The use of appropriate high-tech solutions for road network and condition analysis, with a focus on satellite imagery

Final Report

TRL Ltd – Robin Workman

GEN2070A

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Executive Summary

This project was designed to look to the future for road management in Africa and explore different and innovative cost-effective solutions to well established problems related to a lack of knowledge of rural road networks. There are two main aspects to the project, the high-tech solutions to increase knowledge of low volume rural road networks and the assessment of road condition using high resolution satellite imagery. Trials were undertaken in five countries.

The desk study identified a number of high-tech solutions that are appropriate for rural roads in Africa, with a few of them being informally trialled. The most promising technologies included the use of drones, video cameras, smartphone applications, accelerometers, GIS, crowdsourcing and other satellite applications. There is great scope for innovation in this area and there are also significant opportunities for technologies applied in Africa to leapfrog those already in use in high income countries.

The trials of condition assessment using satellite imagery found that a reasonable level of accuracy could be obtained, the assessment was faster and less resource intensive than traditional means, and that it could be cost effective if significant discounts and/or relaxations on the minimum requirements for procurement of imagery could be negotiated. Also the time savings in assessment and analysis time can be a significant factor in the decision to use this technology, even if the detail and cost are less attractive.

Synergies with other ReCAP projects, such as the Asset Management 'GEM' project, the Climate Vulnerability project and the RAI project were explored. It was found that the satellite assessment system was more effective when used with a RAMS, as this facilitates the functioning and allows it to produce information in an appropriate and manageable format.

A Guideline has been produced, which clearly sets out the situations where this methodology can be used, and where it would not be appropriate. At present this is still most likely to be beneficial in remote or conflict affected areas such as South Sudan or Afghanistan, if there is demand from the local ReCAP partners. The Guideline also includes procedures for image interpretation and recording/analysis of results, as well as options for other high-tech solutions that can be used to increase knowledge of rural road networks.

There is good potential for automation of the visual imagery assessment process, which is also being trialled at present in Zanzibar using Unmanned Aerial Vehicles (UAV) imagery. Further research in this area using Machine Learning and other Artificial Intelligence techniques is likely to bring benefits, especially in terms of accuracy, consistency and cost effectiveness. Developments in the sector tend to be rapid, so the technologies reviewed in this project should be revisited regularly to see what could be learned from and implemented in future ReCAP projects.

Key words

High-tech solutions, low volume roads, satellites, road condition, imagery

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Research for Community Access Partnership (ReCAP)

Safe and sustainable transport for rural communities

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

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Acronyms, Units and Currencies

ACRONYMS

AfCAP	African Community Access Partnership
AoI	Area of Interest
ARMP	Annual Road Maintenance Plan
AsCAP	Asian Community Access Partnership
CERSGIS	Centre for Remote Sensing and Geographic Information Services
DEM	Digital Elevation Model
DFID	Department for International Development
DMI	Distance Measuring Instrument
DROMAS 2	District Road Management System 2
FTL	Frontier Technology Livestreaming
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HD	High Definition
HIC	High Income Country
IRI	International Roughness Index
LGA	Local Government Authority
LIC	Low Income Country
LIDAR	Light Detection and Ranging
QGIS	Quantum Geographic Information System
RAI	Rural Accessibility Index
RAMS	Road Asset Management System
RCMRD	Regional Centre for Mapping of Resources for Development
ReCAP	Research for Community Access Programme
RFB	Roads Fund Board
SAR	Synthetic Aperture Radar
SD	Secure Digital (card)
SDI	Surface Distress Index
SUV	Sports Utility Vehicle
TARURA	Tanzania Rural and Urban Roads Agency
ToR	Terms of Reference
UAV	Unmanned Aerial Vehicle
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development, UK)
UNRA	Uganda National Roads Authority
VHR	Very High Resolution
WRM	World Road Meeting

UNITS

CO_2	Carbon Dioxide
km	kilometre
km^2	square kilometre
m	metre

1 Background

This project was designed to look to the future for road management in Africa and explore different and innovative cost-effective solutions to well established problems, such as a lack of information on low volume rural road networks and issues with prioritising maintenance on such roads. There are two main aspects to the project, the high-tech solutions to increase knowledge of rural road networks and the assessment of road condition using high resolution satellite imagery. The project commenced in April 2016 and is due to complete on 31st July 2018. This final report summarises the results and conclusions, and makes some recommendations for the future with respect to high-tech solutions in Africa.

There are five participating countries; Ghana, Kenya, Uganda, Zambia and Tanzania. These countries were selected because they have very different climates, geography, levels of vegetation cover and rainfall, which provides the necessary range of conditions in which to test the methodology. Tanzania was selected as an extension to the main project in order to test the potential for roll-out of the satellite assessment methodology.

There have been no formal research trials into the identified high-tech solutions, although some of the technologies have been used to establish and audit the ground truthing for the satellite assessment. All five countries have participated in the satellite condition assessments, whilst considering the sustainability of the methodology and how it can be designed to be easily used and replicated by local institutions.

2 Research objectives

The objectives of this project as defined in the Terms of Reference (ToR) are:

2.1 Research

To provide cost-effective and reliable high-tech solutions for the capture of maintenance management data related to the inventory and condition of a country's rural road network. The majority of this research is in the field of satellite imagery, but the project also has the remit to recommend any alternative high-tech solutions that are likely to be appropriate.

2.2 Capacity building and technology transfer

The project aim was to enhance the capacity of relevant partner-county Road and Transport ministries, departments and agencies in the key areas covered by the project. Capacity building and technology transfer was in the form of:

- Presentation of the findings at meetings/workshops in the partner countries;
- Presentation of the findings to the broader Research for Community Access Partnership (ReCAP) member countries and community of practice (e.g. web site, newsletter and Steering Committee meetings);
- Peer reviewed papers for conferences and/or journals, of which at least two were required.
- Training suitable counterpart staff in identified Africa Community Access Partnership (AfCAP) partner countries in the collection and use of appropriate data for rural road management.

2.3 Uptake and embedment

In line with the ReCAP guiding principles the project was expected to incorporate within its programme a process for keeping relevant agencies fully informed, not only on project outcomes but also on how these outcomes can be cost-effectively utilised in normal practice.

3 Methodology

3.1 High-tech solutions

There are a number of high-tech solutions that can be used to increase our knowledge of rural road networks. The High-Tech Solutions Guideline produced under this project covers the solutions that have definite cost effective uses at the present time, but it should be noted that new technologies are being developed all the time and existing technologies are becoming more feasible economically as competition grows and they become available to a wider market.

The Guideline suggests the most appropriate uses for the technologies, as well as opportunities to use a combination of more than one technology together, in order to find the most cost effective and appropriate solution.

The following technologies were found to have potential for use with low volume rural roads:

- Satellite imagery related technologies (apart from the road condition assessment methodology):
    - Back analysis using archive imagery
    - SAR imagery
    - Change detection algorithms
    - Spectral reflectance
    - Online streaming of current Very High Resolution (VHR) basemaps
- Unmanned Aerial Vehicles (UAVs)
    - Multi-copter UAVs
    - Fixed wing UAVs
    - Hybrid UAVs
    - High altitude pseudo satellites
- Smartphone applications, including:
    - Apps to measure International Roughness Index (IRI)
    - Social Media apps
    - 'Street Bump' pothole locating software
- Internet based solutions, such as:
    - FixMyStreet
    - OpenStreetMap
    - OpenRoads
    - Proprietary mapping sites such as Google, Bing, etc.

- GIS based solutions:
    - Digital Elevation Models (DEMs)
    - Drainage identification software
    - Automated mapping
- DashCams

Existing high-tech solutions that can act as complementary technology were also briefly reviewed, but as they are well established technologies there was no benefit in researching their use in detail. Their potential to operate with new and innovative high-tech solutions was considered. The technologies reviewed were:

- Aerial photography
- Light Detection and Ranging (LIDAR)
- Laser profiling
- Roughness measurement (methods vary in level of sophistication)
- Mini satellites
- Photogrammetry
- Interferometry
- Global Navigation Satellite System (GNSS) and Global Positioning System (GPS) devices

In addition to high-tech solutions that have potential now, a number of potential high-tech solutions that could be available in the near future were considered. Most of these are operational or in development, but had no immediate use in the low volume roads sector, but had good potential. The technologies considered were:

- Automated condition assessment using satellite imagery
- Linked data / Semantic web
- Data modelling / Distributed computing
- Artificial Intelligence / Machine Learning
- Internet of Things
- Big Data
- Thermal imaging, infrared satellites

3.2 Road condition assessment by satellite imagery

The methodology for road inventory collection and condition assessment from satellite imagery can be seen in detail in the 'Guideline on the use of high tech solutions for road network inventory and condition analysis in Africa', section 2, which is available on the ReCAP website.

The methodology shown in this Guideline is organised into four separate sections:

- Preliminary tasks
- Inventory collection
- Condition assessment

- Miscellaneous

These sections are summarised below:

3.2.1 Preliminary tasks

The first preliminary task is to determine whether the methodology is suitable for the country it is being considered for. A number of factors such as cost, detail, resolution, environment, climate, accuracy, time, resources and licencing need to be considered. The section concludes with some concise advice on the situations where the methodology would, and would not, be useful.

The section then goes on to deal with imagery procurement, tasked and archive imagery, software and image processing.

3.2.2 Inventory collection

One of the main aspects of this methodology is to identify inventory features from satellite imagery. This section provides guidance on how to identify roads and their inventory features by explaining mapping and how roads can be accurately digitised. It then moves on to deal with the characteristics of the road that can be determined from satellite imagery, as well as road furniture, drainage and how water courses can be located using a Digital Elevation Model (DEM) overlay, road construction material sources and delineation.

The identification of road inventory features depends on several factors, but mainly the imagery resolution and level of vegetation. The conclusion is that most inventory features are hard to determine exactly, and the condition of some drainage features such as culverts and bridges is not possible to determine because it is necessary to inspect underneath or inside the structure, unless of course it has collapsed, which is usually visible from the imagery.

3.2.3 Condition assessment

The condition assessment is the area of the methodology with the most potential as an innovative high-tech solution. It has not been researched in High-Income Countries (HICs) and builds on previous work undertaken by TRL in Nigeria in 2012 (Workman, 2012, Transport Infrastructure Monitoring Project). It has most potential for low volume unsealed roads in Low-Income Countries (LICs) because of the nature of unpaved roads and the features that can be seen on satellite imagery, and because it has the ability to provide information rapidly over a wide spatial area.

This section deals with calibration to the conditions in each particular country, ground truthing, development of an assessment guide, developing a reference document, training in assessment and image interpretation, assessment principles, elements for condition analysis, elements for objective assessment and assessment methodology. The methodology importantly includes guidance on how to calibrate the system to the conditions and rules/regulations that prevail in each country, as the aim is not to introduce new systems or change the existing maintenance assessment principles.

3.2.4 Miscellaneous

This section covers the checking and auditing of the system, using the system in a Road Asset Management System (RAMS) and the integration of other technologies within the system to collect road inventory and assess road condition by satellite imagery.

4 Review of key documents

There are a number of key documents produced for this project, as shown below in chronological order:

- Inception report: April 2016
- Desk study: July 2016
- Progress report 1: September 2016
- Progress report 2: November 2016
- Interim Trials report: February 2017
- Progress report 3: March 2017
- Tanzania scoping study: March 2017
- Final Trials report: May 2017
- Guideline: September 2017
- Technical status report: October 2017
- Tanzania report: April 2018
- Final report: June 2018

They are summarised below:

4.1 Inception report

Link: http://www.research4cap.org/Library/WorkmanRetal-TRL-2016-SatelliteImagery-InceptionReport-GEN2070A-ReCAP-v160516.pdf

A launch meeting was held in London on 25th April 2016 with the ReCAP Project Management Unit, where the proposed contents of the Inception Report were discussed and a number of issues were clarified. It was agreed that the inception report would comment on the ToR and propose a detailed work schedule for the project. It would also set out a detailed methodology for undertaking the project.

4.2 Desk study report

Link:http://www.research4cap.org/Library/Workmanetal_TRL_2016_UseAppropriateHighTechSolutionsforRoadNetworkConditionAnalysis_PRDeskStudy_AfCAP_GEN2070A-v161007.pdf

The Desk Study Report was produced in July 2016. This included a comprehensive review of the potential innovative high-tech solutions that could be appropriate for the rural roads sector. It also included a draft methodology for mapping and condition assessment using satellite imagery, as specified in the Terms of Reference (ToR). In addition a paper on the selection of countries to participate in the project was included as an Annex. This selection was based on environment, climate, geography, vegetation levels, the presence of a local remote sensing organisation and whether the countries were willing to participate and commit resources to the research. Interest was high from all AfCAP countries, but the proposed countries were:

- Ghana - Tropical environment, high vegetation levels, high rainfall
- Kenya - Semi-arid environment, minimal vegetation, low rainfall
- Uganda - Savannah landscape, medium vegetation, moderate rainfall
- Zambia - Savannah landscape, medium vegetation, moderate rainfall

Recommendations were made for potential pilot studies, which for high-tech solutions included social media reporting of road defects, UAVs, mobile phone applications and data, satellite big data, climate resilience, mini-satellites and spectral reflectance. There was no funding for the trialling of these high-tech solutions, so additional funds would need to be provided by the countries themselves if they were interested to research them. A matrix of the potential solutions was produced and a list of references was provided in the report.

The report was peer reviewed by Satellite Applications Catapult as the first part of a two-tier peer review. Satellite Applications Catapult is an independent innovation and technology centre created by the Technology Strategy Board of the UK Government. Its aim is to foster growth through the exploitation of space, by helping organisations use and benefit from satellite technologies.

4.3 Progress report 1

Link:http://www.research4cap.org/Library/WorkmanRetal_TRL_2016_UseAppropriateHighTechSolutionsforRoadNetworkConditionAnalysis_PR1_GEN2070A_161010.pdf

This Progress Report covers the period from July to September 2016. It included confirmation of the countries who would participate, including a summary of initial visits to Uganda and Zambia to assess capacity, identify areas of interest for the assessment and train for/plan ground truthing surveys. The procurement of the satellite imagery was initiated for Uganda and Zambia and the methodology was revised for each country.

4.4 Progress report 2

Link:http://www.research4cap.org/Library/Workmanetal_TRL_2016_UseAppropriateHighTechSolutionsforRoadConditionAnalysis_PR2_AfCAP_GEN2070A_v161119.pdf

Progress Report 2 covers the period from October to November 2016. The activities during this period included initiating the remaining two countries, Ghana and Kenya, and making initial visits to those countries to assess capacity, identify areas of interest for the assessment and train for/plan ground truthing surveys. Imagery was procured for Uganda and Zambia, and the areas of interest were confirmed for Ghana and Kenya. The methodologies were revised for each country. The team leader attended the ReCAP meeting in Caledon, which provided a good opportunity to disseminate information on the project amongst AfCAP and AsCAP country partners and others.

4.5 Interim Trials report

Link: http://www.research4cap.org/Library/Workmanetal-TRL-2017-UseAppropriateHighTechSolutionsRoadConditionAnalysis-InterimTrialsReport-AfCAP-GEN2070A-170228.pdf

The Interim Trials Report was submitted almost two months later than planned, in February 2017, due to delays in the implementation of the trials. The majority of the trials were focused on the condition assessment using satellite imagery, which was implemented in all four countries, Ghana, Kenya, Uganda and Zambia. Other high-tech solutions were investigated, but no formal trials were undertaken at that stage.

Training was completed in two countries, Uganda and Zambia, and three had finished the ground truthing. Zambia had completed an initial assessment by satellite and had analysed the results, but the overall conclusions were pending.

4.6 Progress report 3

Link: http://www.research4cap.org/Library/Workman-TRL-2017-UseAppropriateHighTechSolutionsRoadNetworkConditionAnalysis-IntPR3-AfCAP-GEN2070A-170329.pdf

This is an additional progress report that was necessary due to the delays mentioned in the Interim Trials Report and the further delay in producing the Final Trials Report due to resource constraints in Kenya. It covers the period from 28th February to 31st March 2017. At this stage all of the imagery was procured for all countries, although some delays were experienced in Ghana due to atmospheric conditions. All countries except Kenya had completed their ground truthing and training.

4.7 Tanzania scoping study

Link:http://www.research4cap.org/Library/Workmanetal_TRL_2016_UseAppropriateHighTechSolutionsforRoadConditionAnalysis_PR2_AfCAP_GEN2070A_v161119.pdf

This scoping study was designed to assess the possibility of including Tanzania in the current phase of the project. There was an opportunity to test the methodology in a roll-out situation to see how it could benefit the specific situation in Tanzania. A visit was made to Tanzania between 19th and 24th March 2017 to assess whether an extension for Tanzania was feasible, where meetings were held with the main Tanzania and Donor stakeholders.

The Tanzania Roads Fund Board (RFB) identified a key problem as a lack of accurate information on the rural road networks of Tanzania. The RFB allocates maintenance funds to the implementing bodies based on information provided by those bodies, using a set formula, but the information provided is not complete and its reliability has been questioned. Three possible areas where the high-tech solutions project could help with the specific needs of the Road Fund were identified:

- Confirming road lengths
- Checking road conditions and providing detailed up-to-date maps
- Check the compatibility of the methodology with the DROMAS 2 database (DROMAS stands for District Road Management System)

These solutions were recommended to be trialled during the present phase of the project with a short training, and some counterpart input from the main stakeholders in Tanzania. The Tanzania extension was agreed based on this scoping study and an addendum was issued.

4.8 Final Trials report

Link:http://www.research4cap.org/Library/Workmanetal_TRL_2016_UseAppropriateHighTechSolutionsforRoadConditionAnalysis_PR2_AfCAP_GEN2070A_v161119.pdf

The Final Trials Report was submitted almost three months later than planned, in May 2017, due to delays in the implementation of the satellite condition trials. Other high-tech solutions were also investigated, but no practical trials were completed. The other solutions were, however, found to have a role to play in the final methodology for a combined high-tech solution for network analysis on rural roads in Africa.

The focus of this project was to develop a methodology for cost-effective condition assessment using satellite imagery. Imagery was procured for all countries at very high resolution, along with Synthetic Aperture Radar (SAR) imagery and some lower resolution imagery to test the feasibility of reducing the cost. Training was completed in all countries in GIS applications and image interpretation, which was used to prepare the teams to assess road condition from the imagery.

This report showed the results of the trials. The accuracy of a three level condition assessment was between 80% and 87%, whereas the accuracy of the five level condition assessment was between 63% and 69%. Cost effectiveness was assessed and the satellite assessment was found to be more expensive than traditional assessments, but comparable if discounts could be secured, see Annex 1.

Some conclusions and recommendations were made, which focused on maximising the strengths of the manual assessment system, whilst identifying the weaknesses. These lessons learned were used to develop the methodology included in the Guideline. The project also conducted a workshop at the Technology Transfer (T2) conference in Zambia during May 2017, where the potential for implementation of the high-tech solutions was identified, including the satellite imagery assessment.

4.9 Guideline

Link: http://www.research4cap.org/Library/TRLAirbus-2017-GuidelineUseHighTechSolutionsRoadNetworkConditionAnalysisAfrica-AfCAP-GEN2070A-170928.compressed.pdf

A Guideline on 'the use of high tech solutions for road network and condition analysis in Africa' was produced in September 2017, hereafter referred to as the 'Guideline'. The Guideline is presented in two parts, an overall guide to the range of high-tech solutions that are, and could be, used to increase knowledge of road networks in Africa; and a detailed methodology for assessing road condition from satellite imagery.

There are a number of high-tech solutions that can be used to increase knowledge of rural road networks. The guideline covers the solutions that have definite cost effective uses at the present time, but it should be noted that new technologies are being developed all the time and existing technologies are becoming more feasible economically as competition grows and they become available to a wider market.

The Guideline suggests the most appropriate uses for the technologies, as well as opportunities to use a combination of more than one technology together, in order to find the most cost effective and appropriate solution.

The methodology developed to assess road condition from satellite imagery formed the main part of the practical trials undertaken by the main ReCAP project. The focus of this research was to develop a methodology to assess rural road condition using Very High Resolution (VHR) satellite imagery. This has not been researched before for unpaved rural roads, and research on paved roads is limited. The research considered the technical feasibility of this approach, whether it could be calibrated to suit the conditions and criteria in each country and how cost effective it is compared to traditional means of condition assessment. It was important to use the established condition assessment regime in each country to set the baseline for condition. This would ensure that the condition of the roads to be assessed was well understood by the engineers responsible for roads and had a basis in the local network information understanding. It also meant that the results could be compared like for like to previous years. However, in order to anchor the results in well-established international standards of condition for rural roads, some standard methods were used to assess aspects of condition, such as roughness.

Part 1:

The first part of the Guideline outlines the various different high-tech solutions that are available, or potentially available, and appropriate for Africa; and the situations in which they would be most useful and cost effective. In many cases this will involve a combination of more than one technology, working together.

The range of options is shown in the 'Guideline on the use of high tech solutions for road network inventory and condition analysis in Africa', which is available on the ReCAP website: http://www.research4cap.org/SitePages/Regional%20Projects.aspx

The main trials were undertaken on:

- DashCams: These were used to record the ground truthing surveys so that a technical audit could be undertaken. They were found to be very useful and there is scope to develop a low-cost product specifically for this use.
- Smartphone apps to measure International Roughness Index (IRI): The results from the RoadLab app used were good for paved roads and good condition unpaved roads, but accuracy declined significantly on fair and poor condition unpaved roads. As a low cost solution this is only appropriate within defined conditions.
- Smartphone app to report issues with the road through social media: A draft app was developed by the country counterpart in Ghana, but is yet to be trialled. Development is at present being undertaken by a counterpart engineer.

A number of other technologies are already established, or are being researched and developed by other organisations, which were explored but not specifically researched:

- Unmanned Aerial Vehicles (UAVs): There are a number of research studies using UAV imagery for assessing the condition of unpaved roads or bridge condition. The number of uses to which UAVs are being put is increasing rapidly. It would take more significant funds to carry out research in this area as it has become quite commercialised, so it is an appropriate strategy to wait and assess industry developments.
- Internet based solutions: A number of internet based solutions are also in development, with programmes such as 'FixMyStreet', 'OpenStreetMap', 'OpenRoads' and proprietary mapping sites such as Google Maps and Bing Maps. These are developing independently.
- GIS based solutions: There are many other GIS based resources that can help with road network knowledge, such as Digital Elevation Models (DEMs), drainage identification software and automated mapping. Most are well established so can be complementary to other high tech systems.
- Other satellite based solutions: Satellites can also provide imagery from Synthetic Aperture Radar (SAR), spectral reflectance, change detection algorithms and online streaming of high resolution imagery, as well as the opportunity to use archive imagery for back analysis.

Part 2:

The second part includes a detailed methodology for assessing road inventory and condition from Very High Resolution (VHR) satellite imagery. This has been trialled in six countries, where the feasibility of the system was tested with encouraging results. An important part of this Guideline is section 2.1, which sets out how to decide whether this methodology is appropriate for certain situations.

It is not possible to define an overall result for all four countries in the current research combined, because Ghana used a three level condition system, as opposed to the five level system used by the other countries. However, if Kenya, Uganda and Zambia are combined as a five level system they achieved approximately 66% correlation on 275 km of road, so slightly higher than previous research carried out in Nigeria. If 'unknown' conditions due to cloud cover are removed from the Uganda research, this improves to 70% correlation on 260 km of road. This represents a reasonable result, despite using local resources and rules for the ground truthing and assessment. This improvement can be attributed to the consolidated training courses and the development of calibration guides, neither of which were in place for the initial research in Nigeria.

However, Ghana used a three level system (Good, Fair, Poor), which would be expected to provide more accurate results as there are less levels of condition for the assessors to choose from. When analysed, the results from Ghana showed 87% correlation for unpaved roads (50 km) and 80% for paved roads (24 km), so significantly more accurate than the five level system. This is considered as a reasonable result for what is essentially a subjective assessment. If the results are disaggregated to show how far out the assessments were in terms of missing the condition by more than one level, for example assessing a Good road as Poor, or a Fair road as Very Good, the results are quite encouraging. The Ghana results were more accurate because there is less possibility of assessing more than one level out with a three level system, but other countries achieved 4% or less (Table 1). This result provides a high level of confidence that the manual assessments are able to identify conditions within one level. Given that the assessment is for unpaved rural roads with low traffic, it is hoped that this will be accurate enough for most road organisations to be able to use as a general assessment of condition and hence for prioritisation of maintenance.

Table 1: Levels of inaccuracy

Country	Level of conditions	Percentage 'out' by more than one level
Ghana (Unpaved)	3 - level	1.27 %
Ghana (Paved)	3 - level	0.40 %
Kenya, unpaved	5 - level	1.41 %
Uganda, unpaved	5 - level	4.27 %
Zambia, unpaved	5 - level	4.22 %

Guidance is also provided on how different technologies can work together.

The Guideline was peer reviewed by Satellite Applications Catapult as the second part of the peer review.

4.10 Technical status report

Link: http://www.research4cap.org/Library/Workman-TRL-2018-UseAppropriateHighTechSolutionsRoadConditionAnalysis-TechnicalStatus-AfCAP-GEN2070A-171002.pdf

This report was an additional report due to the Tanzania extension and was designed to assess the current situation of the high-tech solutions project on completion of the research in the four original countries. The main research was completed by this time, October 2017, but the extension in Tanzania was under way to test specific aspects of the methodology. To this point in time certain conclusions had been drawn that confirmed the technical feasibility of the system, and the Tanzania trials were designed to test the methodology in a roll-out scenario for a specific situation. The Guideline had been completed by this time and was available on the ReCAP website.

This report updated the range of high-tech solutions that have potential for increasing knowledge of rural road networks, and how they could work together or with existing technologies. An assessment was also provided on the satellite condition assessment methodology, on how to decide whether to use it, how it could integrate with existing systems and the level of training and support necessary to use it. A number of conclusions were drawn on the project thus far, which showed where the technologies had been successful and their potential for future use.

A presentation on the project results was made at the International Road Federation WRM2017 (World Road Meeting 2017) conference held in Delhi in November 2017.

It is noted that the Uganda National Roads Authority (UNRA) in Uganda have shown interest in extending the satellite condition methodology to survey the northern areas of the country which are difficult to access by traditional means. UNRA have applied for funds to procure DashCams for manual surveys and satellite imagery for the northern areas. They are also tendering for procurement of a UAV, which is intended for use on alignment selection and maintenance surveys.

4.11 Tanzania report

Link: http://www.research4cap.org/Library/Workman-TRL-2018-UseAppropriateHighTechSolutionsRoadConditionAnalysis-TanzReport-AfCAP-GEN2070A-180430.pdf

The Tanzania report assesses the suitability of some technologies used in the high-tech solutions project to the road network in Tanzania. The extension was granted to test the methodology in an appropriate environment and in a roll-out scenario for a specific situation, as defined by the RFB. The satellite imagery was procured for Tanzania and the ground truthing was completed using existing data and videos, and the training was undertaken from 9th to 13th April 2018, at Ardhi University in Dar es Salaam. This report assesses the relevance of the methodology to Tanzania and is based on the results of the training, training exercises, feedback from workshops held at the training and formal course feedback.

There is a parallel project under way in Tanzania under the DFID funded Frontier Technology Livestreaming (FTL) initiative. This project is looking at the potential for automating road condition assessment from the assessment of UAV imagery, which is higher resolution than satellite imagery. The principle is very similar to the manual assessment of satellite imagery and was developed following consultation with TRL when the current project was already initiated. Technologies such as smartphone IRI and video recordings were also used in a similar way to the current project.

5 Data collection

The data collection on this project was largely undertaken by local partners, i.e. the rural road organisations that partner with ReCAP.

The resources necessary for the project were:

- Satellite imagery: This was procured by the project. A total of £19,159 was spent on visual satellite imagery with a total coverage of 1,829 km^2, which represents approximately £10.50 per m^2. Also £3,000 was spent on one 16 km^2 scene of SAR imagery, which is procured per scene, not per m^2.
- High-tech equipment such as DashCams and SD (Secure Digital) cards, smartphone holders, etc. One set was provided to each country. These were also procured by the project.
- Training resources and facilities for satellite condition assessment: The trainers were provided under the project, but the venue and logistics were largely provided by national ReCAP partner organisations.
- Ground truthing: Training in ground truthing was provided by the project, but in most cases the national ReCAP partner organisations undertook the ground truthing (road condition assessment) exercise themselves, using locally established procedures.
- Satellite assessment: This was undertaken by the national ReCAP partner organisations, following the training course.

The process of the initial research was to compare the satellite assessment to the ground truthing, in order to assess how accurate the system was in each country. Some cleaning of data was necessary, for example in one case some roads were incorrectly labelled, so the data had to be checked and re-labelled.

The satellite imagery for the project was acquired by Airbus, who also did the processing of the imagery to ensure that it was orthorectified (geo-located accurately), pan-sharpened (panchromatic imagery is combined with multispectral imagery) and adjusted so that the roads were easily visible to the human eye.

However, as Airbus are partners in the project there was minimal input from TRL or the participating country representatives. If a country was procuring imagery independently then they may need some support in procuring the imagery, as it is not a straightforward process. The processes of orthorectification can be carried out by combining the raw imagery with a DEM of at least 10 m resolution, but it is a specialist process and it is unlikely that local roads organisations could manage this. In this case it is better to buy the image already orthorectified, through a local supplier such as Regional Centre for Mapping of Resources for Development (RCMRD).

The pan-sharpening process is also possible to manage through a GIS program, or using specialist software, but again would be more appropriate to buy it ready pan-sharpened. If a supplier other than Airbus is used, the local roads organisation would need to inform them clearly what the imagery is to be used for, and instruct them to process the imagery to highlight the roads clearly. Airbus used an additional software to process the imagery for road assessment purposes, so if a different supplier were to be used it is likely that some experimentation would be necessary.

An approximate summary of the resources committed by each country towards the project has been included in the Trials Reports.

6 Principles

The overarching principle of this research is that high-tech solutions will have an increasingly important role to play in rural road network information provision, and that this project should explore all possibilities whether they are applicable now and addressing current problems; whether they have the potential to address problems that may arise in the future, or whether they may become more cost-effective in the future.

Although rural roads are often proposed for labour-based and simple solutions, there are opportunities for technology to leapfrog and become appropriate for LICs. In situations where there is a lack of information and road networks are difficult to access due to remoteness or conflict, high-tech solutions can have a role to play. In principle they offer less risk than driven visual surveys and can potentially provide information over large areas in a short time. This would be applicable in environments such as Nigeria (where the initial research was undertaken) and Afghanistan.

A core principle of the research was to use the existing condition assessment system prevailing in each country, so new systems and standards would not be introduced. This means that the methodology had to be flexible enough to adjust to a different system in each country, which it did. There was also a focus on using local resources wherever possible, so RCMRD were brought in to learn the training course and deliver it in Kenya and Tanzania. In each country it was also necessary to partner the roads organisation with a local remote sensing/GIS specialist, usually a government department, so that support could be provided on a more sustainable basis.

Although most of the countries that the research was carried out in did not have a fully functional RAMS, the methodology is in principle more effective and easier to use when linked to a RAMS. In the case of Tanzania the outputs of the methodology were compatible with the local RAMS (DROMAS 2) and the satellite imagery could also be used to audit the results to ensure consistency.

7 Results

The results of the research trials are highlighted in the Final Trials Report, and are summarised again in Annex 2.

7.1 Technical

The results of the research in Ghana, Kenya, Uganda and Zambia were produced in QGIS, in the form of spatialite files, visible on map layers over the satellite imagery raster layer. This is essentially a database of the results that can be manipulated to provide data, although the data would be more easily managed in Tanzania by using DROMAS 2.

The comparison of ground truthing against satellite condition assessment was copied into a spreadsheet to compare the accuracy. Two different levels of assessment prevailed in the four countries:

Three level (Good, Fair. Poor):

- Ghana

Five level (Very Good, Good, Fair, Poor, Very Poor):

- Kenya
- Uganda
- Zambia

The only country with significant levels of paved rural road was Ghana, so the results for Ghana show paved and unpaved analysis. The unpaved accuracy (where the satellite assessment showed the same results as the ground truthing, in the same place) for Ghana was 87% for unpaved roads and 80% for paved roads. This was as expected because the features that indicate condition are more visible on unpaved roads, for example variation in width and surface texture.

For the five level condition countries, the results varied from 63% in Uganda and 69% in Zambia, to 85% in Kenya. However, the Kenya results must be tempered by the knowledge that one road which represents almost half of the sample size had been very recently rehabilitated and was clearly in very good condition. Nevertheless, it was positive that the road was correctly assessed from the satellite imagery.

An analysis was made in the Final Trials Report on the accuracy of assessment in terms of how far away from the ground truthing they were, for example the assessments that were more than one level out (i.e. Good assessed as Poor, or Fair assessed as Very Good) were between 1% and 4%. This indicates that even when the assessment is not exact, it is close, which provides an acceptable level of confidence in the results.

As the Tanzania trial was testing roll-out, based on the results in the other four countries, there was no need to replicate the same tests. However, an exercise on condition assessment using the methodology was undertaken during the training. The results can be seen in Annex 3. The training participants were split into three groups and were asked to assess several roads independently, using what they had learned during the training and the Tanzania Rural and Urban Roads Agency (TARURA) assessment guidelines, which are based on a four level assessment system (Good, Fair, Poor, Bad). The results across the three groups were fairly consistent, and did not vary more than one condition level between groups.

The satellite assessment offers greater possibility for consistency across larger areas because it can be carried out centrally and the assessment process can be more closely controlled. Even if the people carrying out traditional surveys are trained together and consistently, there is less control over how they actually carry out the assessments and how the results are processed. In the case of Tanzania the results are entered directly into the DROMAS 2 database and no audit is carried out on the individual surveys, as is the case in most countries.

7.2 Financial

Cost comparisons were also made between assessment by satellite imagery, and traditional assessment, as discussed in section 4.6.4 and Annex 4 of the Final Trials Report. It can also be seen in Annex 1 of this report.

The costs for condition assessment by satellite imagery were analysed using the approximate costs provided by each country for the various activities involved. It has been assumed that the ground truthing costs are a good approximation for the normal condition assessment surveys, as in each country the existing system of condition assessment was used to carry out the ground truthing. In most cases the ground truthing was undertaken as a stand-alone exercise, so it would probably be slightly more expensive than if it were carried out as part of a larger survey.

For the satellite assessment costs the training has not been included, as this would be a one-off cost. However, the process of calibration has been included and was estimated at up to 10% of the network, which would be the maximum that would be necessary for the first year of operation.

So in summary the cost estimates included:

Traditional visual survey condition assessment:

- Staff wages to travel to site, carry out surveys and analyse results
- Travel and subsistence costs to stay overnight, including accommodation and living allowance
- Vehicle and fuel, plus driver
- Any equipment used, such as GPS or roughness measurement

Satellite assessment:

- Cost of the imagery
- Cost of the calibration, based on traditional survey costs
- Staff wages to assess the imagery and produce results

Two figures are shown for the satellite imagery costs; the first is using the actual costs of the imagery as supplied by Airbus with all relevant discounts applied, and the second is using the headline costs without any discounts. It can be seen that there is a large difference in some cases between the project costs and the headline costs. In most cases the assessment by satellite from the project is only slightly more expensive than the traditional driven surveys, but in order to make the system cost effective it would be necessary to negotiate good discounts for the procurement of such imagery. Experience suggests that this should be possible in most cases.

As previously mentioned one of the main benefits of this methodology is its use in inaccessible areas due to conflict or other reasons. This is difficult to quantify in terms of cost, but should be considered as a factor that may make an assessment more viable, even if it is more expensive than traditional means.

The cost also depends on the density of roads per km^2 of imagery. Areas with high road density are more cost effective. This is demonstrated by Uganda, where the road density in the table is much higher than the other countries. This reinforces the principle mentioned earlier of planning the imagery acquisition carefully so as to not procure any areas without roads.

Costs for drone imagery are not yet available because the projects using the imagery are not yet complete and they are not assessing the cost effectiveness of their system, so are not collecting the necessary information for cost benefit. However, the projects have been able to provide some basic information on costs:

- Drone full package: $10,000
- Base station (GNSS): Costs not provided
- Powerful computer for processing: $1,500
- Storage devices: $300
- Drone license: $10,000
- Pix4d Software and license-: $9,000
- Man Power: Provided under Word Bank project

These costs indicate that to set up the drone project cost in excess of $30,000 for the hardware and software. On top of that would be costs for manpower to transport and fly the drone, maintenance and repairs, as well as logistics such as vehicle, fuel, driver, etc. It is not clear how long it takes to fly a road, but we believe the methodology is to fly each road more than once so that a stereo image can be built up.

Many countries have restrictions on the times and situations where drones can be flown, i.e. not over live traffic, only at certain times, etc. so this can impact on the manpower necessary to provide appropriate imagery. There is also a significant task to provide a mosaic of the drone imagery and orthorectify it accurately.

Given these factors it is probable that the costs of drone imagery, when all factors are taken into account, will be significant. Whether the satellite assessment methodology can be financially competitive with drones will depend on the area of imagery that has to be procured and the discounts that can be negotiated for large orders.

7.3 Time

Perhaps the most significant benefit of the satellite assessment process is the reduced time it takes to assess roads, and the fact that the dependence on logistics and physical resources is much less.

In terms of assessment time, the following was observed:

Visual surveys:

- Uganda carried out 145 km in 5 days = 29 km per day
- Zambia carried out 53 km in 2 days = 26.5 km per day
- Kenya carried out 78 km in 2 days = 39 km per day (not including 2 days travelling to site)
- Ghana carried out 86 km in 3 days = 28.6 km per day
- Tanzania carried out 851 km in 30 days = 28.3 km per day (for the entire Kilosa district)

Despite the different systems and criteria used in each country, the speeds of assessment are remarkably consistent at between 25 km and 30 km per day. Kenya was slightly faster as they relied on roughometer results, rather than just visual surveys. All surveys except for Kenya were within 1.5 hours drive from the road department headquarters, so this travelling time was excluded (as noted above). It is likely that surveys in the other countries would have achieved better coverage if the teams had stayed overnight in the area, thus reducing travelling time.

Satellite assessments:

In all countries, these were carried out at a rate of between 50 km and 80 km per day. It is expected that this will increase with practice, possibly to more than 100 km per day. It is also of course possible to assign many people to the assessment and thus increase the overall length of road assessed per day. This is only limited by the number of people that can be trained.

7.4 Resources

The traditional road surveys typically involve an engineer, one or two technical assistants and a driver. The satellite assessment involves only one person. Given that the satellite assessment can achieve at least twice the length of road per day as the traditional system, this indicates that traditional assessments use at least seven times as much manpower to survey the same length of road, and possibly more if the satellite assessment becomes faster with practice.

There is also much greater administration required to arrange and carry out traditional surveys. The process is subject to delays and inefficiencies, whether that be vehicle maintenance issues, fuel, staff availability or simply weather and accessibility issues; these problems are largely avoided by using the satellite system.

7.5 Environmental

Although this is not a significant issue, the traditional surveys will be less environmentally friendly as they will use fossil fuels for the driven surveys. If Tanzania is taken as an example, to drive 110,000 km of rural road will probably involve at least 300,000 vehicle km to complete a year of surveys, given the travel to site and the fact that most small roads will need to be driven twice (to the end and back). Using a typical online CO_2 calculator (http://www.nextgreencar.com/tools/emissions-calculator/) a standard SUV type vehicle would produce about 130 tonnes of CO_2 for a single year of surveys in Tanzania. It is difficult to estimate the carbon that could be attributable to a satellite image as it depends on how many images the satellite produces, but there are clearly carbon implications of launching satellites into space. However, given that each satellite can produce millions of images in its lifetime, it can be assumed that the carbon footprint of each image would be significantly lower than driven surveys.

8 Conclusions

There are some relevant high-tech solutions that warrant further investigation. Although none were formally trialled during the project, some were tested and used for ground truthing, such as the DashCam, Smartphone IRI and GPS tools. The DashCams were found to be very effective for providing a permanent record of the road condition at the time of assessment, which could be used to check and audit the ground truthing. The videos were also very useful in identifying any anomalies on the satellite image that could not be readily identified from the images. In the final system only a small proportion of the road network will be ground truthed, so this technology has its main benefit in being able to build up a reference document of typical imagery anomalies. The RoadLab IRI smartphone app was also trialled. Although it was found to be less accurate for the lower condition unpaved roads, the recent upgrade does seem to have improved its accuracy. These technologies were included in the final Guideline. Amongst those high-tech solutions that have the most potential to be used in the future are social media apps (partially developed in Ghana), UAVs, back analysis, spectral reflectance and the use of DEMs.

Coordination with existing ReCAP projects, such as the Asset Management, Rural Accessibility Index (RAI) and Climate Change projects, was explored. Although there were strong links with the Asset Management and Climate Change projects, the main role of the High-tech solutions project was seen as contributing information towards the other two projects and confirming the feasibility of some of the processes. The RAI is in the first phase, but it is expected that the High-tech solutions project can provide advice on relevant technologies.

The condition assessment by satellite imagery was trialled in a real situation with minimal direct input from the consultants in the practical aspects. A number of issues were encountered that are related to problems which often arise in LIC implementation, such as funding barriers, efficiency and logistical issues and others. Despite these issues, the results were comparable to the Nigeria research, which was carried out under project conditions using advanced equipment and with adequate direct funding. Also, the assessments in Nigeria were carried out by Airbus DS staff in the UK. This fact suggests a high level of confidence that the results could be replicated by countries independently.

Local remote sensing partners were included in the project, in order to provide the expertise in mapping, image interpretation and GIS capabilities. This partnership worked well and provided some robustness to the process.

The training carried out was effective. Feedback from the first four countries suggested that it could be one or two days longer, with additional practicals and exercises, so this was implemented in Tanzania and was found to be successful. The training in Kenya and Tanzania was carried out by RCMRD, with support from TRL, which proved that local trainers can be appropriate for such high-tech subjects.

The system employed used the existing condition assessment system in each country as a basis for the ground truthing assessment. Hence a five level system was used in Kenya, Uganda and Zambia, whereas a three level system was used in Ghana and a four level system in Tanzania. This has tested whether the system can be calibrated for use in a range of environments, as well as providing results that can be compared to previous years on a similar basis.

The exercise to check the accuracy of the satellite assessment was carried out using the same manual process as in Nigeria, so can be compared on a similar basis. As mentioned earlier the Nigeria project was under project conditions with project funding, whereas this project relied on local funding to carry out the ground truthing and assessments, with the consultants providing some input into the training and other support activities. In this respect it would have been reasonable to experience a lower accuracy of assessment than Nigeria. However, this was not the case. This success can be attributed to the revised methodology used and in particular the detailed assessment guidelines that were produced following the ground truthing. This gave the assessors clear guidance on how to assess the road condition.

The system by its nature is quite subjective. The detailed assessment guideline that was produced for each country has reduced this subjectivity to some extent, but the manual system will always rely on human judgement, as do the visual ground truthing assessments that each country undertook. It is believed that there is scope to develop an automated system for condition assessment from satellite imagery, and this is indeed being trialled in Tanzania using drone imagery in Zanzibar. If found to be feasible this would make the system less subjective, much faster and more efficient.

The results (Annex 2) of the assessments show an overall correlation of 66.6% for unpaved roads, from a total of 224.4 km that were ground truthed, following corrections for anomalies (the total for unpaved was 318.8 km and for paved was 29.3 km). This is in comparison to 64% correlation from 31.5 km of unpaved road in the Nigeria study. The overall correlation from paved roads in Ghana was 80%. It should be remembered that this was a three condition level assessment, so is expected to be more accurate than a five level assessment. In comparison the overall unpaved road assessment in Ghana was 87%. It was expected that unpaved roads would return higher results, because the width of the road can be used to assess, whereas for paved roads this is usually fixed to the paved surface, often with constructed side drains, so the assessment has to rely purely on the surface colour/texture which is often less variable for paved roads. It is assumed that a five level assessment for paved roads would be even harder to assess, although for main roads it may be possible to use the road markings as a factor as well.

It should be remembered that the staff carrying out the assessments only had three days training, and very little practice before they undertook the assessments. If this was their main activity and they had more experience and practice it is likely that they could achieve higher correlation results. Often short term projects are not taken as seriously as the main activity of a person's job, because they are not judged on the results. It could be argued that if a person were assigned to this job full time and judged on their results, the outputs would be more accurate.

The data and information was difficult to manipulate and assess without a road specific database. Most RAMS that are in operation are now GIS based, which is ideal for analysing this type of data. Incorporating the information into a database, such as the one used in Tanzania, would make the system much more user friendly and would give the user a much larger range of options when processing the data. For example the GIS database should be able to locate structures or defects on a linear as well as on a geo-referenced basis, which is useful as most countries still use chainage to locate their road assets.

Provision of a database, RAMS, or other type of management system would enhance the utility and user friendliness of the satellite assessment methodology. This was trialled to some extent in Nigeria, and additional consultations were undertaken in Tanzania with the DROMAS 2 program being developed there. Ultimately, however, the satellite assessment system needs to be flexible enough to link with a range of different databases and asset management systems, because there are many different types already established around the world. It is not justifiable to change the RAMS to accommodate the satellite assessment system, but the satellite system should be able to provide information that can be useful to the RAMS.

Cost is also an important factor. In order to be feasible the assessment by satellite imagery needs to be cost effective. Given the figures shown in Annex 1, the system is more expensive than carrying out traditional driven surveys. The main costs are in procuring the satellite imagery, but there are ways to reduce this expenditure by planning the acquisitions carefully and not procuring areas without roads, as well as by negotiating the cost of imagery when large areas are to be procured. Additionally, as with many high-tech solutions, the cost is likely to come down in the near future as many more satellites are launched and competition increases. The cost effectiveness of the system is therefore likely to be more feasible in the medium to long term, rather than the short term.

In comparison to traditional condition assessment systems, the satellite assessment system is faster and is logistically less onerous. For example one person can assess the satellite imagery for condition at a rate of about 75 km per day, whereas the traditional systems used in this project collected data on about 30 km per day, using a team of 2 or 3 people, a driver, vehicle and equipment. The big difference in cost is the imagery itself. The extensive savings in time to assess roads, which would also translate into cost savings, are an important outcome of the research. Even if the outputs have less detail and the imagery is more expensive, the time savings should be considered as a major advantage of using this methodology and could outweigh the cost and detail concerns in some circumstances.

Satellite imagery is starting to be made available on a reference basis (for example: OneAtlas by Airbus), where the user does not own the imagery, but has access to it for limited periods. This would make regular condition assessments more feasible and cost effective, although the user would probably want to procure imagery at certain intervals as well. Environmentally the satellite assessment system does have an advantage, as it does not rely on having to drive every road, with the consequent use of fossil fuels. The manpower inputs are also less. Most of the work can be carried out in the office environment, without the need to travel.

Given the current financial and procurements constraints, the most beneficial environment to use the satellite condition assessment methodology is still likely to be remote or conflict affected areas, which are expensive or dangerous to access by traditional means. This was proved in Nigeria, but ReCAP countries such as Afghanistan and South Sudan could benefit greatly from such a process, whilst minimising the risks to road organisation personnel who would no longer need to physically visit dangerous regions. There would however be a need for interventions, if a road is identified as poor condition, but this could be a focused intervention with relevant security in one location. A survey team would be required to cover the whole area, for which effective security may be more difficult to arrange.

In terms of uptake and embedment, there have been some positive results. Some of the high-tech solutions, such as DashCams and smartphone applications were found to be useful, and are continuing to be used. Some countries have expressed an interest in procuring additional DashCams as they are a cost effective way of recording road condition and can be referred to in case of dispute. The satellite methodology was embraced by Uganda especially, who sent two additional staff members to the Tanzania workshop to gain a better understanding of the methodology because the Ugandan National Roads Authority is considering using this technology to map some of the more remote and inaccessible areas in the north of the country.

There are potential uses for some of these technologies in climate change resilience; most notable the change detection and back analysis. The imagery itself can also be useful in combination with the DEMs to work out catchment areas and waterways that are likely to affect the road network.

The system is capable of providing appropriate, cost effective support to an asset management system. However, it may not be the best solution for every situation, so a careful assessment process needs to be carried out by the user to determine if the system meets their requirements in terms of the information collected and its quality, against the cost to collect the information. The main advantages of the system are that it provides a permanent record of the assessments, it allows accurate maps to be produced, it is auditable and it is less environmentally damaging. It is more appropriate for areas with lower levels of vegetation and longer dry seasons, it is more accurate with less condition levels and it can be carried out more quickly with less logistic input. The disadvantages are that VHR satellite imagery is still relatively expensive; the manual assessment is still quite subjective (although no more so than traditional surveys), and will require additional skills and experience within the roads organisation. It is less effective for areas with very high vegetation levels and long wet seasons, and tends to be less accurate for systems with five condition levels.

9 Recommendations

The following recommendations have been made for the future use of high-tech solutions in Africa, with comments on wider use in LICs in general.

- From the high-tech solutions covered in the various project reports, and specifically the Guideline, a number can be useful to increase our knowledge of rural road networks. This is a rapidly changing field and even some of the information in the Guideline has already been superseded in reality. The Guideline should therefore be regarded as a reference document, but further investigations will need to be made to determine the most recent state of the art in each subject. This can usually be achieved through a focused internet search.
- There is scope for innovation with the high-tech solutions that have been researched. Many innovations involve applying an existing technology to a different use, such as smartphones for road roughness measurement. There are significant opportunities for technologies applied in Africa to leapfrog those already in use in HICs, for example satellite technology would add little to the information on established road networks in Europe, but could be very useful for countries in Africa and Asia where knowledge and accessibility are limited. So the Guideline should be considered as a reference document that has the tools for innovation.
- Some significant technologies that are likely to come into mainstream use for road related applications in the near future in Africa, as shown below. It is recommended that ReCAP consider

some of these for future research into feasibility for increasing knowledge of low volume rural roads in a cost effective way. The technologies include:

- UAVs/drones: Already being used in research into automated road condition assessment on the Frontier Technology Livestreaming (FTL) project in Zanzibar, bridge inspection, 3D mapping and monitoring of projects, as well as many non-road related activities in Africa (with possibilities for synergies). It is noted that some roads organisations are in the process of procuring their own UAV (i.e. Uganda), so there are potential synergies here.
- Pseudo drones: Technology being developed but has the potential for very high resolution imagery, video and LIDAR of roads, with very high temporal frequency and flexibility to visit areas on demand.
- Video cameras with a GPS enabled facility: Low cost, high definition videos that are GPS enabled provide a cost effective solution for recording road condition. Research is also being carried out to use them for automated road condition assessment.
- Smartphone applications: With GPS facility and built in sensors such as accelerometers and gyroscopes, smartphones have the potential to contribute significantly to road network knowledge.
- Accelerometers: These are starting to be used to independently measure road condition and how agricultural crops are vulnerable to damage during transit. Accelerometers with much higher frequency than those used in smartphones have the potential to capture very detailed information of roads.
- Other satellite applications: At present many satellite applications, such as radar imagery, are still prohibitively expensive to use on rural roads. However, there are initiatives in the process of development that have the potential to make satellite imagery more accessible, such as online streaming of imagery that is high resolution and recent (within 6 months). This is a development that has potential to make satellite assessment more financially feasible.
- GIS platforms: Software such as QGIS is freely available and can be a good platform for storing and processing road information. Most RAMS use GIS platforms, such as the DROMAS 2 system in Tanzania which is based on QGIS or the TRL iROADS which is based in ArcGIS.

It is recommended that road organisations who are interested in using high tech solutions for monitoring of their network consult the Guideline and check latest developments of any technologies they are interested in applying. There is also the possibility to contribute to the High-tech Solution blog on the ReCAP Regional Projects website: http://www.research4cap.org/SI/Lists/Satellite%20Imagery%20members%20list/NewMember.aspx?Source=http%3a//research4cap.org/SitePages/SatelliteImagery.aspx

- Crowdsourcing: This is a potential source of information on roads, especially those that may be less accessible or where resources are limited for monitoring. Examples of crowdsourcing are the 'Fix-my-street website https://www.fixmystreet.com/, which has a number of partner organisations in Africa. Research is also being carried out on data harmonisation, which combines different data formats to produce a consistent output that is useful for the end user. Project counterpart in Ghana also started to develop a social media app to help gather information on the road. There is potential in the future for countries to link with such existing crowdsourcing or social media establishments to increase their knowledge of rural roads. Other crowdsourcing pothole identification systems include 'Street Bump' and 'Waze'.
- This research has proven that satellite assessment of road condition is feasible in the right conditions, if the outputs are appropriate for the host organisation, mainly from the perspective of the speed of data collections and the reduced resources and administration it offers. In order to

determine whether the methodology is suitable for a particular country or region, section 2.1 of the Guideline should be referred to. At present the methodology is still most applicable in remote or conflict environments, so it could be appropriate for use in ReCAP countries such as South Sudan or Afghanistan.

- The satellite methodology can also be used as a source of remote auditing by local roads organisations or funding agencies, or as a means of checking maintenance strategy over a number of years – particularly for gravel roads. This can be achieved in a cheaper way by using a series of archive imagery sets of the same area.
- It should be noted that discounts should be available to large areas of procurement, as well as relaxed limitations on the minimum area of imagery to be procured. The project has investigated the terms and conditions with Airbus, who have indicated that to procure, for example, imagery to cover the 110,000 km of rural road in Tanzania, the minimum width of 5 km and the overall price would be negotiable. At a width of 5 km the user would be procuring a large amount of imagery that is not necessary, so a reduction in this limit alone would greatly decrease the costs. So it is recommended that the user always negotiates with the supplier over limits and cost.
- If a country or region decides that they do want to use this methodology for assessing road networks and road condition, it is recommended that they consult the various reports, documents and training materials that are on the ReCAP website under 'Regional Projects', 'Satellite Imagery': http://www.research4cap.org/SitePages/SatelliteImagery.aspx . It is also recommended that they are given at least basic training in the various procedures and processes associated with satellite imagery interpretation and GIS procedures to process the information, which would be available from regional suppliers such as RCMRD in Nairobi and CERSGIS in Accra, which are both based in Africa. Other local country-based suppliers may also be able to supply similar training, as well as Universities or local government departments which specialise in remote sensing. Such local government departments were included in the training with Airbus so that local capacity was developed and the methodology could be sustainable beyond the project. The extent of such training would depend on the existing capacity within the roads organisation.
- RAMS: Where possible it is recommended that the satellites methodology link with an existing RAMS, either by providing inputs into the RAMS or by auditing the outputs and providing consistency across wide areas. It would be possible to implement the methodology country-wide without the use of a RAMS, but it would be easier and more user friendly to link to one, especially if there is one existing and operational. The methodology has proven to be flexible enough to provide information for a range of scenarios, having been used with two different RAMS, in Nigeria and Tanzania.
- There is a role for the high-tech solutions project to contribute to the Asset Management, Climate Change and RAI projects, by informing of appropriate technologies to collect data, and particularly that for RAI assessment. Future collaboration with these projects should continue through ReCAP.
- There is scope to review the cost of UAVs as a potential tool for road assessment. UAV technology is evolving rapidly and is destined to play an increasingly important role in road assessment in LICs. There is scope for a focused study into the potential uses of UAVs across all aspects of road and transportation. With the improved resolution of UAV imagery, there is potential for them to play a greater role in the assessment of paved roads, where satellite imagery has been found to be less useful.
- Automated condition assessment from remote sensing imagery: Research is ongoing in this area, both on the DFID funded FTL Project with UAV imagery and internally at TRL with satellite imagery, using Machine Learning and Change Detection. It is recommended that ReCAP maintain links with both organisations and review the results within the context of this project to explore synergies

and future collaboration. TRL have agreed with TARURA and Kilosa district that they will cooperate on future research in this area independently of AfCAP, which will support a PhD being undertaken at TRL that is building on this original research.

- Future collaboration: At the recent presentation to the RFB in Tanzania, the Board representatives noted that they are interested in the technologies presented and would like to stay informed of future developments in the area. This positive attitude was also experienced in the other participating countries, and was echoed in the positive feedback from the T2 workshop in May 2017. This type of collaboration should be encouraged in the future and it would be beneficial if ReCAP could facilitate the raising of awareness of the potential that high-tech solutions can play in the knowledge of rural road networks.

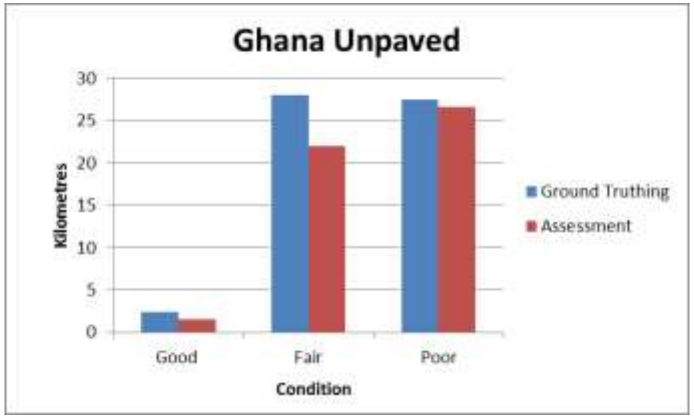
Annex 1 Cost assessment

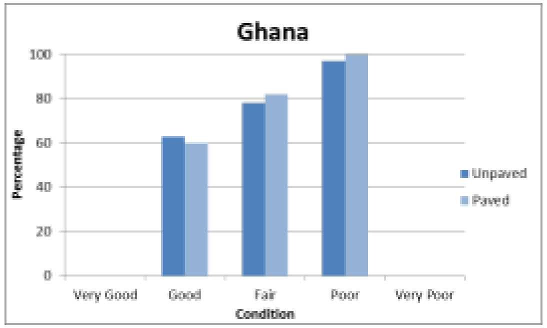
	Road details	Cost of training facilities	Road Density km/km^2	Imagery cost per km road	Cost of satellite ass'ment	Cost of ass'ment per km	Cost of calibration per km	**Satellite ass'ment per km this project**	**Satellite ass'ment per km this project headline prices**	Cost of ground truthing	Cost of ground truthing per km	Cost of analysing ground truthing	Cost of analysing ground truthing per km	**Cost of traditional ass'ment per km**
Ghana		£		£	£	£	£	**£**	**£**	£	£	£	£	**£**
Length of road	37.562	1,805.00	0.25	15.73	180.00	4.79	2.13	**22.65**	**67.12**	780.00	20.77	20.00	0.53	**21.30**
Square area	153													
Imagery cost	590.75													
Kenya														
Length of road	77.882	1,375.00	0.27	26.81	125.20	1.61	2.14	**30.56**	**58.40**	1,629.36	20.92	37.56	0.48	**21.40**
Square area	288													
Imagery cost	2088													
Uganda														
Length of road	145.72	1,133.33	0.78	5.74	524.44	3.60	0.92	**10.26**	**23.49**	1,167.82	8.01	175.56	1.20	**9.22**
Square area	187													
Imagery cost	836.46													
Zambia														
Length of road	52.719	1,090.91	0.44	23.74	204.55	3.88	3.00	**30.62**	**40.24**	1,527.27	28.97	54.55	1.03	**30.00**
Square area	119													
Imagery cost	1251.5													

Annex 2 Results of Trials

Ghana

Unpaved

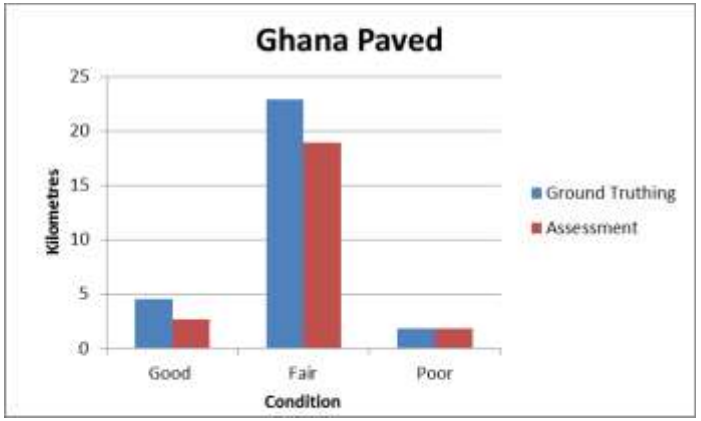




UNPAVED Assessment			Misclassified as;					
	Ground truthing (km)	Corresponding Satellite assessment (km)		Good	Fair	Poor		Unknown
Good	2.441	1.547			0.158	0.736		0
Fair	28.026	21.979				6.047		0
Poor	27.516	26.65			0.866			0
	57.983	**50.176**						

Correlation			Percentage of correctness
Good	2.441	1.547	63%
Fair	28.026	21.979	78%
Poor	27.516	26.65	97%
	57.983	**50.176**	**87%**

Misclassified as more than one level out:
0.736 1.27% > 1 level out

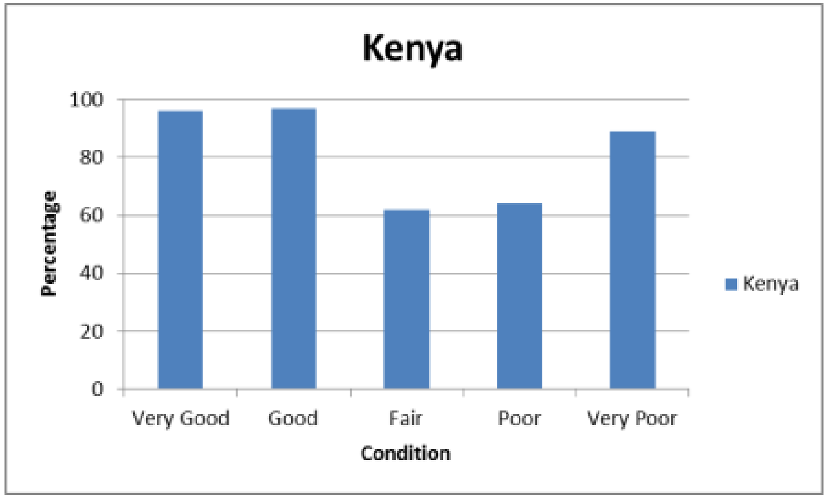


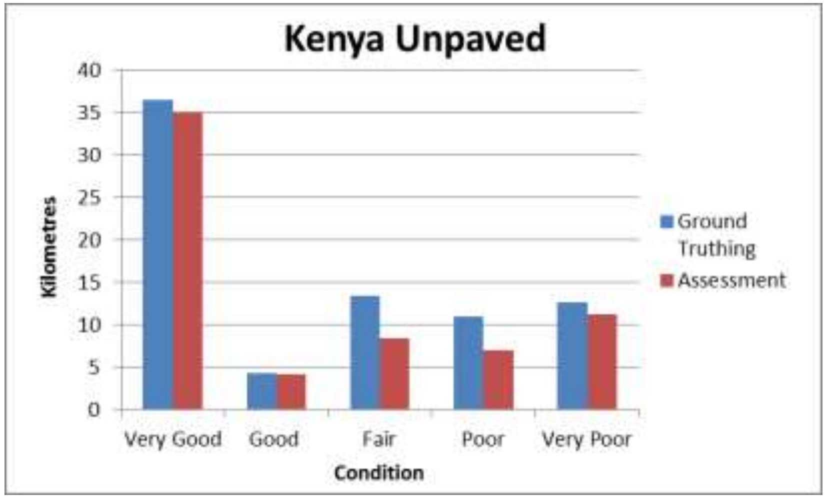
PAVED Assessment			Misclassified as;					
	Ground truthing (km)	Corresponding Satellite assessment (km)		Good	Fair	Poor		Unknown
Good	4.527	2.716			1.693	0.118		0
Fair	22.934	18.918		3.467		0.549		0
Poor	1.845	1.845						0
	29.306	**23.479**						

Correlation			Percentage of correctness
Good	4.527	2.716	60%
Fair	22.934	18.918	82%
Poor	1.845	1.845	100%
	29.306	**23.479**	**80%**

Misclassified as more than one level out:
0.118 0.40% > 1 level out

Kenya unpaved





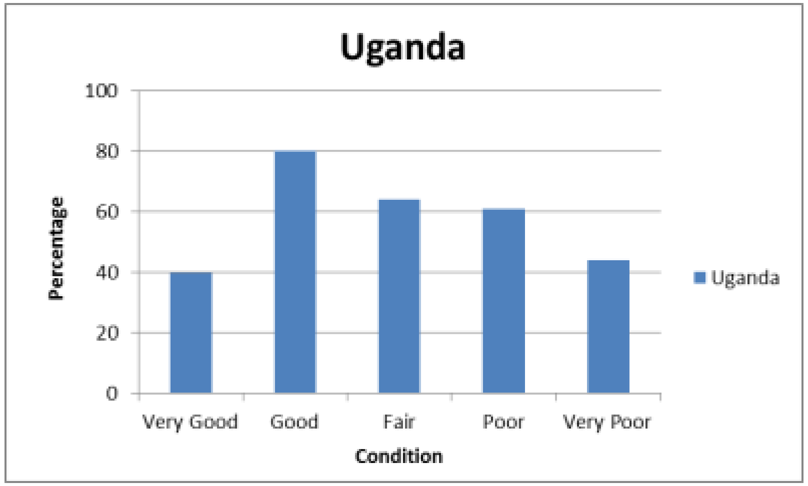
Assessment			Misclassified as;					
	Ground truthing (km)	Corresponding Satellite assessment (km)	V.Good	Good	Fair	Poor	V.Poor	Unknown
V Good	36.432	**35.13**		1.302				
Good	4.318	**4.202**	0.116					
Fair	13.479	**8.377**				4.004	1.098	
Poor	10.983	**7.07**			0.95		2.963	
V Poor	12.67	**11.271**				1.399		
	77.882	**66.05**						

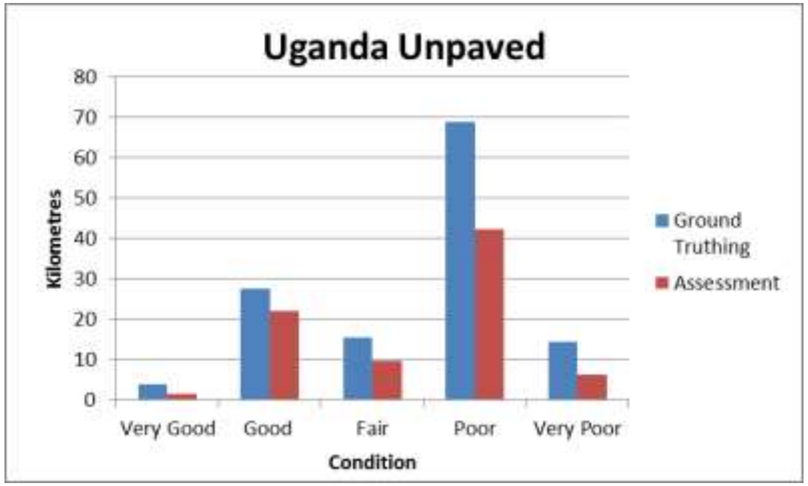
Correlation			Percentage of correctness
V Good	36.432	35.13	96%
Good	4.318	4.202	97%
Fair	13.479	8.377	62%
Poor	10.983	7.07	64%
V Poor	12.67	11.271	89%
	77.882	**66.05**	**85%**

Misclassified as more than one level out:

1.098 1.41% > 1 level out

Uganda unpaved





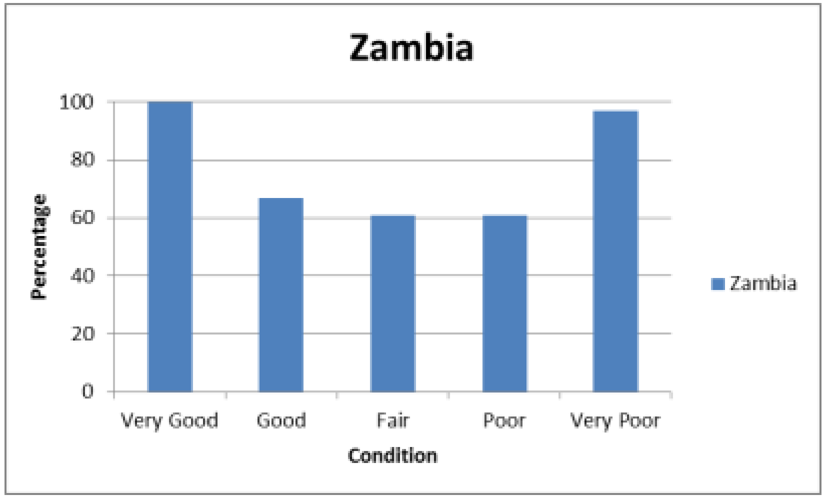
Assessment			Misclassified as;					
	Ground truthing (km)	Corresponding Satellite assessment (km)	V.Good	Good	Fair	Poor	V.Poor	Unknown
V Good	3.878	**1.54**		2.338				0
Good	29.036	**22.128**			3.831	1.34	0.279	1.458
Fair	17.739	**9.79**				3.917	1.705	2.327
Poor	78.893	**42.237**			9.488		17.101	10.067
V Poor	16.199	**6.345**			2.903	5.273		1.678
	145.745	**82.04**						

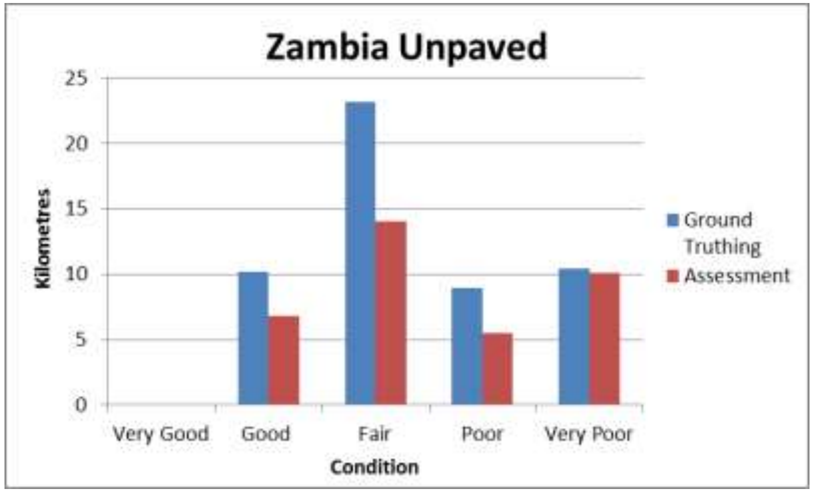
Correlation			Percentage of correctness
V Good	3.878	1.54	40%
Good	27.578	22.128	80%
Fair	15.412	9.79	64%
Poor	68.826	42.237	61%
V Poor	14.521	6.345	44%
	130.215	**82.04**	**63%**

Misclassified as more than one level out:

6.227 4.27% > 1 level out

Zambia unpaved





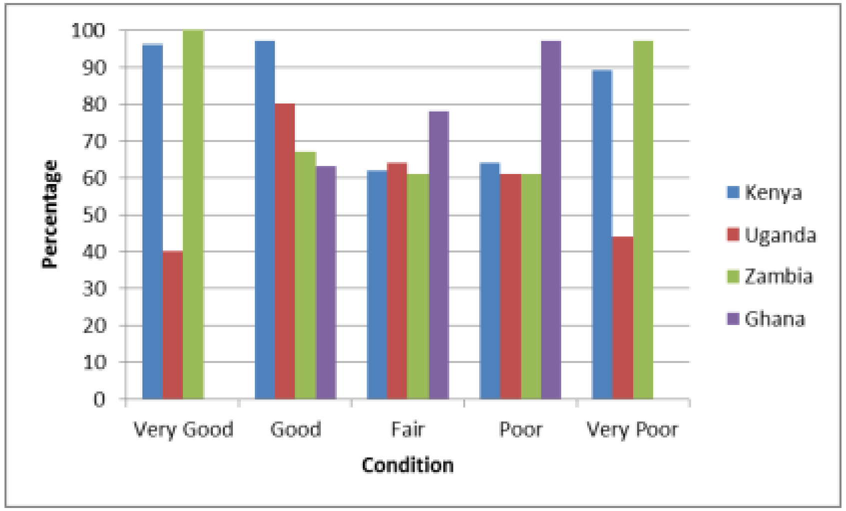
Assessment			Misclassified as;					
	Ground truthing (km)	Corresponding Satellite assessment (km)	V.Good	Good	Fair	Poor	V.Poor	Unknown
V Good	0	**0**						
Good	10.191	**6.829**			1.139	2.223		
Fair	23.153	**14.087**		6.835		2.231		
Poor	8.973	**5.514**			3.459			
V Poor	10.402	**10.129**				0.273		
	52.719	**36.559**						

Correlation			Percentage of correctness
V Good	0.00	0.00	100%
Good	10.191	6.829	67%
Fair	23.153	14.087	61%
Poor	8.973	5.514	61%
V Poor	10.402	10.129	97%
	52.72	**36.56**	**69%**

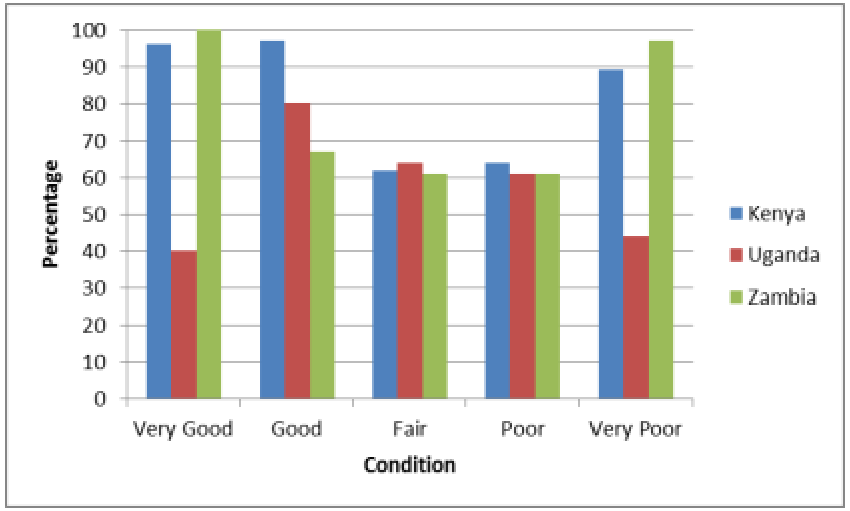
Misclassified as more than one level out:

2.223 4.22% > 1 level out

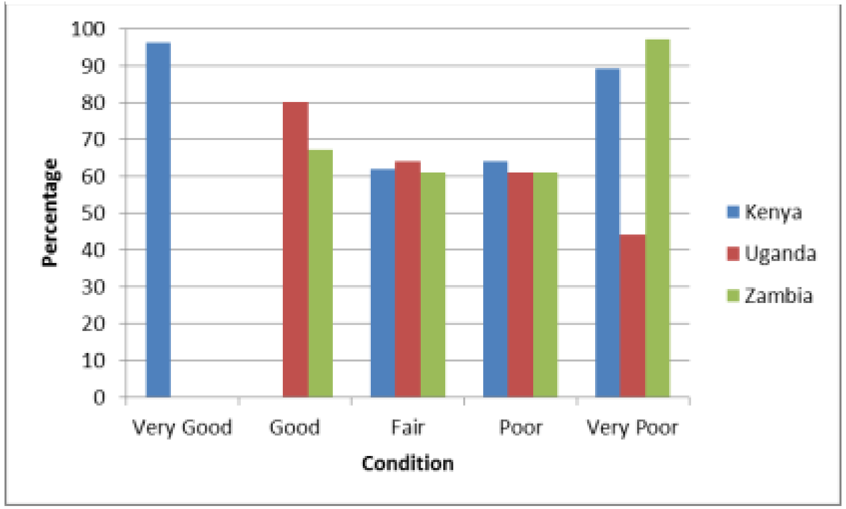
Combined Analysis



All results



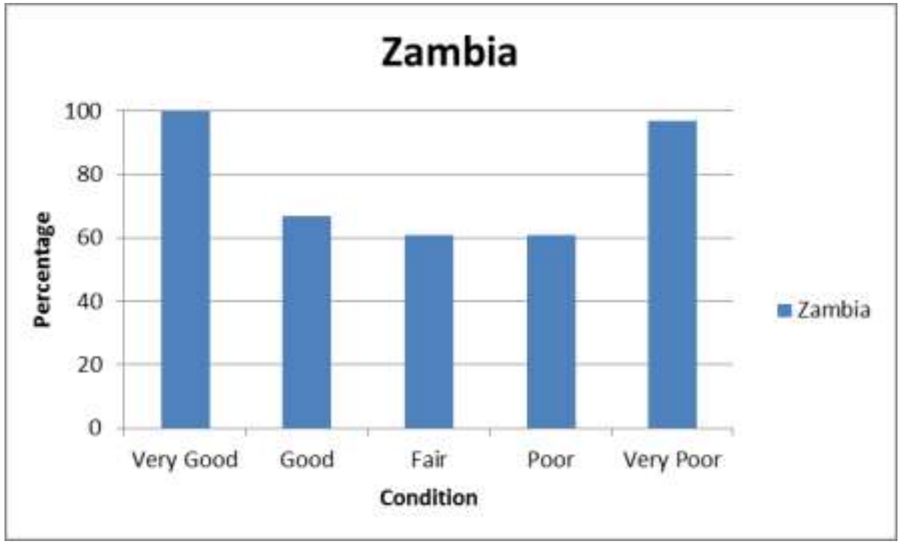
Only results for five condition level analysis

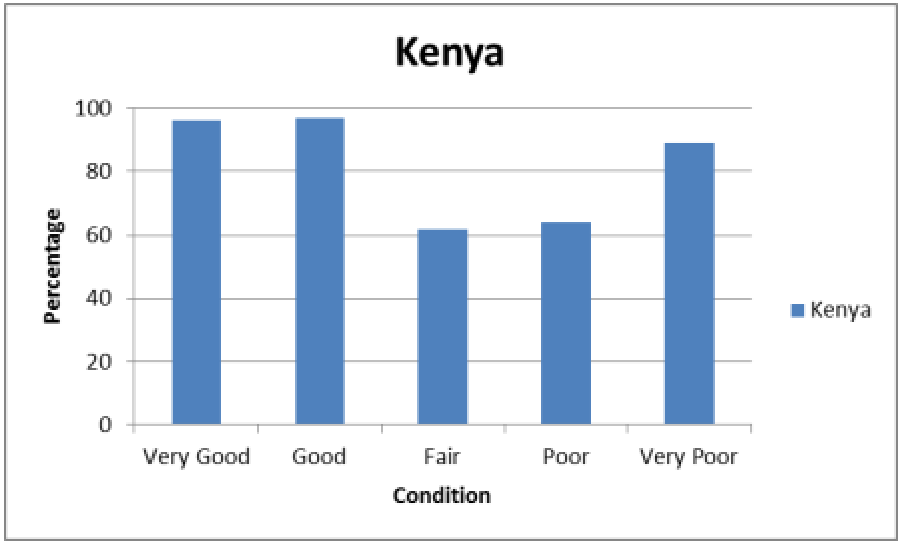


Results for five level analysis, less small sample sizes

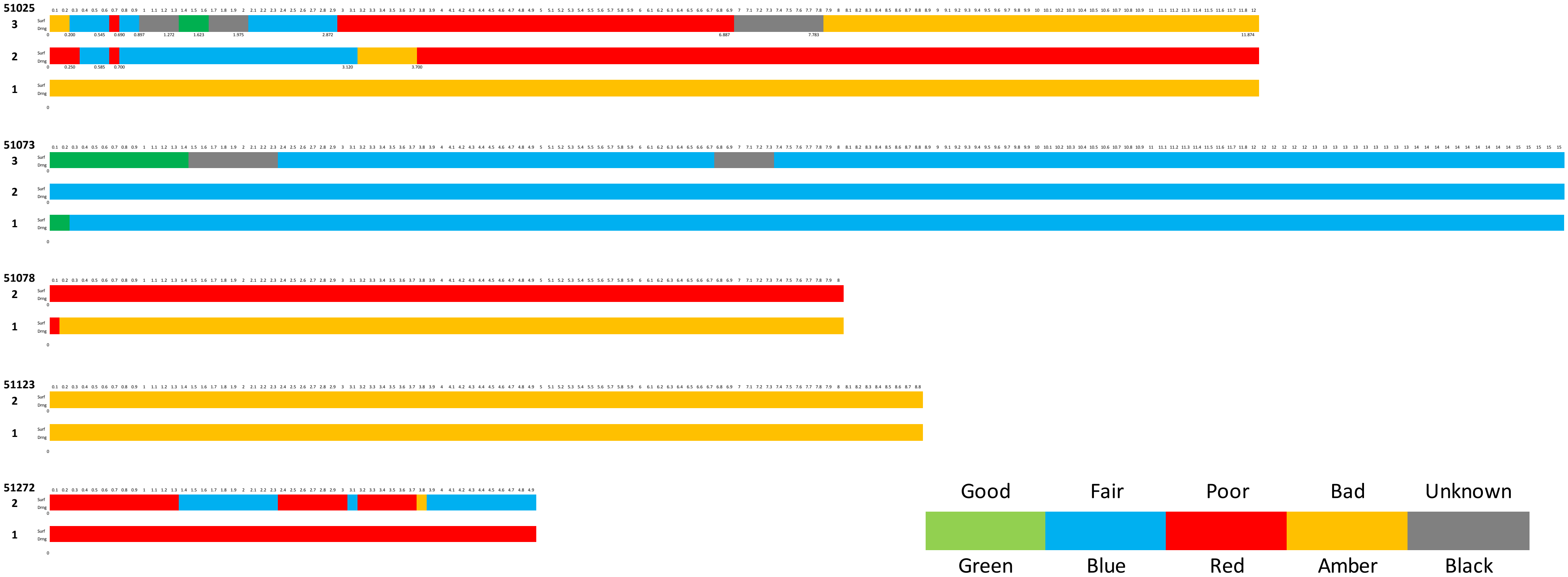
Pattern of Analysis

For percentages where the assessment matched the ground truthing





Annex 3 Tanzania assessment



The results shown above represent five roads from Kilosa that were assessed during the training. The standard DROMAS 2 colour coding has been used to indicate condition. The road numbers and the group numbers are shown on the left. Where there are disagreements it is mostly between Poor (red) and Bad (amber) condition, which is the new distinction introduced by TARURA recently. For many participants this was the first time they had to assess using four conditions, and some were not familiar with the condition assessment guide of TARURA, so it can be concluded that more practice should improve the overall accuracy of the assessment. In addition only two roads were available for ground truthing, plus some video, and the range of conditions was limited, so better ground truthing should also improve the accuracy of assessment.