRs. Their effectiveness can be increased by lime stabilisation (+) Lime stabilised black cotton soils can be used sustainably as sub-bases in sealed LVRRs. Cost savings of 15-40% can accrue

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
				Cost of materials	compared to using conventional materials

The study by Newill et al. (1987) investigated the use of four different low-grade volcanic cinder gravels in road bases in Ethiopia over 7½ years. Twenty consecutive sections of road were assessed, built on a standard sub-base and sub-grade according to specifications given in Road Note 31 (TRRL, 1997). All sections were subject to the same traffic loading (440,000 ESALs) and climate. Eleven sections were surfaced with a double surface dressing, three were surfaced with 50 mm of roadmixed asphalt and the remaining six sections were unsealed. The comparison of the performance of the two different surfacing materials has been discussed in the preceding section, whilst the performance of the unsealed gravel sections was discussed in section 0. Of the 11 surface-dressed sections, five had mechanically stabilised and two unstabilised cinder gravel bases. The four others had bases of dry-bound macadam, Sodere agglomerate and volcanic tuff, with crushed stone as the control section. The study assessed the performance of the road bases annually in terms of the condition of each trial section measured by the extent of surface cracking, rutting and deflection. It was found that all 14 surface dressed road bases were still performing satisfactorily after 7½ years. Further, the 11 double surfaced dressed trial sections showed no significant signs of rutting on any of the sections and all but one section showed little or no cracking.

An evaluation by Wason and Oli (1982) considered the use of low-cost locally available moorum and stabilised black cotton soils for road bases and sub-bases for LVRRs founded on black cotton soil areas in India. The use of such materials could achieve savings of up to 15–40% compared to the cost of using conventional materials. Twenty road sections, designed according to specifications given by the Indian Road Congress (1973a), and categorised broadly into four groups, were built and trialled over 16 years (see Table 4.9). The twenty 200 m long consecutive trial sections were monitored four times (after 3, 5, 9 and 16 years), and their performance was judged by visual assessments of potholes, cracking and surface deformation, and measurement of rut depth. Only routine maintenance was carried out on the sections during this time frame. After five years, when it might normally be expected that a surface dressing maintenance treatment would be applied to the road sections to prolong their lives, it was found that 12 of the trials (60%) were still performing satisfactorily, three (15%) required maintenance and five (25%) had failed prematurely. After 16 years, it was found that 8 out of 20 (40%) road sections were still performing satisfactorily, six (30%) were in need of maintenance and six (30%) had failed completely. The study found that of the eight sections where local moorum (stabilised or unstabilised) had been used in the base and sub-base course, 50% had performed satisfactorily and two sections had failed completely. The latter was attributable to the lack of adhesion of the bituminous surface dressing. Half of the trials (n=2), of roads built with a water-bound macadam with a moorum–lime stabilised sub-base were found to be performing satisfactorily and two sections required major maintenance. Of the four trials which utilised water-bound macadam and lime-stabilised moorum in the base course, together with lime-stabilised black cotton soil in the sub-base, one (25%) was found to be performing satisfactorily whilst two sections (50%) were in need of major maintenance. One section had failed. Four of the trials had followed the exact specifications of the Indian Road Congress without utilising local materials: two of the road sections were in need of major maintenance (50%) and two had failed. Nine of the 20 trials had used a conventional double-surface dressing as a wearing course, and of these, four (44%) had failed.

Lionjanga et al. (1987) reported a road experiment lasting seven years in Botswana that considered the use of four types of calcrete road bases and sub-bases, representing the range of calcretes that occurs in the region. The use of calcrete was investigated since it is virtually the only source of hard aggregate or gravel materials suitable for use in pavement layer construction in Botswana. The outcomes of the trials were measured in terms of the surface deformation, rutting, cracking, longitudinal roughness and surface deflection of nine different consecutive road sections, each of 100 m. In three of these sections, one of the calcretes of lower quality was also used to evaluate its suitability for stabilisation with Portland cement or hydrated lime, or mechanically with local Kalahari sand. A double surface dressing had been applied to all nine sections. Two control sections with standard gravel bases were also monitored. The study showed that, based on the minimal amount of rutting that occurred (<10 mm) and the absence of other forms of deformation or of cracking, the four untreated calcretes used in six of the sections performed satisfactorily and as least as well as the control sections over the monitoring period of seven years. However, the behaviour of cement- and lime-stabilised calcretes and the mechanically stabilised calcrete was unsatisfactory, as all three trial sections demonstrated substantial rutting (>20 mm) due to instability in the base layer.

A five-year study by Bhasin et al. (1987) investigated the use of locally available low-grade and low-cost materials in LVRR bases and sub-bases in India. Eighteen consecutive sections of 50 m length were built according to the design standards specified by the Indian Road Congress (1973b). The road bases and sub-bases consisted of locally available soil-gravel (Kankar) constructed to a depth of 100–250 mm and stabilised with lime. Fourteen of the sections were provided with a 20 mm thick surface dressing. The performance of the sections was assessed visually in terms of the formation of potholes, ravelling and cracking of the road surface. All of the sections with the surface dressing were found to perform satisfactorily for a period of four years. However, in the fifth year, the performance of all of those sections with a construction depth of less than 200 mm showed significant signs of distress and need of maintenance. On the other hand, all surface-dressed sections with a base/sub-base depth of more than 200 mm continued to perform satisfactorily. By contrast, the four sections which were not surface dressed remained in a satisfactory condition for only the first year after construction, and showed significant deterioration thereafter; by the third year, they were in an unsatisfactory condition.

PERFORMANCE OF LVSR IN GENERAL

Four studies were found which considered the performance in general of low-volume sealed roads (LVSR). Three were slice-in-time studies, by Rolt et al. (2013) Pinard (2011) and Gourley and Greening (1999), and one was a 6½ year field monitoring programme described by Sahoo et al. (2014).

A high-quality study by Rolt et al. (2013) presented the findings of a back-analysis study of 22 discrete sections of eight previously constructed sealed LVRRs in Mozambique. The roads had been constructed to previous design standards and consisted of sealed surfacing underlain by a variety of base and sub-base materials and thicknesses on different sub-grade soils. The road sections were between two and twelve years old. The performance of the roads was assessed in terms of visual condition (cracking and potholes) and structural condition (deflection, CBR and rutting). Despite high levels of traffic loading (0.3–2.7 MESAs) in relation to the maximum expected on an LVRR of approximately 1 MESAs, and the presence of weak bases in some sections (56% of in situ road base CBR values were below specifications), no significant structural failure was apparent on any of the sections. This was attributed to the overall strength of the road sections, which despite the relatively weak bases, was found to be significant. All road sections were assessed as having modified structural numbers commensurate with traffic loading capacities equal to or greater than 1.5 MESAs; 95% were found to be equal to or greater than 8 MESAs, and 82% were assessed as having traffic loading capacities of greater than 30 MESAs. Accordingly, the road sections had traffic loading capacities of between 5 and 23 times their estimated traffic carried. This in part was found to be related to strong sub-grades, 80% of which had CBR values of greater than 20%. Nevertheless, despite the structural strength of all of the road sections exceeding greatly the estimated traffic loading to the time of the study, 6 out of the 22 sections (27%) had failed according to the visual assessment of the surface condition (the rest of the sections were found to be in good to fair condition). The failure of the surfacing of a section where the road section is structurally sound suggests that surface failure is caused by environmental factors or road construction issues. Laboratory analysis of the bitumen used on Mozambique roads tended to corroborate this, as it showed that the bitumen was too brittle and aged up to twice as fast as should be expected. The failure of the surface condition on six of the sections had not apparently been so severe as to allow moisture ingress, despite relatively high annual rainfall, as the moisture content of all roads apart from one (four sections) was found to be lower than the optimum moisture content. The four sections (on one road) experiencing higher than optimum moisture content values, conversely, were performing well in terms of both structural (traffic loading capacity >30 MESAs) and visual condition (lowest average roughness values and second lowest average cracking index).

The back analysis slice-in-time study by Gourley and Greening (1999) described the performance of 59 sections of in-service sealed LVRRs in Botswana, Malawi and Zimbabwe, up to 25 years old, constructed with 10 different natural gravel road base and sub-base materials (quartzitic gravels, weathered rocks, lateritic gravels, and calcareous gravels and sands). The roads were assessed in terms of overall road pavement performance via parameters including moisture, strength (in situ CBR), riding quality (roughness), deformation (rutting), deflection, modified structural number and visual surface condition. The strength of the bases and sub-bases was also assessed in terms of CBR values. In terms of road pavement performance, a statistically significant proportion of the roads (88%; $p < 0.05$) were assessed as being in satisfactory (fair or better) condition. The wet season average modified structural number of a statistically significant number of the roads was above 2.5 (98%, $p < 0.05$). The CBR values of all of the bases were found to have remained at least as high as their design values, whilst a statistically significant proportion of the road sub-bases (97%, $p < 0.05$) were at least as high as their design values. Consequently, Gourley and Greening suggest that the major groups of natural gravel road base materials used in Zimbabwe, Malawi and Botswana can be used successfully in the upper pavement layers of sealed LVRRs.

Pinard (2011) describes a field- and laboratory-based study of six in service rural roads which had been constructed directly on the existing earth running surface. These roads, essentially two-layer road pavement systems, had therefore been constructed to less exacting (and costly) standards than dictated by current design manuals (which require a three-layer system). Furthermore, the materials used in the construction of the roads did not comply fully with the traditional standards and specifications normally applied in Malawi in terms of plasticity, grading and strength requirements. All of the six roads were between 10 and 30 years old and had all carried less than 0.25 MESA since construction. The performance of the roads was assessed via in situ measurements of their visual condition, drainage, rut depth, roughness and strength (CBR), supported by laboratory analyses of a number of properties of their constituent materials. These assessments showed a general absence of any significant deterioration on any road sections, indicating that all the roads were structurally sound and had performed well in the prevailing service environment (moisture regime, materials quality, traffic loading). Pinard (2011) concluded that for the relatively low volume of traffic carried, the performance of two-layer sealed road pavement systems was as satisfactory as the traditionally constructed three-layer systems. Such roads would allow savings in construction costs of 166–233%.

The performance of roads constructed with thin (20 mm) bituminous seals on road sections designed according to Indian Road Congress (2002) standards was investigated by Sahoo et al. (2014). In their 6½ year study of 19 in-service road sections, each 100 m long, built on sub-grade soils of elastic modulus values ranging from 41–119 MPa, they found that 32% had failed according to either the rutting performance criteria or the road roughness performance criteria. Of these two sections had failed in both rutting and roughness (11%) and four in excessive roughness alone (21%). However, maintenance could usually be expected to be carried out after approximately five years on such roads, after which time only three sections (16%) had failed.

ROAD MAINTENANCE APPROACHES

The high-quality study by Jones (1984a) (summarised in Table 0.10) demonstrated that maintenance of unpaved roads could be achieved by heavy equipment, intermediate equipment (tractor technology) or labour-based methods, confirming an earlier report by TRB (1981). In order to achieve the same degree of maintenance, labour-based methods would need to be applied more frequently than intermediate equipment, which would in turn require more frequent application than heavy equipment. The research, however, raised questions regarding the sustainability of the labour-based approach without an appropriate organisational and supervisory regime. This has since been reinforced by other studies not included in this review (e.g. O'Neill et al., 2010). Tractor-based maintenance has been demonstrated to be cheaper and more appropriate to a developing country environment by other investigations (Gongera and Petts, 2000; Petts, 2012). More powerful agricultural tractors are now commonly available in developing countries, and heavier (more powerful) towed graders are also now fabricated in developing countries (2-5 tonnes), compared to the one-tonne towed graders that this study investigated. LVRR technology justifies further rigorous comparative research on current construction and maintenance options.

The study reported on experiments designed to compare the relative performance of gravel LVRR when maintained by motor grader, towed grader, mechanical drags and-labour intensive methods. They were carried out over two years on four roads in Kenya. The comparisons were based on the measurement of changes in surface roughness, rut depths, gravel loss, depth of loose surface material and journey times, over a representative sample of eight road test sections subjected to different maintenance strategies. The study found that towed graders were capable of maintaining properly constructed gravel roads carrying up to 200 vehicles per day. LVRR with volcanic tuff gravels and carrying up to 100 vpd could be maintained to their initial roughness levels using tree booms every 7 days, tyre sledges every 14 days and mechanical drags at frequencies of between 14 and 35 days depending on the type of drag. Similar effects could be achieved using a towed grader every 49 days. For quartzitic gravel roads carrying up to 60 vehicles per day effective maintenance could be achieved using a tree boom every 30 days, a tyre sledge every 21-50 days, drags approximately every 60 days or a towed grader every 90 days.

Labour-intensive methods based on an intervention period of every 60 days were found to be adequate for the roads investigated in the study. However, the degree of supervision was found to influence considerably the quality of the remedial works and the subsequent rates of deterioration. Jones (1984a) found that the following improvements in roughness for gravel roads could be achieved: for roads with a roughness of 5,000–5,500 mm/km, a decrease in roughness of 20–30 mm/km, for roads with an average roughness of 5,500–6,000 mm/km, a reduction of 25-90 mm/km, and for roads with a roughness values of 6,000-7,000 mm/km, a reduction of 40-100 mm/km.

Table 0.10: Studies of road maintenance approaches

Authors	Technologies	Trial	Environment	Measures of sustainability	Outcome (+/- sustainability)
Jones (1984a)	Heavy equipment, intermediate equipment (tractor technology) and labour-based methods	2-year monitoring programme of 8 LVRR gravel sections each of 300 m length with transitions at each end of 25 metres on four roads in Kenya	AADT: 48-90 mvpd Gravel roads Monitored sections were chosen with continuous vertical gradients in one direction only	Changes in surface roughness, rut depths, gravel loss, depth of loose surface material and journey times, over a representative sample of road test sections which were subjected to different maintenance strategies	(+) Towed graders are capable of maintaining properly constructed gravel roads carrying up to 200 vpd. They can be used in preference to the more expensive motor graders but they cannot be used for reconstruction purposes (+) Mechanical drags can temporarily (for up to 2 months) improve the surface conditions of gravel roads. They are better adapted for use on roads where the surface roughness is less than 9000 mm/km and where the depth of loose material is not greater than 30 mm. (+) Labour-intensive methods were found to be adequate; however, the quality of the

					maintenance is significantly influenced by the degree of supervision

4.4 FURTHER EXPLORATION OF THE SUSTAINABILITY OF RURAL ROAD TECHNOLOGIES

Most studies (n=9) focused on a few technologies (less than three technologies) and provided limited evidence of sustainability. Usually, the sustainability of the technology was defined in terms of improving the physical performance of the road (with the perceived benefit of increased access and reduced access costs), using marginal materials (i.e. those that would not normally be used in road construction and which were in plentiful supply) and reducing the required maintenance; in some cases, this was linked to improved benefits and/or reduced costs of providing the technology, as opposed to alternative technologies. Whilst a number of studies postulated whether the technologies might be socially and/or environmentally sustainable, little or no data were provided to support these assertions, nor were the costs considered in global terms. Some studies introduced the concept of environmentally optimised design (EOD) (see for example Roughton International, 2013b and TRL, 2009) as a means by which different surfacing technologies could be introduced at the project level of road management, to suit a variety of task and environmental factors such as sub-grade properties, rainfall, material availability, construction capacity, gradient and flood risk. However, studies did not report where the procedure had been used nor did studies quantify its economic, social or environmental effectiveness.

All studies focused on the operational level and none considered whether a mix of technologies (for example construction types) could meet sustainably the LVRR requirements, as part of a wider transport policy, of a particular region or country. These issues are explored briefly by technology type below.

This review has defined a technology as being sustainable if it: (i) is performing adequately, and (ii) is capable of being maintained to the planned, designed and constructed standards, (iii) with the available financial and physical resources and the local operational arrangements, (iv) in the local environment. In order to be considered worthwhile, the technology would also need to have a positive effect on the road, or its environment. Therefore, for a technology to be shown to be sustainable studies should show that: (i) the benefits of the technology, over a defined period of time, exceed the economic, social and environmental costs of the technology, and (ii) the road agency or community has the required resources over the long term to meet the requirements to provide the benefits. For example, the benefits of a new surfacing may outweigh its costs; however, the benefits may not be fully realised unless the community has the resources (technical and financial) to maintain the surfacing. Further, sustainability suggests that benefits and costs need to be considered globally, rather than in the immediate environment in which the technology is to be applied.

ROAD PAVEMENT CONSTRUCTION

BLOCK SURFACES

The use of four different block surfaces for LVRRs was described in two high-quality studies (TRL, 2009; Roughton International, 2013b) (see Table 0.6). These were shown to perform adequately from an engineering point of view, for the lengths of the trials considered (up to 5 years), and their maintenance could, with the right socio-economic conditions, be sustainable. However, all of the technologies have other sustainability considerations which were not addressed fully in the studies. Clay bricks require the use of locally abundantly available soil; however, they also require know-how and energy for their production. Stone surfacing requires local stone to be quarried and it performs best when used in conjunction with mortar, which needs both water and potentially scarce cementitious materials. The production of concrete blocks, similarly, requires know-how to be produced adequately (the strength of the material was identified as a key component of its durability in both studies), as well as both cement and water. Maintenance of the block surfaces was identified as an issue in both studies, particularly of the mortar between joints; however, the ability and mechanisms needed for the communities at hand to carry out such maintenance was not addressed in any depth. Further, in both studies, the block surfaces were considered as an alternative within a designed LVRR, and therefore when considering their sustainability, that of the entire road pavement and its constituent materials needs to be considered.

CONCRETE ROAD SURFACES

The three types of concrete surfaces considered by Roughton International (2013b) and TRL (2009) were found to provide adequate surfaces, which were likely to provide good performance and require little maintenance (albeit the length of the longest study, five years, is somewhat shorter than the 20-year plus design life of the technologies) (see Table 0.7). However, both studies demonstrated that the performance of the concrete road surfaces was very dependent on the quality of the concrete used and the construction of the road. These require adequate facilities for manufacture and appropriate know-how, the availability of which need to be considered in relation to sustainability. The materials used in the manufacture of concrete also often need to be imported and are high in greenhouse gas emissions. Like the studies on block roads surfaces, concrete was considered as a surfacing within a designed LVRR, and therefore when considering its sustainability, it is necessary to consider the sustainability of the entire road pavement and its constituent materials.

SEALED SURFACES

Studies on sealed surfaces focused on whether sealed roads could be provided to improve the performance of LVRRs, in terms of surface condition and all-season access (n= 10) and reduce maintenance costs (n=2) at low initial cost. A number of the studies also demonstrated that alternative, less stringent designs than those specified locally provided LVRRs which performed at least as well as those designed using the more exacting standards. Pinard (2011) for example, showed that many such roads built in Malawi continue to perform adequately after over 25 years of service. However, all of the studies explored the use of sealed surfaces which utilise bitumen in one form or another. Bitumen, a by-product of the oil refining industry, is a scarce finite resource which has a number of environmental impacts, including carbon production associated with its manufacture. It also often needs to be imported. In this context, no studies attempted to determine the feasibility and implications of using bituminous surfaces for LVRR construction or maintenance, particularly as the unsealed LVRRs of many LICs/LMICs account for up to 80% of the entire road network, i.e., many thousands of miles of roads.

UNSEALED SURFACES

EARTH ROADS

The physical parameters required for earth roads to perform adequately in various environments were addressed by Rolt et al. (2008) and Hodges et al. (1975). Both studies showed that access via the earth roads studied was limited during the rainy season, and that maintenance and provision of adequate drainage was critical to their performance. However, the wider issues of whether the technical and economic capabilities existed to achieve the maintenance of the earth roads of the regions considered was not addressed within the studies. Issues associated with the incidence of in situ materials suitable for application of EER surfaces to build part or all of the LVRR networks in the region considered were not addressed. In terms of suitability of earth road surfaces for the range of vehicles available to poor rural communities and their seasonal transport requirements, there is a notable lack of evidence.

GRAVEL ROADS

The performance of gravel surfaced roads was considered in depth by eight studies which highlighted how roads of different types of gravel may perform under a range of physical environments. The rate at which surface gravel was lost from such roads and the requirement to replace the lost gravel was also addressed in all studies. Cook and Petts (2005), Jones (1984b) and Hodges et al. (1975) mentioned that finite gravel resources, particularly those of adequate quality, were being depleted with the age and number of gravel roads being built and that the distance required to transport gravel was also increasing with increased road network size. Operational issues of gravel selection and specification compliance are consequently becoming more critical in terms of the suitability and sustainability of this surface type. Cook and Petts (2005) found that a sustainable rate of gravel loss for the networks considered in their study was in the order of 20 mm per year. Similar analyses are required in other regions to determine the sustainable number and type of gravel roads that may be considered sustainable in a region. This would assist with the development of a suitable road type policy.

BASES AND/OR SUB-BASES

The studies by Newill et al. (1987), Lionjanga et al. (1987), Bhasin et al. (1987) and Wason and Oli (1982) focused on the use of locally available low-cost materials in the LVRR road bases and sub-bases and found that such materials, from an engineering point of view, could be utilised often at lower costs than materials stipulated in local standards. Provided these roads were sealed, had adequate drainage and were maintained appropriately, they could perform satisfactorily. However, none of the studies considered whether the application of the required seal was sustainable (see above), nor whether the local financial and technical resources would enable the roads to be maintained adequately.

ROAD MAINTENANCE APPROACHES

One high quality study by Jones (1984a) considered the effectiveness of different maintenance technologies on the performance of gravel roads. Whilst the study demonstrated that labour-based maintenance can be effective under adequate supervision, the issue of whether the supervision exists or whether there is an appetite, or culture, for labour-based maintenance was not addressed.

5 SUMMARY AND DISCUSSION

5.1 INTRODUCTION

This chapter summarises and reflects on the synthesis findings reported in Chapter 4 and informs the conclusions outlined in Chapter 6. Initially a summary of the main findings is given by technology type; thereafter, a reflection of the nature of those findings is presented, including a consideration of the current gaps in the evidence base. This is followed in Chapter 6 by the recommendations for policy, practice and research and finally the strengths and limitations of this systematic review are discussed.

SUMMARY OF MAIN FINDINGS

All of the 23 included studies quantitatively measured the impact of technology interventions; 15 of these were judged to be of sufficient quality to inform findings on the sustainability of the intervention, whilst the remaining 8 studies were excluded from the synthesis.

Sustainability was measured in all 15 studies in terms of the performance of technologies in engineering terms. Seven studies also included some analysis of cost. Fourteen of the studies assessed the use of materials in the construction of roads (including two which focused on gravel surfaced roads and one on engineered earth roads); 11 of them focused entirely on the use of locally sourced or marginal materials. One study considered the effectiveness of low-cost and labour-intensive maintenance techniques for gravel roads as alternatives to the use of capital-intensive heavy machinery. Six of the studies reported on the performance of specially constructed sections of road built to trial particular technologies, whose performances were monitored periodically over 2 to 16 years. In all of these studies the performance of the trialled technology was assessed against a control section of gravel-surfaced road. Eight studies measured the performance of existing in-service roads, of which five took a slice-in-time view of road sections of various ages in various conditions. Three others measured the performance of roads over a two-year period, one of these considered the effectiveness of maintenance technologies. One other study monitored the performance of newly constructed in-service roads for 6½ years. Table 0.1, based on Roughton International (2013b) and TRL (2009), summarises the sustainability of the trialled road pavement technologies against some key indicators, the relative importance of which may be considered to be specific to the local environment. In Table 5.1 an average score is given for each technology; however, this has assumed that each of the key indicators has the same weighting, and therefore the average score should only be considered as a guide to the sustainability of any of the technologies in a given environment. For specific contexts and environments, scores may be obtained by utilising approaches, such as a pair-wise comparison, to obtain the weights based on expert opinion of their relative importance (Saaty, 1980).

Table 0.1: Trial technologies against some key markers

		Measure of sustainability													
	Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak sub-grades**	**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
	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

		Measure of sustainability													
	Technology	**Local/marginal material**	**Labour based**	**Simplicity of construction**	**Maintainability**	**Suitability in high rainfall environs**	**Suitability for use on weak sub-grades**	**Small contractor suitability**	**Local economy advantages**	**Resistance to axle overloading**	**Initial cost**	**Possible whole life cost advantage**	**Environmental impact**	**Achieved road serviceability**	**AVERAGE SCORE**
	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 sub-grades**	**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.

COUNTRY CONTEXT

It is important to note that the selection of a sustainable technology is related not just to the technology, but also to the geo-socio-political environments 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 routine and/or periodic 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, and include:

(i) **Roads managed and financed by a traditional district council**. In this case, the roads are typically looked after by the district works department and are financed through the district council budget (local revenues, plus grants from central government). Typically, there is an acute shortage of qualified technical staff; work is often done by force account, but may also be done by local contractors. Design and supervision is problematic and so is the provision of regular maintenance funds. Accordingly, 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**. Here the roads are looked after by a special-purpose rural roads department (i.e., either a free-standing central government department or part of a central local government department). The roads are financed through the central government budget and the staff form part of the national civil service. Typically, these organisations employ technically qualified staff (salaries are often lower than private-sector comparators), they usually use private-sector contractors (although central government agencies do not always manage local contractors effectively, because they are far away from the roads department) and get reasonable (but not always adequate and timely) budgets for maintenance. There is a slight bias against using labour-based construction and maintenance technologies because they make it more difficult for the road agency staff to seek ‘gratification’ payments. Maintenance funds are not always allocated in a timely fashion. Sustainable technology in this context:

- could use cutting edge 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 of roads**. In this case, the roads are managed and maintained by consultants and contractors working as agents for the local road agencies. Funds typically come from a national road fund, but could also come through the ministry of local government. All road works are strictly 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.

What is the evidence supporting the technology selection for low-volume, rural roads in low-income countries?

ROAD PAVEMENT CONSTRUCTION

BLOCK SURFACES

The performances over 2–5 years of four types of block LVRR surfaces (clay fired brick, concrete bricks, dressed stone and cobble stones) were described in two studies of field trials of road pavements. Both studies demonstrated that block surfaces are a sustainable option for surfacing a LVRR and are particularly suited to environments where the rainfall is high (>2000 mm/year), and the sub-grade is weak (see Table 4.6). The most sustainable surface (Table 5.1) was found to be dressed stone/cobble, in particular where they could be locally sourced and manufactured using labour-intensive methods. Fired clay and concrete bricks may be regarded as marginally less sustainable since they require energy sources to produce.

A disadvantage of dressed stone/cobble surfaces, however, is that they offer a much rougher surface than clay and concrete bricks, and therefore they may not provide a suitable solution for LVRRs where it is important to minimise road-user costs, for example taking cash crops to market. As a result of the high roughness of these surfaces, both studies found that motorcyclists and cyclists tended to use the shoulder of stone/cobble surfaced roads, causing edge wear. Over time, this may cause water ingress into the pavement structure, accelerating its deterioration.

DETERIORATION

(i) **Dominant defects**: Joint and surface deterioration were observed to be the dominant defects in both studies, although mortared joints appeared to have some advantages over sealed sand joints in high erosion environments, albeit with a possible disadvantage in the loss of inter-block flexibility.

(ii) **The seals on block surfaces**: The studies demonstrated that the seals performed very poorly, and in many cases were completely eroded within two years. This is partly to be expected as recent international findings, reported in the studies, suggest that a second sand seal should be laid within six months of construction to ensure its continued performance.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

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

(i) the quality of construction of the surfacings

(ii) the compliance with brick (clay and concrete) specifications. The minimum strength requirement of 20-25 MPa for manufactured engineering quality bricks was found to be important

(iii) timely and regular maintenance, which can ensure that good performance can be retained for a long time (particularly with respect to joints and seals). Repairing joints and seals may be regarded as a very necessary routine maintenance task to ensure both the integrity of the wearing surface and to help prevent water ingress into the pavement structure.

(iv) the low tensile strength of joints (other than possibly those of prohibitively expensive pitch or bitumen); they thus tend to break down under repetitive wheel loads. It is important therefore when designing block road surfaces to ensure that the base is strong enough to sustain the loading environment.

CONCRETE ROAD SURFACES

Two studies reported the performance of concrete road surfaces in Vietnam, Cambodia and Lao PDR; both studies described trials of both bamboo and non-reinforced concrete slabs; one described the outcome of trials using a concrete geocell (Lao PDR), whilst the other study also assessed steel-reinforced concrete road surfaces. The evidence from the two studies suggests that all four types of concrete road surface perform satisfactorily in all environments considered, provided that they are constructed to appropriate standards and the joints are maintained adequately (see above). As far as riding quality is concerned, concrete road surfaces provide an advantage over most other surfaces since they have low roughness when constructed properly, and require little maintenance other than to the joints (see above). However, they have high initial construction costs. Therefore, LVRRs constructed from concrete may be considered most appropriate when the major requirements are to provide all-season access and to ensure that road-user costs are minimised.

In structural terms, concrete reinforced with steel was found to perform marginally better on weak sub-grades than non-reinforced options. This is to be expected since in bending under traffic load, the lower part of a concrete road section is in tension. However, since the tensile strength of concrete is relatively low, the lower part of the road pavement may require appropriately placed reinforcement when constructed with material which is strong under tension (such as steel rods) to prevent the concrete slab from cracking, particularly when traffic loads are high and sub-grade support conditions are weak. Steel, however, needs to be imported and is relatively expensive. Further, it may also be questioned whether reinforcement is necessary on LVRRs, since they are designed to carry light traffic loads, albeit they can be subject to significant (illegal) overload. Bamboo, chemically treated to prevent its deterioration, has also been used as reinforcement in concrete LVRRs and its efficacy was investigated in the two studies. Both studies showed that road sections made from concrete reinforced with bamboo performed at least as well as those without reinforcement (see Table 4.7), but bamboo-reinforced slabs were found to be more expensive to manufacture in part due to the requirement for them to be chemically treated. However, a detailed supporting analysis carried out as part of the study reported by

Roughton International (2013b) suggested that the bamboo did not contribute to the structural integrity of the pavement due to its disintegration and was therefore considered to be an unnecessary addition.

Both studies found that inter-slab joints could be prone to early deterioration (see above) and it is therefore a significant feature when considering the life-cycle cost of concrete slabs with respect to other surfacing options.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

The maintenance costs of the concrete sections may be considered to be low in the environments considered; however, as mentioned above concrete road sections have a high initial construction cost, are likely to require the use of imported material, and require precise construction. Further, the two studies found that repairs to inter-slab joints seals were required after 2–3 years of operation (see above). There may also be significant costs associated with the repair of cracks. Poor construction according to both studies, was also a major factor in contributing towards poor concrete slab performance.

One of the studies suggested that the use of a sand bedding layer for the concrete should not be recommended as the advantages of its use appear to be outweighed by the risk of erosion and undercutting, particularly in high rainfall and flood-prone areas. Rather, the study recommended that the concrete slabs may be constructed directly on a smooth well-prepared sub-base.

SEALED SURFACES

The performance of sealed LVRRs was assessed in 10 studies. Six of these reported the results of controlled trials of different types of seals, three were slice-in-time analyses of existing roads and one reported the performance of newly constructed in-service roads designed to meet national standards. All 10 studies established that the sealed LVRRs were sustainable and many of the roads examined in the studies were found to be performing adequately after the expected lifetime of the seal (5 -10 years), 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.

A main purpose of sealing a road surface is to prevent moisture ingress into the road pavement, seals also provide a satisfactory all-season running surface, which reduces road-user costs through lower road roughness. LVRRs deteriorate predominantly as a function of the environment (i.e. rainfall and temperature) rather than due to traffic loading (assuming that the roads are not subjected to traffic loads greater than that for which they have been designed, i.e. cumulative loads of less than approximately 0.5–1.0 MESA). Water ingress in road pavements tends to soften any fine-grained load-bearing sub-grade, thus weakening the road foundation. Furthermore, water ingress and the softening of the sub-grade may also result, under traffic load, in the upward migration of fines into the sub-base and base layers (i.e. pumping), further damaging the road pavement structure. Therefore the ability of seals to maintain their integrity and prevent water ingress is of fundamental importance and by so doing seals can allow for the use of weaker (marginal) materials, or a reduced thickness of more competent materials, within the road pavement.

A valid comparison of the use of many types of seals, operating under a variety of environmental conditions, which is supported by the evidence from the studies considered in this review (see Table 5.1) is given by Gourley and Greening (1999) and summarised in Table 0.2. The information in the table suggests that, as expected, the extra thickness of surfacing material provided by double and Cape seals enables them to perform the best of all those seals considered and in a wide range of environments, particularly where gradients are steep, albeit at higher initial construction cost. This would suggest a policy where double or Cape seals could be used for steep gradients in excess of 10%, with single seals being used for other parts of a sealed LVRR.

In low-rainfall environments where low road roughness is an important consideration, an emulsion sand seal may provide an appropriate solution (see Table 5.1), as it provides a good 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, these technologies require the use of scarce finite material resources and, with the exception of emulsion stone chip seals, necessitate the use of mechanical equipment to construct and maintain them.

Table 0.2: Selection criteria for different sealed surfacings (Gourley et al., 1999)

Surfacing type	Situations of use			
	Requiring little maintenance	Steep gradients (>10%)	Wet climate or poor drainage	Turning trucks
Single seal (conventional)	No	No	Yes	No
Double seal (conventional)	Yes	Yes	Yes	Yes
Single graded seal (e.g. Otta)	Yes	No	Yes	No
Double graded seal (e.g. double Otta)	Yes	Yes	Yes	Yes
Slurry seal	Yes	No	Yes	Yes
Cape seal	Yes	Yes	Yes	Yes
Sand seal	No	No	No	No

There is additional evidence, which may be very specific to the environments in which the studies were made, as follows:

(i) In one study in Ethiopia, the use of a 50 mm road-mixed asphalt was found to perform much more poorly than a bituminous double surfaced-dressed seal. There is evidence that this may be related to issues associated with construction.

(ii) In Vietnam, there is evidence that:

- the double bitumen emulsion chip seals DBST(e) performed better than the Vietnamese standard hot bitumen DBST seals.
- the penetration macadam performed better than either DBST or DBST(e) seals.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

Poor construction quality was found to be a major issue with many seals, greatly affecting their performance and that of the road pavement. Two studies demonstrated that where contractors had significant experience with a particular seal, the seal was constructed to a reasonable standard and as a result performed adequately.

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. The early maintenance of such defects prevents water ingress into the road pavement structure, in particular, and therefore the softening of the sub-grade and possible premature failure of the road (as discussed above). Routine maintenance notwithstanding, periodic maintenance re-sealing is required after approximately five years (for single seals) to ten years (for double seals) (depending on environmental conditions and to a lesser extent the cumulative traffic loading).

BASE AND SUB-BASE PERFORMANCE

The performance of seals can be influenced by base, sub-base or sub-grade performance, providing further evidence that an adequate structural design of the road is required. One study, for example, demonstrated a link between reflection cracking in seals and lime- or cement-stabilised bases. This phenomenon is well documented in the literature, which shows that the prevalence and damaging effects of reflection cracking are a function of the percentage of stabiliser used.

SHOULDERS

Four studies demonstrated the benefit of sealing the shoulders of LVRRs, thus enabling a drier environment to be maintained under the road pavement, even during periods of high rainfall. Sealed shoulders, in conjunction with an adequately designed road drainage system, facilitate the movement of moisture well away from the wheel track thereby preventing the moisture from softening load-bearing fine-grained sub-grades, and hence preventing accelerated road pavement deterioration.

BASES AND SUB-BASES

Ten studies reported on the performance of LVRR sealed roads constructed with a variety of bases and sub-bases. Seven of these reflected on the use of locally available, low-cost and marginal materials. Three of these were slice-in-time studies of existing road sections, whilst four assessed the performance of trial road sections over periods of 5–16 years. The studies found that in the LVRRs constructed with the majority of base and sub-base materials investigated, performance was satisfactory from a functional and structural point of view, provided that the road was sealed, designed appropriately and well-constructed (see Table 4.9).

USE OF MARGINAL MATERIALS

All studies showed that marginal materials (including all gravels considered) could be used as bases and/or sub-bases, with lower than conventionally accepted strengths (CBR values), provided that these layers were protected from moisture ingress via an impervious seal and through appropriate drainage (for the reasons mentioned above), and that the road structure had been designed adequately to carry the expected cumulative traffic loads. The latter is important since it should prevent the materials within the road pavement structure (i.e. the base, sub-base materials and sub-grade), from being stressed to levels which would cause them to fail before the end of the road's design life.

UNCONVENTIONAL PAVEMENT DESIGNS

Two slice-in-time studies, in Malawi and Mozambique respectively (see Table 4.9), suggested that two-layered sealed LVRRs could perform sustainably over a number of years, from a structural point of view. Such roads might reduce construction costs of conventional thicker designs, which incorporate three layers, by 166-233%. This is further evidence of the need to adopt appropriate structural design standards for LVRRs. A major purpose of the pavement layers within a flexible road pavement structure is to prevent the stresses and strains in the sub-grade that are induced by road traffic from exceeding those that the sub-grade is capable of withstanding, for a predetermined design period. These stress and strain settings are based on the expectation of a suitable remedial treatment being provided at the end of the design period. Thicker road pavements structures (i.e. in general those with more layers, assuming that the elastic properties of the layers are similar) reduce the stresses in the sub-grade by a greater amount than thinner road pavement structures. However, as the traffic (and therefore the loads) carried by LVRRs is generally of relatively low magnitude, the necessity for thick road pavement layers is reduced. Therefore, many LVRRs may not require thicker three-layer designs, but instead two-layer designs may be adequate, particularly where the road is founded on a relatively strong sub-grade (i.e. CBR ≥30%).

STABILISATION

In three of the studies, the performance of marginal materials was found to be enhanced by chemical stabilisation (with lime and/or cement). Another study demonstrated that the behaviour of marginal materials with inappropriate grading characteristics could be enhanced by mechanical stabilisation with fines. Appropriately stabilised road bases and sub-bases, however, are very reliant on good construction practices.

However, one study (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 (only modification occurred) and the instability of the bases under road traffic, during which time the material behaved similarly to single-sized sands.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

All four of the studies in which trial road sections were constructed with different road bases and sub-bases and monitored over a period of time found that only those sections which were sealed appropriately performed satisfactorily. Notwithstanding, the studies showed that without periodic maintenance singled-sealed roads started to show signs of significant deterioration after approximately five years. This is approximately the time when resealing of these LVRRs would be expected, and if such maintenance was to take place, the useful life would be extended.

ENGINEERED EARTH ROADS

A slice-in-time study was carried out to determine the performance of a large number of existing earth roads in Cambodia. The findings from the study may be regarded as being limited, since the different environments (traffic, climate, soil types and topography) considered were small in comparison to those which occur in all LICs/LMICs. Furthermore, in practice EERs provide the majority of access for most communities in LICs/LMICs. Nevertheless, the study and other documented research 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. EERs have an advantage over all other types of LVRRs considered in this review, since they do not require the use of other than local material. Such roads, however, must be designed appropriately, including the provision of adequate drainage and cross fall. Their sustainable use however is very much reliant on regular maintenance, particularly after heavy periods of rainfall, and the prevention of overloading.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

Prerequisites for a sustainable application from the study considered appear to include the following:

- In situ soil material with suitable particle grading and plasticity properties, and adequate wet strength. It is noted that CBR strengths of ≥15% are recommended. However findings from research in non-LICs (Ahlvin and Hammitt, 1975) suggest that lower strengths (CBR >8%) can provide vehicular access, but with higher maintenance reshaping requirements.
- Adequate camber, side drain, turnout drain and cross drainage arrangements to effectively shed and disperse rain water, as many soils lose strength when soaked.
- Regular routine maintenance of camber (by light or heavy equipment mechanical or manual reshaping) and continuity of drainage is essential, as surface deterioration can be high (depending on a range of factors) and can lead to increased roughness and possibly impassability, unless responded to appropriately and in a timely manner.
- It appears that longitudinal gradient progressively increases surface erosion and maintenance requirements. Good practice experience usually limits usage to gradients below 6%.

GRAVEL ROADS

For many years, natural gravel surfacing has been the commonly accepted solution for providing rural access in developing regions. However, limited and depleted sources and questions of maintenance management, life-cycle cost and environmental sustainability have prompted increased investigations regarding this surface type.

Three studies (see Table 4.4), all examining the engineering performance of gravel roads, measured the sustainability 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 (traffic, climate, soil types and topography). Two studies considered existing roads in Kenya over two years, whilst the third was a slice-in-time study of a large number of gravel roads in Vietnam. Like EERs, it is essential for the long-term performance of natural gravel LVRRs to design them appropriately, with the provision of adequate drainage and cross fall, and maintain them routinely. A major disadvantage of gravel roads is that as a result of gravel loss, they require gravel replacement at regular intervals, which is not sustainable where gravel is a scarce and expensive resource.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

A separate study reported below considered various low-cost options for maintenance.

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 systematic review and other experience identify widespread non-compliance with these requirements, with the resulting gross underperformance of many gravel road investments. Routine and periodic (regravelling) maintenance of gravel surfaces is widely deficient due to a lack of delivery capacity not properly identified at road design and construction stage. These factors include:

- setting and achieving (through an adequate quality assurance regime) the application of appropriate specifications relating to particle grading, plasticity and particle strength, blending mechanically if necessary to achieve this
- restricting application to roads carrying traffic of less than 200 vpd for manageable maintenance and gravel loss
- restricting application to environments with a rainfall of less than 2,000 mm/year for manageable maintenance and gravel loss (see Table 0.4)
- restricting application to longitudinal gradients of less than 6% for manageable maintenance and gravel loss
- ensuring the provision and maintenance of adequate camber and run-off arrangements through side drains, turnout (mitre) drains and cross drainage

- timely resourcing and provision of regravelling to replace material losses.

ROAD MAINTENANCE APPROACHES

THE IMPACT OF ROAD MAINTENANCE APPROACHES ON LVRR SUSTAINABILITY

One high-quality study considered the effectiveness of three different maintenance approaches (heavy equipment, intermediate equipment or labour-intensive) on the condition of gravel roads immediately after the maintenance and for a number of days thereafter. The study showed that technologies 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 the more capital-expensive options (e.g. a mechanical grader). Developed countries aim to mechanise maintenance, as labour is expensive and productivity can nearly always be increased using modern technology. However, in LICs, heavy plant and its operation are significantly more expensive than labour which is usually inexpensive and readily available. In addition, heavy plant, and its replacement parts, are nearly always imported and plant is therefore problematic to maintain. Thus maintenance of unpaved roads offers scope for using intermediate equipment and labour, and they can be very cost effective if labour rates are low, heavy plant availability is low and heavy plant procurement expensive.

CONSTRUCTION AND MAINTENANCE REQUIREMENTS

The study demonstrated that any labour-intensive technology requires adequate supervision to be effective. Furthermore, less-expensive technologies require more frequent maintenance cycles to achieve the same effectiveness of maintenance.

REFLECTION ON THE SYNTHESIS FINDINGS AND GAPS IN THE EVIDENCE BASE

Originally engineered low volume rural roads in low-income countries were earth roads or roads made from gravel. The latter are often designed to a specification designed to protect the underlying sub-grade from the environment in which they operate. Both low-cost surface types require regular routine maintenance of camber and drainage system to be sustainable. However, earth surfaces are normally unable to provide year-round all-season surfaces in many regions. Gravel surfaces also require regular periodic maintenance, to replace gravel material losses. Such maintenance is often relatively expensive compared to the initial construction cost of the gravel road. Further, gravel loss from road surfaces can be extreme in many environments, and replacing a finite, and often increasingly scarce, resource can be unsustainable. Consequently, alternative road constructions and materials have been, and are being, considered. Primary outcomes of interest for these approaches, and for this review, are whether LVRRs constructed using these alternatives can be considered to be an improvement on existing earth or gravel roads in terms of providing all-season access and whether the alternative may be considered to be sustainable.

Generally, it can be said from the review that the large majority of the technologies under study can be considered to be sustainable provided that they are used in appropriately designed LVRRs, and the roads are constructed well and subject to good maintenance. However, the behaviour of roads over time may be considered to be 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 behaviour of their constituent materials and the frequency and effectiveness of their maintenance regimes. Further, the behaviour of individual components within a road is also influenced by the performance of other components. Therefore since LVRRs deteriorate gradually over time (except earth and gravel surfaces) as a function primarily of the environment, carefully designed experiments, lasting at least until a component of the road has considered to have reached the limits of its serviceability, are required to properly assess sustainability. During this time, the performance of the road and the environment should be periodically monitored, in order to assess properly the performance of the road and its constituent materials. 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, such experiments, it may be argued, should take place over at least two planned maintenance cycles so that the effect of maintenance can 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 (16 years), although road condition data were captured on only four occasions during this time and none of the roads were maintained. 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. None of these studies, however, captured the impacts of maintenance. Three other slice-in-time studies, which aimed to capture the performance of roads at different stages of their life-cycles, also provided experimental evidence and included by their nature the impacts of maintenance on the current road condition. Five studies indicated the effectiveness of the environments in which gravel and/or earth roads may perform satisfactorily. One of these considered the impacts of maintenance.

There were also issues associated with assessing sustainability. All of the studies which considered materials or methods as alternatives to gravel or earth roads demonstrated conclusively, from an engineering point of view, that they offered both improved road performance and all-season access. However, they were not able to address, due to resource constraints and lack of appropriate data, whether the trialled technologies could be considered to be sustainable according to economic, social and environmental considerations, or indeed whether they could be considered to be at least as sustainable as the gravel or earth roads they sought to replace. Several studies, however, recognised the complexity of these issues (e.g. TRL, 2009; Roughton International, 2013b). Studies are required therefore, which build on the concepts presented in several studies, such as environmentally optimised design (TRL, 2009), as well as those which 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 regional context. In the light of climate change, such analyses should also consider how predicted changes in the climate, and the occurrence of extreme weather events in particular, may influence both strategy and design choices.

Considering that the majority of road transport routes in developing regions are still to earth standard and many communities rely on earth road access, there appears to be a lack of research into the applicability and performance of EERs. EER could make a fundamental contribution in an environmentally optimised design (EOD), where the limited sections of route not suitable for EER are provided with spot improvements in an affordable and cost-effective way.

OTHER FACTORS NOT PRESENT IN THE STUDIES

It was hoped at the outset of the review that studies would be found which provided 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. Relevant tools exist, for example, HDM-4 the World Bank’s de facto standard for road investment appraisal, and other tools which are based on HDM-4, such as RED (Road Economics Decision) and RONET (Road Network Evaluation Tools), albeit with reduced functionality. Whilst a large number of studies have been carried out on behalf of road agencies and donor organisations using the HDM-4 methodology to compare different technology choices, only a very small proportion have been published, and there were none found that met the systematic review selection criteria
- the management of construction and maintenance of LVRRs (in particular reporting the local context).

Additionally, only one study associated with maintenance techniques was found and it focused on gravel roads.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

There is a sound evidence base of engineering-based technologies which can be used to improve upon the functional and structural performance of earth or gravel rural roads in LICs/LMICs. These technologies may be considered to be sustainable in physical terms in specific environments. Claims that these technologies are financially, economically, operationally, environmentally or socially sustainable cannot be made strictly from the evidence of the review alone. However, the evidence from the review 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.

6.2 RECOMMENDATIONS FOR POLICY AND PRACTICE

- To consider revising LVRR design standards so that they are performance-based rather than specification-based. Traditionally, LVRR pavement design standards have been based on empiricism, by which the materials to be used within the road pavement and their quantities are specified using a recipe or catalogue. This has resulted in inappropriate designs for the environments at hand. Mechanistic performance-based road pavement design standards, however, would allow the engineer to utilise a variety of materials and approaches in a rational process which is not allowed for within traditional design approaches. Such an approach would provide an enabling environment for the use of technologies appropriately, including:

  (i) two-layered road pavement designs

  (ii) the use of marginal materials

  (iii) the use of alternative surfacing

  (iv) environmentally optimised design

  (v) feasible alternative technology options

  (vi) the development of more effective quality assurance regimes

  (vii) the development of pragmatic EOD approaches

  (viii) encouragement of further innovation.

- To encourage whole-life cost approaches which consider adequately the construction, maintenance and vehicle operating, accident and environmental costs, and the whole-life benefits (e.g. economic and social benefits). This would require a multi-criteria approach which utilises economic tools such as HDM-4 together with methodologies which are able to consider non-monetary benefits. It may be argued that it is invalid to use the HDM model or its derivatives for technology selection because much of the road performance and vehicle operating cost data come from high- and middle-income countries. However, complex decision making and modelling inevitably involves borrowing information from a very wide range of international studies.

- To provide a facilitating environment that ensures that LVRRs are constructed to the given design standards, using specified materials, under adequate construction supervision. The studies which described the use of different materials within a road pavement demonstrated that good construction practices are required to ensure the long term durability of the road (i.e. the road's physical sustainability).
- To introduce effective asset management practices and invest adequately in road maintenance and associated management processes and tools. The review has found that the majority of the trialled technologies will perform adequately initially in specific environments, including earth and gravel roads, provided they are designed and constructed adequately. However, all roads deteriorate over time as a function of traffic and the environment, and therefore it is vital that they are maintained at appropriate intervals. Such maintenance needs to be properly planned and budgeted. An appropriately maintained road not only ensures the integrity of the road, but prevents high maintenance costs associated with rapid deterioration, enables access to goods, markets and social amenities and minimises road-user costs, thereby providing economic and social benefit.
- When attempting to introduce a proven LVRR technology into a new physical or operational environment, to consider this not simply as a technical-engineering matter. Rather it depends on the country context and on 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. Accordingly, it is necessary to carry out a detailed assessment of the applicability of the technology and identify with stakeholders the challenges and prerequisites for success. Adaption, piloting, demonstration and training for the technology will usually be required. Often political or management reluctance or inertia against the acceptance of new approaches may need to be addressed. New technology approaches will not be sustainably embedded until policy, standards, specifications, contract documentation and arrangements are adapted to accommodate the new technology.
- To appreciate the very different resource environment in LICs/LMICs, which is characterised by the scarcity and high cost of finance/capital for the private sector, low labour costs, the availability of usable non-standard materials, typical overdependence on imported materials, skills and equipment, and a weaker institutional support framework. This necessitates the development of more sustainable and local resource-based technologies, such as those identified in this review, and operationally effective asset management systems.

6.3 RECOMMENDATIONS FOR RESEARCH

PRIMARY RESEARCH

Further high-quality research needs to be conducted, which will enable improved assessment of the sustainability of materials used to build low-volume rural roads. The majority of the studies identified focused on the physical performance of materials. However, robust data are required which support an analysis of other aspects of sustainability associated with the materials. This should include the capacity and performance of the construction and maintenance regimes to achieve cost-effective asset management, environmental issues, including the impact on global and local environments in which the materials are used, and the sustainability of the supply of scarce resources. Allied to this, economic sustainability studies are required which consider the costs and benefits of selected options, over the life cycle of road pavements, including methodologies for capturing non- monetary benefits.

INSTITUTIONAL ISSUES

Donors, ministries of local government and road funds require advice on which technology is likely to be sustainable in the context of a particular country. Accordingly, in relation to the data set of studies described in this report, it would be helpful if the analysis could be extended to take account of institutional issues, and in particular to provide the following information:

- who financed the initial cost of the roads
- who designed the roads
- the initial construction cost of the road
- who built the roads and who supervised the construction
- who monitored performance and defined required maintenance interventions
- who provided funds for maintenance.

This information would add significantly to the ability of governments and donors to cost-effectively support rural communities in LICs/LMICs.

MAINTENANCE PRACTICES

High-quality studies are required which assess whether LVRRs built using novel and/or marginal materials or techniques, such as those which have been the subject of most of the studies identified in this review, can be maintained from practical, operational, financial and economic points of view. These need to consider whether resources, technologies and know-how are available to support the required maintenance.

ECONOMIC ANALYSES

Very few studies were identified which included an economic analysis of different technologies that is combined with original road performance and deterioration data. There have, however, been a large number of commercial (unpublished) studies using the HDM-4 methodology comparing different technology choices carried out on behalf of road agencies and donor organisations. Whilst these did not meet the strict selection criteria used for this systematic review, it is recommended that such studies could either be obtained or reproduced to demonstrate the economic evidence supporting the selection of a particular technology. For example, a parametric study could be carried out using HDM-4, together with simulated and real data, to compare different technologies under a variety of controlled operating and environmental conditions.

IMPACT OF CLIMATE CHANGE

The changing climate is predicted to increase the amount and frequency of rainfall in many LICs/LMICs, and at the same time increase the occurrence of extreme weather events. These are likely to increase the rates of deterioration of LVRRs and reduce their availability. Research is therefore needed to enable national governments to identify relevant climate adaptation and resilience strategies and to identify potential threats, risks, and emerging issues and opportunities. This will allow for better preparedness and the incorporation of adaptation into the longer-term policy-making process. Allied to this, climate-resilient technologies for the design and maintenance of LVRRs are also required.

ENGINEERED EARTH ROADS

Engineered earth roads constitute the majority of LVRRs in LICs/LMICs. It is unlikely that resources will enable all LVRRs to be upgraded to all-season roads and maintained in the foreseeable future. Research is therefore required to identify ways in which the performance of such roads can be increased to enable them to be useable in more extreme environments than currently. The concept of EOD is in its infancy and work is required to develop assessment and operational tools to optimise these approaches.

REVISIT JUSTIFICATION OF ‘TRADITIONAL’ SECTOR PRACTICES

This review has demonstrated that many of the accepted techniques applied to LVRRs in LICs/LMICs have been experientially developed and are not based on systematic research. Many were developed more than 30 years ago and do not take cognisance of the current financial, economic, market and social realities. There are a very wide range of technologies available to the sector, however many of these do not have systematically researched justification in today's physical and operational environment in LICs/LMICs. It will be beneficial for LVRR planners, managers, practitioners, trainers and academics to revisit then reassess the scope, benefits and applicability of these very extensive options.

SYSTEMATIC REVIEWS

A systematic review needs to be conducted similar to that reported here, but considering other than LICs/LMICs.

On the basis of this systematic review, relevant practitioners and academics can be consulted to identify and conduct in-depth review syntheses relevant to specific regional policy and practice and wider sustainability goals to further inform the evidence base of technologies which can be used sustainably in the LVRR LIC/LMIC context.

6.4 STRENGTHS AND WEAKNESSES OF THIS REVIEW

As far as the authors are aware, this is one of the first systematic reviews which attempts to synthesise findings from studies evaluating the evidence for the use and sustainability of technology in LVRR in LICs. A systematic search of electronic databases and appropriate websites was carried out to identify published and unpublished research. This process was supplemented by contacting authors and members of the review's Advisory Group. However, despite attempts to conduct a comprehensive search, the review was time-bound, restricted to English language databases and to studies written in English, and limited to those studies of which a full transcript could be obtained. Seven studies which may have added to the weight of evidence of the review could not be obtained within the given time frame. Insufficient allocated project time and financial resources were available to identify and include studies written in other languages, nor to have studies translated. Systematic reviews in international development require further methodological consideration concerning ways to systematically identify and synthesise non-English-language studies; this will not only provide a more exhaustive evidence base, but also one that can provide the contextual detail that is often required when answering review questions relevant to policy makers and practitioners in this field.

The review was strengthened by the involvement of a number of practitioners in the field, in addition to those who were part of the Review Team, and policy makers. These included a peer Advisory Group of practitioners and academics working in this area.

Although this review is concerned with the evidence of the use of technology and its sustainability in low-volume rural roads in low-income and lower-middle-income countries, there is a wealth of good practice guidelines, built up from the experience of senior practising road engineers, which exist in the industry. These were excluded from the review since they did not present data in the form of longitudinal studies.

A large number of studies on the use of technology for LVRR in other than LICs/LMICs have been carried out. These may have supported the findings of this review and could be the subject of a parallel review which focuses on the usefulness of such technologies to low-income country environments.

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6 APPENDICES

APPENDIX 1: AUTHORSHIP

AUTHORS

Dr Michael Burrow (University of Birmingham)

Mr Robert Petts (Intech Associates)

Professor Martin Snaith (University of Birmingham)

Dr Gurmel Ghataora (University of Birmingham

Dr Harry Evdorides (University of Birmingham)

Correspondence: m.p.n.burrow@bham.ac.uk

This document should be cited as:

Burrow MPN, Petts RC, Snaith MS, Ghataora GS, Evdorides H (2015). *What is the evidence supporting the technology selection for low-volume, rural roads in low-income countries and what evidence is there to support the sustainability of different rural road technologies? A systematic review*. London: EPPI-Centre, Social Science Research Unit, Institute of Education, University of London

ADVISORY GROUP

Dr Ian Heggie (formerly Senior Transport Economist, the World Bank)

Mr John Hine (formerly Thematic Group Leader for Rural Transport, the World Bank and Senior Research Fellow, TRL Ltd.)

Mr Juan Quintero (formerly Senior Environmental Specialist, the World Bank).

ACKNOWLEDGEMENTS

The authors are very grateful to a team from the EPPI-Centre, overseen by Professor Sandy Oliver, for their assistance throughout the review process. In particular they are extremely grateful for the continual guidance and invaluable comment provided by Ms Kelly Dickson throughout the review stage and in helping to draft this report. The patient assistance of Mr Jeff Brunton in helping the review team to make best use of the EPPI-Reviewer software is also gratefully acknowledged. The review team are also grateful for the guidance and advice provided by the project's Advisory Group. The three researchers who assisted greatly with the searching process, namely Mehran Eskandari Torbaghan, Danielle Fintleman and Fiona Raje, are thanked for their patience and thorough endeavours. We would also like to thank the peer reviewers for their input. The systematic review has been funded by the DFID. The advice provided by DFID’s Ms Liz Jones and Mr Suman Baidya in addressing the research question is also noted with gratitude. Finally, the review team would like to acknowledge the work of the authors of studies included in this review and those who participated in them, without which the review would have had no data.

CONFLICTS OF INTEREST

Where a paper written or co-authored by a member of the Review Team was considered for or included in the review, the author was not involved in decisions relating to its selection or quality assessment.

APPENDIX 2: EXCLUSION CRITERIA

Studies were screened and excluded if they:

(EXC1) Language: were not published in English

(EXC2) Geographical location: were carried out in high-income or upper-middle-income countries

(EXC3) Roads: did not investigate low-volume rural roads

(EXC4) Technologies: not investigating methods, materials, equipment or tools used in the appraisal, investment, design, construction or maintenance of low-volume rural roads

(EXC5) Study design and comparators: were not carried out over the entire life cycle of a low-volume road or did not compare the outcomes before and after the implementation of the technology (i.e., they were not empirical studies)

(EXC6) Outcomes: did not demonstrate whether a technology was sustainable (from an engineering, economic, political, social or environmental point of view).

(EXC7) Date: were published before 1950.

Low-income and lower-middle-income countries are defined by The World Bank (2015).[3] The countries classified as low-income are: Afghanistan; Bangladesh; Benin; Burkina Faso; Burundi; Cambodia; Central African Republic; Chad; Comoros; Congo, Democratic Republic; Eritrea; Ethiopia; The Gambia; Guinea; Guinea-Bissau; Haiti; Kenya; Korea, Democratic Republic; Liberia; Madagascar; Malawi; Mali; Mozambique; Myanmar; Nepal; Niger; Rwanda; Sierra Leone; Somalia; Tajikistan; Tanzania; Togo; Uganda and Zimbabwe. The countries classified as lower-middle-income are: Armenia; Bhutan; Bolivia; Cabo Verde; Cameroon; Congo Republic; Côte d'Ivoire; Djibouti; Egypt, Arab Republic; El Salvador; Georgia; Ghana; Guatemala; Guyana; Honduras; India; Indonesia; Kiribati; Kosovo; Kyrgyz Republic; Lao PDR; Lesotho; Mauritania; Micronesia, Federated States; Moldova; Mongolia; Morocco; Nicaragua; Nigeria; Pakistan; Papua New Guinea; Paraguay; Philippines; Samoa; São Tomé and Principe; Senegal; Solomon Islands; South Sudan; Sri Lanka; Sudan; Swaziland; Syrian Arab Republic; Timor-Leste; Ukraine; Uzbekistan; Vanuatu; Vietnam; West Bank and Gaza; Yemen Republic; Zambia.

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[3] This list is based on the World Bank classifications for 2014; however, this is no longer available online, so for the convenience of readers, a reference has been given to the current listing, which is slightly different. On the World Bank web page, countries which have changed classification since 2014 are indicated in bold.

APPENDIX 3: SEARCH STRATEGY FOR ELECTRONIC DATABASES

DATABASES AND WEBSITES SEARCHED

Table App2.1: Information sources

Databases	Search engines	Organisation-specific databases
ANTE (Abstracts in New Technology and Engineering)	Google.com	AFCAP (African Community Access Programme)
British Standards Online	Googlescholar.com	American Society of Civil Engineers (ASCE)
Civil Engineering Abstracts (ProQuest)	FindIT.bham.ac.uk	DFID (UK Department for International Development) including the Engineering Knowledge and Research (EngKaR) Programme
Compendex (Engineering Village)		gTKP (global Transport Knowledge Partnership/Practice)
Engineering Handbooks Online		Institution of Civil Engineers (ICE), UK
Engineering Research Database (ProQuest)		IRC (Indian Roads Congress)

GEOBASE (Engineering Village)		SSATP (Sub-Saharan Africa Transport Policy Program)
Intellectual Property Office		Transport Research Laboratory (TRL) Ltd
Web of Science (ISI)		Transportation Research Board (TRB) Transportation Research Record (TRR/TRID)
SCIRUS (Elsevier)		WB (World Bank/IDA)
Transport Research International Documentation (TRID)		
Wiley Online Library		

SEARCH STRATEGY

The review team piloted the specified search terms used in each database before finalising the search strategy. Engineering and science databases were searched on a range of terms relevant to ‘Rural Roads’ and ‘Low value’ (for example, terms related to ‘rural roads’, e.g. Country road and Countryside road and terms related to ‘Low value’, e.g. unpaved, gravel and unsealed) before being combined with the concept terms of ‘low-income countries’. Sample search strategies for a database and a website are given below.

ABSTRACTS IN NEW TECHNOLOGY AND ENGINEERING (26 MARCH 2014)

(((KW= ("Rural Roads" or (Country road or Countryside road) or (“Low value” or” unpaved roads" or gravel or unsealed) or (KW= (Low value or rural roads or gravel roads)))

OR

‘road*’ AND ‘rural*’

‘low value’ AND ‘road*’

‘rural’ AND ‘road*’

‘unpaved AND road*’

WORLD BANK PUBLICATIONS DATABASE – OPEN KNOWLEDGE REPOSITORY (OKR)

Since both ‘low income countries’ and ‘other than low income countries’ were listed in the Subject term column, no definition of country type was included in the searches. A brief overview of the results follows:

- An initial search was conducted, using the main search term ‘low volume roads’. This yielded nine documents.
- A subsequent search was carried out with ‘rural roads’ as the main term and this resulted in 293 hits.
- At this stage, it was felt that the initial nine documents should be kept in the results but the larger set of 293 should be further refined. In order to do so, additional search terms (taken from the Technology column of Table 2.1) were applied to the 293 documents, with each additional term resulting in hits as shown below:
    - Technology 62
    - Materials 32
    - Labour 99
    - Equipment 51
    - Finance 107

    - Management tools 168
    - Design 40
    - Construction 85
    - Maintenance 125.
- Each of these documents (the initial nine plus those resulting from each of the secondary searches listed above) was visually scanned to check for relevance to the review. Reasons for elimination from further consideration included a focus on subjects such as international corridors, inter-city transport and urban roads. If a document was considered relevant, the pdf version was saved.
- As the search process evolved, a number of documents started to appear in repeated searches (with different search terms). Ultimately, 93 documents were found to be of some relevance to the general subject area.

These 93 papers/reports were re-checked, through a closer scan, to trim the overall set to better match the specific review aims (for example, eliminating documents which focused on hypothetical/suggested approaches and general/descriptive infrastructure reports). This process resulted in 41 documents.

FURTHER SEARCHING

Citation searching: the citations of included studies were also checked to identify further included and linked studies (e.g. articles reporting the same study but published separately).

Additional searching: during the in-depth reviewing stage, additional searches were carried out to ensure that any relevant studies were identified. These included website searches, reference checking and forward reference checking.

APPENDIX 4: DEVELOPED CODING TOOL

A: Description of the research

1. Is the study on low-value rural roads?
2. Is the study on low-income or lower middle-income countries?
3. Does the study report on technology?
4. Have the data been reported elsewhere?

B: Quality of evidence

1. Does the study report empirical in situ data?
2. Are the outcomes related to a measure of road serviceability?
3. Does the study report longitudinal data?

C: Description of technology

1. Does the technology include vehicular traffic?

D. Weight of evidence

1. WoE A: Soundness of study
    - High
    - Medium
    - Low
2. Appropriateness of study design
    - High
    - Medium
    - Low
3. Relevance of study focus to the review
    - High
    - Medium
    - Low

LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AFCAP	African Community Access Project/Programme
ASCAP	Asian Community Access Project/Programme
ASCE	American Society of Civil Engineers
CBR	California Bearing Ratio
CVPD	Commercial vehicle per day
DBST	Double bitumen stone chip seal
DBST(e)	Double bitumen emulsion chip seals
DCP	Dynamic cone penetrometer
DFID	Department for International Development (UK)
EER	Engineered earth roads
EOD	Environmentally optimised design
EPPI-Centre	Evidence for Policy and Practice Information and Co-ordinating Centre
ESAL	Equivalent standard axle
GNI	Gross national income
HDM	Highway development and management
HGV	Heavy goods vehicle
IRI	International Roughness Index
Km/h	Kilometres per hour
LIC	Low-income country
LMIC	Low-middle-income country
LVRR(s)	Low-volume rural road(s)
LVSR	Low-volume sealed road

MESA	Million equivalent standard axles
MPa	Mega Pascal
Mph	Miles per hour
MVPD	Motor vehicles per day
NPV	Net present value
P	Probability
S BST	Single bitumen stone chip seal
SBST	Single bitumen surface treatment (bitumen sprayed coat with stone chippings)
SEACAP	South East Asia Community Access Programme
SN	Structural number
SR	Systematic review
SSA	Sub-Saharan Africa(n)
SSATP	Sub-Saharan Africa Transport Policy Program
TRB	Transportation Research Board
TRR	Transportation Research Record
TRL	Transport Research Laboratory
VPD	Vehicles per day
WB	The World Bank
WoE	Weight of evidence