USING HIGH-TECH SOLUTIONS AND REMOTE SENSING TO INCREASE KNOWLEDGE ON THE EXTENT AND CONDITION OF RURAL ROAD NETWORKS

Robin Workman
TRL Limited
Crowthorne House, Nine Mile Ride, Wokingham, Berks, RG40 3GA, U.K.
rworkman@trl.co.uk

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1 INTRODUCTION

Many Low Income Countries (LICs) have limited data on the extent of their rural road network and its condition. A lack of resources restricts their ability to fully establish an inventory of their road assets. Without a full and current inventory, objective budgeting and prioritisation of maintenance is almost impossible, resulting in neglect and deterioration. Restricted access, inappropriate transport services and continued rural poverty are the consequence.

Remote sensing and high-tech solutions can assist in providing knowledge of road networks (Schnebele E. et al, 2015). This paper draws its evidence from a project designed to look towards the future of road management in Africa and explore different and innovative cost-effective solutions to well established problems. The two main aspects of the project are to consider high-tech solutions to increase knowledge of rural road networks, and to develop a methodology and guideline for the assessment of road condition using high resolution satellite imagery.

This paper will focus on the second aspect, to assess road condition from satellite imagery, although the high tech solutions considered in the first aspect also play a part in the final recommendations. An initial study was carried out in Nigeria in 2013/14 (Workman R. 2015), which was designed to test the feasibility of rapidly assessing rural roads over large areas that were inaccessible due to conflict and/or remoteness. The results were encouraging and led to the implementation of the present project, which has four participating countries; Ghana, Kenya, Uganda and Zambia.

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. A key aspect is to assess the cost effectiveness and sustainability of the system, and how it can be designed to be easily used and replicated by local institutions.

1.1 Overview

The many different and diverse environments and situations within Africa called for a methodology that can be flexible and can be calibrated to suit local conditions and criteria.

It is also important to recognise that in many cases the solution will not be a single application, but a combination of high-tech solutions that can work together to provide an optimum holistic output. A wide range of high-tech solutions were considered for use in the road sector and it is not possible to go into them all in detail in this paper. However, the range of solutions included:

- Satellite applications (including the focus of this paper)

- Unmanned Aerial Vehicles (UAVs)
- Smartphone applications
- Internet based solutions
- GIS based solutions
- Video and DashCam technology
- Other remote sensing applications: aerial photography, LIDAR, photogrammetry, interferometry

A number of other high-tech solutions were also considered for future application. Although these are not feasible in the short term due to lack of technical sophistication or high cost, there is evidence that they will become feasible as time moves on and technology improves and becomes more affordable.

2 ROAD CONDITION ASSESSMENT FROM SATELLITE IMAGERY

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 (Emery W.J. 2012). 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.

2.1 Define an Area of Interest

The first step is to define an Area of Interest (AoI). In each country an AoI was selected that contained a wide range of road conditions. This was important so that the calibration process could be carried out effectively. Advice was taken from local engineers and technicians regarding which areas to select and site visits were carried out in advance of the research to confirm the areas.

2.2 Ground Truthing

The technical feasibility of the methodology was assessed by comparing a manual assessment of the satellite imagery with actual condition data collected by local engineers, using their established methods, processes and, where appropriate, equipment. This process was called ‘ground truthing’ as it was used to establish the actual condition in the field. The ground truthing was considered as a baseline by which the satellite assessment could be judged.

The methods for condition assessment (ground truthing) included:

- Visual assessments from a drive-through survey, using a variety of forms that are filled manually.
- Speed was used in Ghana as an indicator of condition. The roads organisation has a set scale of conditions that are determined by the speed a vehicle can travel on a particular road.
- In Kenya a roughometer was used to assess the roughness of the roads surveyed.
- All teams used a smartphone app to measure road roughness. These apps are easily and cheaply applied by fixing the smartphone in the vehicle and running the app as the vehicle travels.

- A high definition video camera was used in all countries to allow for checking / auditing of the results of the ground truthing. The cameras used were simple DashCams that are actually designed to record damage and accidents to vehicles, but they were found to be appropriate for this purpose. In addition to the video, the camera collected GPS information, speed of the vehicle, orientation and an approximation of roughness. This proved to be valuable information for the ground truthing teams.

This combination of technology and approach led to a reliable assessment of the actual road condition.

2.3 Image acquisition

After the ground truthing was established, the next step was to acquire the satellite imagery for the AoI. The majority of satellite imagery can be procured online, but it is always advisable to make contact with the supplier first in case any discount can be negotiated or any special deals are available. Also it should be possible to liaise with the supplier to have the images processed to suit a particular need, for example for road condition particular hues or contrasts may provide a clearer image for assessment. The imagery for this project was procured from Airbus DS and DigitalGlobe.

For this project, Very High Resolution (VHR) visual imagery with a processed resolution of 0.5m was used. Lower resolutions were considered but found to be inadequate to provide the level of detail required to assess road condition. In Uganda the 0.5m imagery was downsampled to 1.0m and 1.5m resolution respectively, but condition assessment was not possible to any degree of accuracy.

There are a number of tools available in GIS software that allow the user to alter the appearance of the imagery. Basic processing of the image is important to allow it to be presented in the most appropriate way for its intended use, so for road condition assessment the road surface needs to show as much detail as possible. In this case Airbus DS processed the imagery so that it was appropriate for road condition assessment.

2.4 Software

GIS software is an essential aspect of this research as it was required to process the imagery and carry out the interpretation and condition assessment. The QGIS software was used because it can be downloaded without charge and is therefore more sustainable than using software that requires significant fees to be paid yearly for its use. There are however terms and conditions of use that the user should check before committing to this software.

2.5 Training

It was necessary to carry out a specialised training course to teach the image assessors how to interpret the imagery. Local teams were established to carry out the satellite assessment. The teams varied slightly in composition in each country, but generally consisted of three or four engineers/technicians from the local roads organisation, plus three or four GIS experts from a local remote sensing organisation. As GIS is not a prevalent skill within roads organisations, it was decided to partner them with a local remote sensing organisation who would have this knowledge and would be able to support the roads based teams. This worked well and generally the two organisations liaised effectively.

Most of the training was carried out by Airbus DS and TRL, but the Regional Centre for the Management of Resources for Development (RCMRD) also assisted as a local partner. It was found to be important that the trainers included both roads experts and GIS/remote sensing specialists, as both of the skill sets are essential for a successful outcome.

2.6 Mapping

Once the imagery has been processed it is ready for mapping and condition assessment. If accurate and up to date GIS-based maps are already available, it should not be necessary to produce any new mapping from the imagery. However, the mapping is an important part of the project so it was checked carefully in each country to ensure that the maps were accurate and appropriate for use. The quality of mapping varied greatly, such that even where good maps existed they were to some extent out of date and needed revision. Therefore, in all cases the team digitised new maps from the imagery to ensure their accuracy. There are various established ways to semi-automatically generate maps from satellite imagery (Bhadauria H.S. et al, 2013, M. Mokhtarzade M. et al, 2008), all of which require some manual input for checking and revision, but in this case it was decided to manually create the maps.

2.7 Calibration

It was necessary to calibrate the system for each country, because the nature of roads, materials, construction specifications and maintenance methods varied greatly, and all of these factors can have an influence on the appearance of the road on a satellite image. If the road features vary greatly within a country, it may be necessary to calibrate by regions.

Calibration is achieved by identifying a sample area or roads that are broadly representative of the network to be assessed. Local regional or district road administrations were involved in this process, as they had a better knowledge of the rural network than the national road organisations.

A select number of roads were used in each country to develop a manual assessment guide for calibration. When the ground truthing was finalised, the assessment guide for calibration was developed using sample satellite images from each condition of road, along with notes on image interpretation and if possible some objective guidelines to interpreting the images, such as the variation in road width. The assessors then used this guide when assessing the imagery.

A reference document was also developed to note any anomalies or features on the imagery that could not be identified easily. These were located and then checked against the DashCam videos to determine their nature. The reference document was initiated to build up a record of anomalies and special conditions for future reference and to allow the assessor to better understand the nature of condition assessment by satellite imagery.

2.8 Satellite imagery interpretation

The final step was to carry out a condition assessment of the roads within the AoI by using satellite imagery interpretation. This was carried out manually by acquiring imagery for the area that was ground truthed and assessing the road condition based on features that could be distinguished on the images. The training focused on giving the assessors a good understanding of QGIS and how it can be used to manage the process of image interpretation, as well as guiding the assessors in image interpretation itself. The main principles of image assessment are location, site/situation/association, size, shape, height and depth, shadow, tone and colour, texture and pattern (Riebeek H, 2014).

These principles were used to develop some elements of condition that could be identified on the imagery and assigned as indicators of road condition. This was initially developed for the Nigeria research, and then refined in the current project. The elements of condition assessment that were developed are:

- ***Road width:*** The width of the road and how much it varies along the length of the road is a good indicator of condition. Where the road width is consistent and does not vary, it usually indicates a good condition road, signifying that the side drains have been maintained and the surface has been graded.

- ***The straightness/consistency of the road edge.*** The straightness of the road edge also tends to indicate how well the side drains have been maintained, and again whether vehicles are moving across the shoulder and beyond to avoid defects on the surface.
- ***The shading/texture/hue of the road surface:*** The road surface itself can provide clues to its condition. Poor areas tend to exhibit greater changes in texture and hue.
- ***The colours present in the road surface and surrounding land:*** Colour can indicate the type of road materials present, for example gravel tends to be a lighter, yellowish colour, whereas an earth surface appears darker and browner. Paved roads tend to appear as black or grey, depending on their age. Colour variation can also help to indicate the road condition.
- ***Shadow, to indicate bridges, culverts and causeways:*** Bridges tend to be quite easy to locate on a satellite image, because there is usually a waterway crossing a road and a shadow cast from the bridge. Culvert headwalls can also cast shadows, although these are harder to see.
- ***Patterns in the surface of the road made by wheeltracking from vehicles:*** Where the wheeltracking of vehicles is visible on the imagery, it is a good indicator of condition. Straight wheeltracking indicates good condition, whereas winding wheeltracking indicates that the driver is manoeuvring to avoid potholes or defects in the surface.

Most of these indicators are quite subjective and have to be judged by the assessors. However, some can be measured to a limited extent, such as the variation in road width.

Spatialite files were set up in QGIS to allow easy digitisation and assessment of the roads. A traffic light system was used to identify the road conditions based on colour, as can be seen in Figure 1.

Very Good	Good	Fair	Poor	Very Poor	Unknown
Dark Green	Light Green	Yellow	Amber	Red	Blue

FIGURE 1 Condition colour scheme for five levels

Different linear symbols in QGIS were used for ground truthing and for assessment. The symbol used for ground truthing is a double solid line, whereas the symbol for condition assessment is a broken line. This allows the actual assessment to be superimposed on top of the ground truthing, whilst both remain clearly visible. This makes it possible to see both at the same time, and therefore makes it possible to make an assessment of the correlation between the two. This can be seen in Figure 2, below.

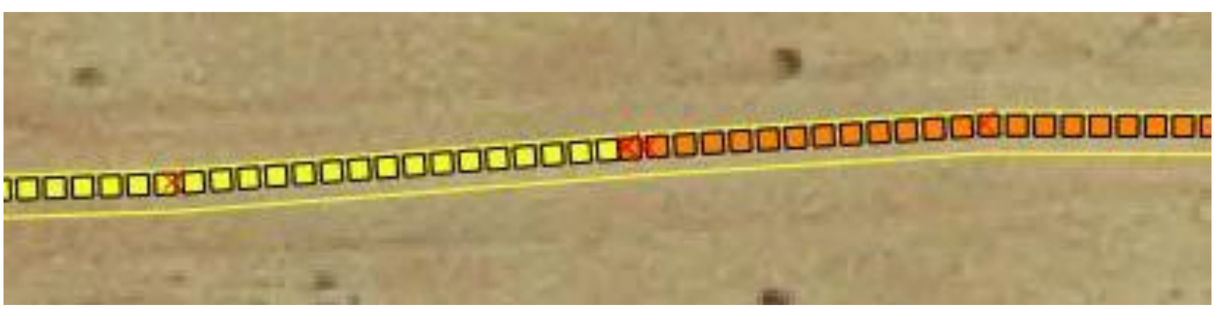

FIGURE 2 Ground truthing and assessment comparison

The assessors were given guidance in how to assess the imagery. After some time they became more proficient, but the trials were quite limited, so it can be assumed that they will improve with practice.

3 RESEARCH RESULTS

The results from each country were analysed using a spreadsheet developed by the team in Uganda. This compared the results of the ground truthing and the satellite imagery interpretation and produced a correlation between the two.

3.1 Correlation

In the Nigeria research the correlation between the ground truthing and the satellite imagery assessment was overall approximately 64% for a five level assessment system. However, this was a relatively small sample with only 32 km of road assessed, plus the results were created under project conditions which mean that consistency and reliability of results were easier to achieve.

It is not possible to show an overall result for all four countries in the current research combined, because Ghana used a three level condition system. 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 the Nigeria research. 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 improvement, 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.

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 (Figures 3 and 4).

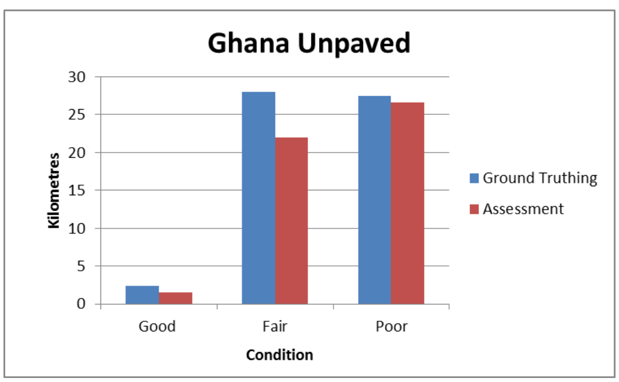

FIGURE 3 Unpaved correlation in Ghana

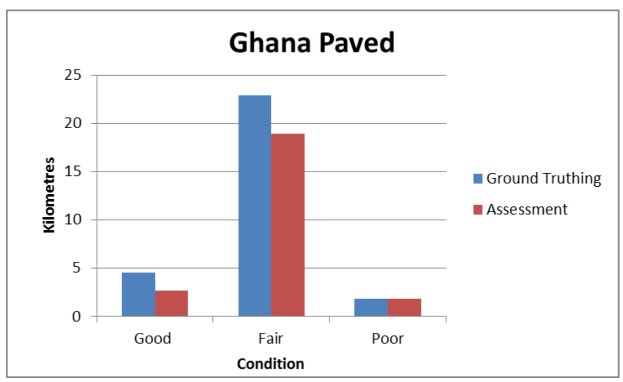

FIGURE 4 Paved correlation in Ghana

This is considered as a reasonable result for what is essentially a subjective assessment. Also, 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. Table 1 below shows the different levels of inaccuracy.

As expected, the Ghana results were more accurate because there is less possibility of assessing more than one level out, with a three level system. Kenya showed good results as well because almost half of the roads were newly rehabilitated and showed ‘Very Good’ condition, which was relatively easy to identify.

Uganda and Zambia were consistent at just over 4%. This result provides a high level of confidence that the manual assessments are able to identify conditions within one level up or down. Given that the assessment is for rural roads, unpaved 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 %

In order to compare the results of the assessments they have been translated into graphs. Figure 5 shows all of the results, including the Ghana results which used a three level assessment system.

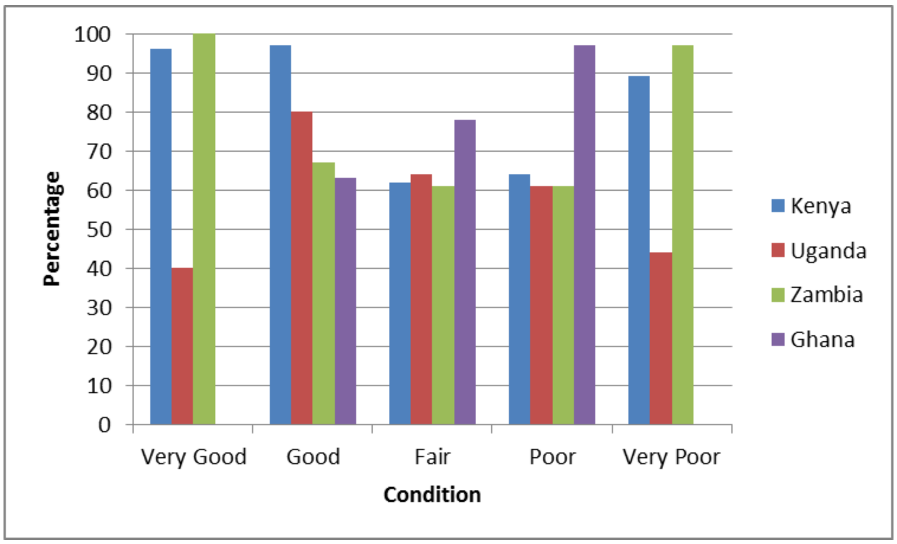

FIGURE 5 Graph of overall correlation

Already it can be seen that the results for very good and very poor condition are more variable. The low results from Uganda in these categories seem to be at odds to the other results, which all show a high correlation for the extreme ends of the condition scale. This could be attributed to the fact that there were actually very few roads in these categories in Uganda, just 2% and 10% respectively.

3.2 Cost effectiveness

The costs for condition assessment by satellite imagery were analysed using the approximate costs provided by each country for the various activities involved, see Table 2. 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.

In summary the cost estimates for traditional visual survey condition assessment included staff wages to travel to site, carry out surveys and analyse results; travel and subsistence costs to stay overnight; vehicle, fuel and driver; plus any equipment used, such as GPS or roughness measurement. The costs for satellite assessment included the cost of the imagery, cost of the calibration based on traditional survey costs, and staff wages to assess the imagery and produce results.

TABLE 2 Costs for traditional assessment and satellite assessment

Country Details	Network Details	Satellite assessment per km this project	Satellite assessment per km headline prices	Traditional condition assessment per km
Ghana		**£**	**£**	**£**
Length of road km	37.562			
Square area km^2	153	**22.65**	**67.12**	**21.30**
Road Density km/km^2	0.25			
Imagery cost £	590.75			
Kenya				
Length of road km	77.882			
Square area km^2	288	**30.56**	**58.40**	**21.40**
Road Density km/km^2	0.27			
Imagery cost £	2088			
Uganda				
Length of road km	145.715			
Square area km^2	187	**10.26**	**23.49**	**9.22**
Road Density km/km^2	0.78			
Imagery cost £	836.46			
Zambia				
Length of road km	52.719			
Square area km^2	119	**30.62**	**40.24**	**30.00**
Road Density km/km^2	0.44			
Imagery cost £	1251.52			

Two figures are shown for the satellite imagery costs; the first is using the actual costs of the imagery as supplied by Airbus DS 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. The cost also depends on the density of roads per km^2 of imagery. Areas with high road density are more cost effective. The time taken for ground truthing varied from 26.5 km per day in Zambia to 39 km per day in Kenya.

The satellite assessments 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 up to 150 km per day, thus reducing the assessment costs. 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 to the number of people that can be trained, although consistency of assessment could become an issue with a subjective system such as this.

Although the satellite assessment system is more expensive, due to the high price of satellite imagery, it can be competitive if good discounts are negotiated. It can also be carried out more rapidly over a wider area and does not use scarce resources to carry out the assessments, which is less damaging for the environment. However, the level of accuracy would have to be considered when making price comparisons, and whether the roads organisation is willing to accept slightly lower accuracy in return for wider coverage, rapid assessments and a permanent auditable record of the assessments.

3.3 Incorporating into a GIS database

The data and information from the ground truthing and satellite condition assessment was difficult to manipulate and assess without a GIS based database. Part of the Nigeria study was to include the information in a Road Asset Management System (RAMS), which was very successful, but there was no provision for this in the current project. The consideration of linking with a RAMS is very relevant to the future use of this system. The ideal platform for this system would be to incorporate it within a fully operational and sustainable RAMS, but it is recognised this may be the exception, rather than the norm.

4 DISCUSSIONS

There are a number of conclusions that can be drawn from the trials and from initial investigations into high-tech solutions. 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 typical in LIC implementation, but the results were still comparable to the Nigeria research. 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 expertise in mapping, image interpretation and GIS capabilities. This partnership worked well and provided some robustness to the process. Some training was also carried out by local partners, suggesting that locally resourced training would be feasible in the future.

During the condition analysis ground truthing the use of DashCams and IRI smartphone apps was trialled. The DashCams were found to be very effective for providing a permanent record of the road condition at the time of assessment, and the results could be used to check and audit the ground truthing. Smartphone roughness apps were also trialled, and although they were found to be less accurate for the lower condition unpaved roads, the output was still useful to provide a relative comparison of road roughness.

Mapping was produced from the roads digitised on the VHR imagery and has proven to be very accurate. It was digitised in QGIS and can be overlaid on a number of background images to suit its use.

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. This has established that the system can be calibrated for use in a range of environments and provided 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 essentially the same manual process as in Nigeria, although slightly refined. This was achieved by measuring the correlation of the satellite condition assessment and the ground truthing assessment. The results can therefore be compared on a similar basis. In this respect it could have been reasonable to expect a lower accuracy of assessment in the current research, but this was not the case. The improved accuracy can be attributed to the methodology used and in particular the detailed guidelines produced from the ground truthing.

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. There is therefore scope to develop an automated system, and this will indeed be trialled in Tanzania in the near future, funded by DFID. If found to be feasible this would make the system less subjective.

The results of the assessments for all four countries show an overall correlation of 73.66% for unpaved roads from a total of 318.8 km that were ground truthed (total of unpaved and paved was 342.1 km). This is in comparison to 64% from 31.5 km of road in the Nigeria study. The current study is more than ten times the size, and also included 29.3 km of paved roads for Ghana. However, this needs to be qualified by the fact that the Ghana study only used three levels of condition assessment, so showed a higher accuracy, and the Kenya study included a newly rehabilitated road, which was consistently assessed as very good, again improving the overall accuracy of the assessment. Without these anomalies the overall assessment correlation would be down to 66.6% from 224.4 km of unpaved road.

The overall correlation from paved roads in Ghana was 80%, from a total of 29 km. This was a three condition level assessment, so is expected to be more accurate than a five level assessment. The overall correlation for 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 indicate condition, 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.

The staff carrying out the assessments only had three days of 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. Also, it is often the case that short term projects are not taken as seriously as the main activity of a person’s job, because staff 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 use of freely available existing imagery was considered for condition assessment, such as Google earth and OpenStreetMaps. The main problem with these sources is the variability of the imagery quality, plus the date of acquisition, with many maps being several years old and therefore inappropriate for road condition assessment.

The data and information was more difficult to manipulate and assess without a GIS 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 would make the system much more user friendly and would, for example, allow the identification of defects on a linear as well as on a geo-referenced basis, which is useful as most countries still use a ‘chainage’ system to locate their road assets. The provision of a database, RAMS, or other type of management system would enhance the utility and user friendliness of the satellite assessment system.

In summary, the assessment of road condition from satellite imagery is possible and can be useful to roads organisations, depending on the accuracy and level of confidence that can be gained and whether this fits to the accuracy required by each country. The resolution of the satellite imagery available is also likely to improve, as it has done consistently over the past few years, which should increase the accuracy and level of confidence in the results.

Cost effectiveness is also an important factor. In order to be feasible the assessment by satellite imagery needs to be cost effective. Given the figures shown above, 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. The cost is however likely to come down in the near future as many more satellites are launched and competition increases, which would allow the system to compete economically with traditional systems in the near future.

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. However, satellite imagery is now starting to be made available on a reference basis, 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. This could prove to be a ‘game-changer’ in terms of making the system more affordable. There are also potential uses for some of these technologies in climate change resilience; with the imagery itself having the potential to be used in combination with Digital Elevation Models (DEMs) to work out catchment areas and waterways that are likely to affect the road network.

In conclusion, the system is capable of providing appropriate, cost effective support to an asset management system, and has the potential to enhance that 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 allows large areas to be assessed rapidly and potentially at a reasonable cost, it provides a permanent record of the assessments, it allows accurate maps to be produced, it is auditable and is less environmentally damaging. Also it is more appropriate for areas with lower levels of vegetation and longer dry seasons, because the road edges are more visible and the imagery capture period is longer. Results show that the system 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, plus it is still quite subjective 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. However, the strength of the system is in its potential to transform rural road condition assessment in LICs, from both a technical and economic perspective. In the short term the system is likely to have most benefit for remote, inaccessible and conflict restricted areas, where traditional systems are too logistically difficult, dangerous or expensive to undertake.

5 RECOMMENDATIONS

A number of recommendations can be made from these trials. The final guideline for satellite assessment of road condition includes recommendations for the appropriate use of high-tech solutions, combined with the methodology for condition assessment by satellite imagery. A holistic approach should be adopted, which includes appropriate combinations of the different high-tech options. The solutions that were found to be most appropriate during the research are:

- Dashboard Cameras, for use in ground truthing
- Smartphone apps for measuring an approximation of IRI

- UAVs for specific uses where highly detailed images are required
- Back analysis for various uses, including to identify the frequency for road condition surveys
- Social Media, which has the potential to inform road authorities of issues

In addition Big Data, internet and computer applications could be developed for specific uses. The possibility of automated condition assessment from satellite imagery is being explored in Tanzania, which is a logical next step for the system.

Further investigation into the use of roughness apps and roughness measuring equipment should be carried out, possibly in association with MTRD in Kenya, who have already initiated research into comparing different types of roughness measurement. Traditional condition assessment systems are variable between countries, especially for unpaved roads, so any standardisation that can be applied would be welcome. DashCams or similar video technology should also be used for calibration of the system. It is recommended that liaison is established with the manufacturers to develop the camera for specific use on unpaved and rural roads in LICs.

The system remains focused on using the existing condition assessment system in each country, but where a roads authority can be flexible a three level system should be used in terms of achieving a higher quality of assessment. Local remote sensing partners should also be identified to work with road authorities in the future, until local road authorities can attain a higher capacity in GIS applications.

Condition assessment by satellite imagery should be concentrated on unpaved roads, as there are more identifiable visual factors that can be used to determine the condition. For paved roads the images could be used to identify condition using spectral reflectance, but further research would be required in this area. As the system matures a reference document should be built up that identifies typical anomalies and areas on a satellite image that are not readily identifiable.

The system should be incorporated into a GIS based RAMS, which will make the analysis and manipulation of data much easier. This is desirable for the practical and efficient use of the system, but where a RAMS does not yet exist, the cost could be prohibitive. The ideal situation would be to integrate the two systems as a bespoke solution to suit the environment in each country. In this way both the RAMS and the satellite assessment system would be enhanced for the benefit of the users.

Where the system is used, the imagery acquisition should be carefully planned to avoid procuring unnecessary imagery that has no roads. In addition the roads authority should enter into negotiations with the imagery provider to get the best possible deal.

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