THE JOURNEY TOWARDS AUTONOMOUS FULL SPECTRUM PAVEMENT CONDITION DATA ACQUISITION AND EVALUATION IN SOUTH AFRICA: A ROAD LESS TRAVELLED

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ABSTRACT

The undertaking of road condition assessments, for input to computerized road asset management systems (RAMS), has been systematically carried out by road authorities in South Africa since the mid 1980's. Considerable advancements in data processing and analysis has been made in this time, but concurrent development in the actual acquisition of road condition data has not happened, with this fundamental aspect being predominantly based on manual collection methods i.e. the use of people.

Semi-automated data collection, such as the use of purpose-built surveillance vehicles equipped with cameras and profiling equipment, have been implemented by the larger road authorities over the past ten years, and whilst this is a significant improvement over manual methods, the data collected is generally limited to profile related aspects, e.g. riding quality and rut depth whilst the assessment of distress mechanisms is still undertaken with a physical visual inspection.

The development of new laser technologies in recent years has changed pavement data collection, enabling a fully automated approach to be investigated. The ability to undertake fully automated road condition data collection will offer significant and meaningful benefit to road authorities in terms of cost and time savings, safety and accuracy of data whilst road users should benefit from more timeous and appropriate maintenance interventions.

This paper presents the findings of an investigatory study towards establishing autonomous fully inclusive TMH9 compliant road condition data collection and evaluation.

1. INTRODUCTION

The South African road network, of 750,000 kilometres (with 165,000 kilometres being all weather surfaced roads), is the tenth largest in the World [South African National Department of Transport, 2019]. The various road agencies, whether national, provincial or municipal all have a common goal and responsibility of managing its road network in a good "engineered" condition and safe "functional" condition for vehicular and pedestrian traffic. Given that all road agencies have limited budgets, maintaining the requisite standards must be achieved with the lowest cost and highest benefit. This requires the collection and analysis of road pavement data so that optimised maintenance and rehabilitation strategies can be identified, prioritised and implemented through the agency's RAMS.

Network level road condition surveys are an essential and integral component of any RAMS with the accuracy of these assessments being critical to the validity of the systems output in terms of priority, optimisation and financial budgets and the allocation of technically and economically appropriate remedial interventions.

2. NETWORK LEVEL ROAD CONDITION ASSESSMENTS: PAST AND PRESENT

The following sections discuss network level road conditions assessments in South Africa.

2.1 Road Condition Data Collection - Historical

Systematic road condition data collection has been carried out in South Africa for around 40 years as discussed in the following sections.

Traditional methods of determining pavement condition have primarily focused on information obtained from a physical visual assessment of the road surface in accordance with the Draft TMH9 Manual [Committee of Transport Officials (COTO), 2013]. Occasionally the visual assessment was augmented with functional data in the form of riding quality using an LDI vehicle and structural measurements from a falling weight deflectometer (FWD) or similar device.

Physical visual assessment requires experienced and skilled human resources, is dangerous, stressful and time consuming with production of +/- 60 to 80 kilometres per day in a rural environment and up to 20km per day for urban roads.

At the outset of RAMS In South Africa, in the mid 1980’s, there was no obligatory requirement for the visual assessors to be qualified, or tested to verify their capabilities, but over the years various initiatives to improve the quality of the acquired data were implemented ranging from comparatively casual calibration sessions to the practice of formal accreditation by competency testing with theoretical and practical examinations.

On a network level survey, 2 or more persons drive in a vehicle at +/- 10-15km/h with both the driver and the “assessor” discussing the evident distress as the vehicle travels along the road section. Typically, 3 to 5 stops are made to check binder condition and take a closer look at the road surface. The capture of “degree” and “extent” road condition assessment ratings onto a TMH9 compliant pre-printed paper assessment form (Figure 1) has been the “norm” for over 30 years in South Africa though in comparatively recent times some authorities have migrated to the use of electronic data capture devices.

As indicated in Figure 1, the standard network level visual assessment methodology uses a 5-point degree and extent rating system for 16 individual surface and structural distress mechanisms and 5 functional items.

The use of paper assessment sheets has long been the standard in South Africa and has advantages and disadvantages with the latter outweighing the former. It is true that interim ratings can be marked up as the vehicle travels along the road, but an additional stop is required to complete the assessment form which must then be kept for subsequent data capture to the RAMS.

Entering the visual assessment ratings directly onto an electronic device and directly into the RAMS data base is an improvement on using paper assessment forms as it obviously negates further data capture effort but is still time consuming in itself. It should also be considered that this method is neither new or innovative as such devices were introduced in mid-1980's in Europe.

VISUAL ASSESSMENT : FLEXIBLE PAVEMENTS

COTO

ROAD AUTHORITY :
REGION / SUBURB :
ROAD NO / STREET NAME :
SEGMENT (FROM - TO) :
SEGMENT DIMENSIONS : LENGTH m WIDTH m

	1	2	3	4	5
ROAD CLASS :	1	2	3	4	5
TRAFFIC :	VL	L	M	H	VH
GRADIENT :	Flat		Med		Steep
TERRAIN :	Flat		Rolling		Mount

ENGINEERING ASSESSMENT

SURFACING					
TEXTURE	COARSE	MEDIUM	FINE	VARYING	
VOIDS	MANY	FEW	NONE	VARYING	

CURRENT SURFACING :

	0	DEGREE: MINOR 1	WARNING 2	3	4	SEVERE 5	EXTENT: ISOLATED 1	2	3	4	EXTENSIVE 5
SURFACING FAILURES											
SURFACING PATCHING											
SURFACING CRACKS											
BINDER CONDITION (DRY / BRITTLE)											
AGGREGATE LOSS A N											
BLEEDING / FLUSHING											
SURFACING DEFORMATION / SHOVING											

STRUCTURAL	0	DEGREE: MINOR 1	WARNING 2	3	4	SEVERE 5	EXTENT: ISOLATED 1	2	3	4	EXTENSIVE 5
BLOCK CRACKS											
TRANSVERSE CRACKS											
LONGITUDINAL CRACKS											
CROCODILE CRACKS											
PUMPING											
RUTTING											
UNDULATIONS / SETTLEMENT											
PATCHING											
FAILURES / POTHOLES											

FUNCTIONAL ASSESSMENT

ROUGHNESS		Very Good	Good	Moderate	Poor	Very Poor
	Problem			undulations	moles	corrugations
SKID RESISTANCE		Very Good	Good	Moderate	Poor	Very Poor
	Problem				bleeding	polished
SURFACE DRAINAGE		Adequate		Inconsistent		Inadequate
	Problem	rutting	shoulders	undulations	failures	side drains
SHOULDERS (unpaved)		none	Safe	Inconsistent		Unsafe
	Problem	eroded	overgrown	inclined	too high	too narrow
EDGE DEFECTS		0 1 2	3 4	5 1	2 3	4 5
	Problem			edge break	drop off	edge cracks

SUMMARY

OVERALL PAVEMENT CONDITION	Very Good	Good	Moderate	Poor	Very Poor
COMMENTS:					
OTHER PROBLEMS	service crossings	trees	moles		mechanical damage

ASSESSOR : DATE :

Figure 1: Visual Assessment Sheet as per TMH9 Document

Further to the above constraints, an obvious failing with the use of physical visual surveys is that the recorded condition of the road will be influenced by a certain amount of subjectivity. The use of independent rating checks and panel inspection, together with integral validation and exception routines in the more sophisticated RAMS can reduce the subjectivity element but cannot eliminate or even significantly minimise the real and serious consequences of this issue.

The severity of effect on data validity is dependent on a number of factors, e.g., experience / training of assessors, fatigue, traffic and noise levels etc.

2.2 Road Condition Data Collection – Status Quo

The status quo in South Africa is that the vast majority of road network level condition data is **STILL** dependent on undertaking physical visual assessments – as described in the previous Section. The South African National Roads Agency (SANRAL) and most of the provincial / metropolitan road authorities also undertake profiling and FWD measurements on higher order roads, but this is seldom done at municipal levels.

Two Provincial road authorities in South Africa have been routinely undertaking semi-automated full spectrum surveys of their road network using Network Survey Vehicles (NSV) examples of which are illustrated in Figure 2.

Figure 2: Paved (Left) and unpaved (Right) Road Network Survey Vehicle

Compared with manual methods, the use of these vehicles provides a significant increase in productivity with a data acquisition of up to 500km per day. The fact that the data is collected at traffic speeds also offers a significant reduction in risk of accidents whilst undertaking the road assessment.

In addition to measurement of functional characteristics such as riding quality, rut depth, texture, ravelling etc, high definition digital imaging and automated crack detection is undertaken to record the condition of the road surface for input to the RAMS paved and unpaved management modules.

Unlike the significant majority of other road authorities, these provinces use the **"post rating"** technique to evaluate and assess the condition of the road. With this method, digital images and cracking data collected by the NSV's are assessed in terms of the TMH9 manual – as is the case for a physical field assessment – with the difference being that the defects are rated in the comfort and safety of an office environment by experienced visual assessors (Figure 3).

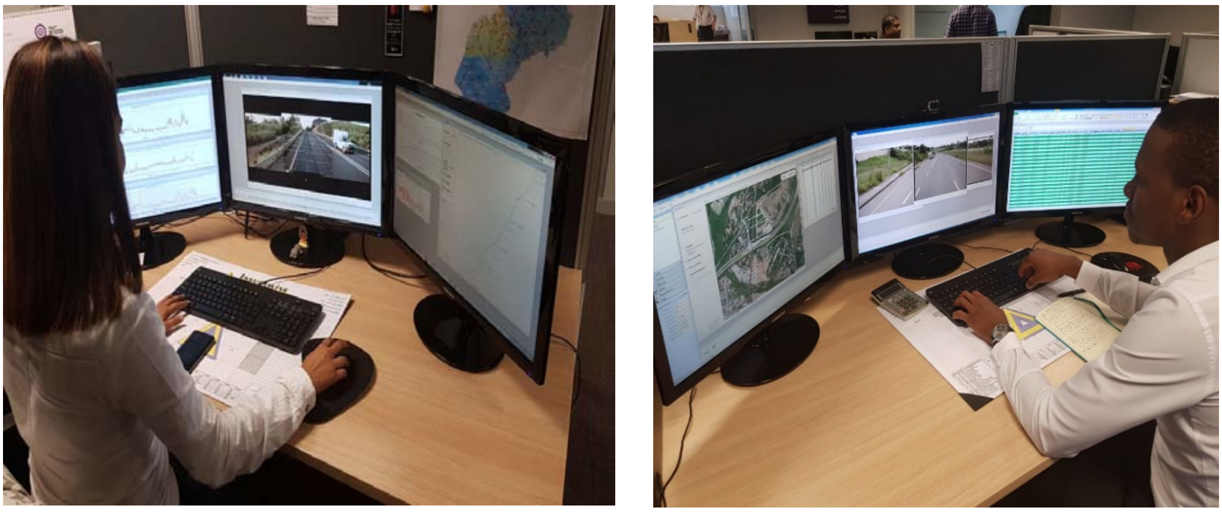

Figure 3: Post rating of pavement condition data captured by NSV

This process is obviously much safer than undertaking physical field surveys and is significantly more productive (+/- 150 kilometres of assessment can be rated per assessor per day) and less fatiguing.

The method does have an element of subjectivity but this is much reduced in comparison to field assessments primarily due to the fact that the assessor can scroll over the images several times whilst referring to the TMH9 document. Quality assurance is via exception/validation algorithms incorporated into the data capture software whilst quality control is managed through independent "double rating" of random road sections and panel inspection.

The acquisition of network level pavement structural data is (or should be) routinely undertaken on a systematic basis by most provincial, metropolitan and larger municipal road authorities.

Pavement structural data is provided by the measurement of pavement deflections which are typically measured using a falling weight deflectometer (FWD) For network level surveys, these deflections are typically measured at 200m intervals in the outer wheel path of the slow lane [SAPEM, 2014]. Using a 100m stagger for each direction of travel this equates to a measurement point every 100m along the road centreline. Using this method, approximately 35 to 40 kilometres of deflection measurements can be carried out daily meaning that even a modestly sized network will take an extended period to complete.

Figure 4: FWD with Internal Deflection Measurement Mechanism

In addition to being time consuming, the measurement of deflections with an FWD is a static test requiring well organised and managed traffic accommodation that, notwithstanding, can only mitigate and not eliminate the inherent danger in taking these measurements.

In summary, the methodology paradigm for undertaking network level road condition assessments in South Africa can be described as being discrete, non-synchronised and semi-automated at best and at worst, obsolete.

In an initiative towards providing more complete automation of road condition data collection, ARRB Systems South Africa (ASA) have been operating the intelligent Pavement Assessment Vehicle (iPAVe) incorporating traffic speed deflectometer (TSD) and other road pavement distress collection equipment in South Africa since 2017. A similar vehicle is owned and operated by the South Africa National Roads Agency (SANRAL).

This is considered to offer a significant advancement in the management of road assets as it is able to collect simultaneous surface and structural pavement condition data at road speeds of up to 80 km/h. The iPAVe – refer Figure 5 – integrates the Traffic Speed Deflectometer (TSD) developed by Greenwood Engineering with the Automated Road Rehabilitation Business (ARRB) Systems Hawkeye 2000 platform and is one of six iPAVe vehicles operated globally.

Figure 5: The iPAVe TSDD

The iPAVe's TSD utilises high precision Doppler lasers to measure the pavement deflection velocity/slope from which the deflection bowl is calculated (Muller & Roberts, 2012) whilst the Hawkeye platform is responsible for measuring road surface characteristics such as cracking, potholes/failures, roughness, rutting, ravelling, texture and geometry together with spatial information and digital imaging, in essence, the iPAVe can be considered to be an NSV with the ability to measure structural response in addition to surface characteristics.

3. NETWORK LEVEL ROAD CONDITION ASSESSMENTS: THE FUTURE?

The technology for fully automated road condition data acquisition is readily available in South Africa although not perhaps fully appreciated by industry. The logical progression is to now automate the data analysis and, in particular, the visual condition assessment.

Systems using artificial intelligence (AI) neural networks have and are being developed that are capable of identifying and rating the individual pavement distress items thereby removing the "human element" and associated serious effects of subjective condition rating. Work on this "quantum leap" has been ongoing globally for some time though South Africa has mostly lagged behind in this development with the exception of one or two private companies.

The creation of fully automated road visual assessment systems using AI image recognition is a lengthy and human resource intensive process and, therefore, the possibility of using expert system algorithms rather than machine learning to generate TMH9 compliant degree and extent ratings for pavement distress has been examined by ASA through a smart visual assessment system (SVAS).

3.1 Automation of TMH9 Compliant Road Condition Ratings

As discussed in previous Chapters, both iPAVe and NSV's collect synchronised road condition data such as cracking, aggregate loss, rutting, deformation, potholes, failures etc with the differentiator being that the iPAVe also collects integrated continuous deflection measurements. An example of the automated crack detection (ACD) imaging output is illustrated in Figure 6.

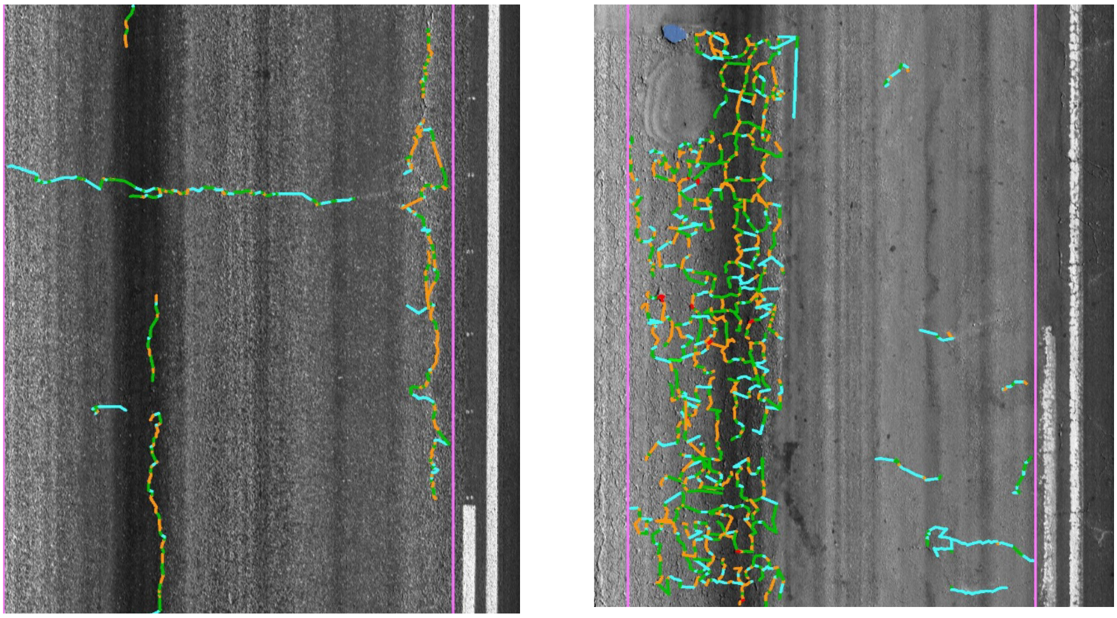

Figure 6: ACD Output

Figure 6 clearly shows crocodile cracking in outside wheel track (left hand plate) whilst the right-hand plate indicates the start of block cracking. Colours denote crack severity in terms of width and, for the crocodile cracking, density.

By utilising severity and quantity data as processed by the operating systems in the data collection vehicles, it is possible to create a “proxy” TMH9 compliant visual assessment that is completely autonomous.

The severity for the 16 distress items, established individually and in terms of the stipulations of the TMH9 for “degree”, is based on direct measurement, i.e. width and density in the case of cracking, depth and size in the case of rutting and potholes, volume of aggregate lost for ravelling etc.

The intensity of the distress cannot be assessed strictly in terms of the TMH9 definitions for extent because this is based on human interpretation. As an alternative, the autonomous system uses percentage of the length or area of the road segment under consideration.

In terms of distress type identification, this is mainly automatically managed by system processes although some mechanisms need further differentiation through additional algorithms e.g., surface vs structural failures being distinguished by depth or surface cracking vs crocodile cracking being discerned by location in wheel path or not.

The TMH9 standard visual assessment includes the assessment of 7 surface distress items and 9 structural distresses together with functional items such as riding quality, surface texture etc and any automated system will need to include the same to be compliant. At this relatively early stage of the study, a number of distresses have successfully been automated whilst others have not, this as presented in Table 1.

Table 1: Status quo of automation process

HORIZON	TMH9 DISTRESS ITEM	AUTOMATION ACHIEVED	
		DEGREE	EXTENT
SURFACE	Surface Failure	√	√
	Surface Patching	X	X
	Surface Cracks	√	√
	Aggregate Loss (including activity)	√	√
	Binder Condition	X	X
	Bleeding/Flushing	√	√
	Surfacing Deformation/Shoving	√	√
STRUCTURE	Block/Stab. Cracks	√	√
	Longitudinal/Slip Cracks	√	√
	Transverse Cracks	√	√
	Crocodile Cracks	√	√
	Pumping	X	X
	Rutting	√	√
	Undulation/Settlement	√	√
	Patching	X	X
	Failures/Potholing	√	√
FUNCTIONAL	Roughness	√	
	Skid Resistance	√	
	Surface Drainage	√	
	Skid Resistance	√	
	Edge Breaking	X	
	Current Surfacing	X	
	Texture and Voids	√	

As can be observed from the above, 5 of the 7 surface related distress mechanisms (71%) have been automated in terms of the 5-point TMH 9 degree and extent rating system. In terms of pavement structure, 7 of the 9 standard distress items (78%) have been automated. Functional TMH9 items such as width, length, gradient, terrain, texture / voids, riding quality, surface drainage etc can all be directly measured by either NSV or iPAVe.

The items that have not yet been addressed are typically those that rely on human evaluation e.g., binder condition or those which cannot be directly measured with the current processing systems i.e., pumping of fines and patches. Some functional aspects such as surface type recognition, edge break and shoulder condition are also not definable at this stage. These current constraints notwithstanding, it has been established that 74% of all TMH9 distress mechanisms can be assessed autonomously.

3.2 Validation and Algorithm Adjustment

Once the initial automation procedure was established, tested and proven, accuracy validation was carried out on 10 road sections by comparing the automated TMH9 assessment with the results of a manual visual assessment obtained from three experienced assessors.

The road sections included 5 urban roads with lengths of 150 to 200m and 5 rural roads where 1 kilometre sections were used.

The assessments results were evaluated in terms of the Visual Condition Index (VCI) [Committee of Transport Officials (COTO), 2013] and the Deduct Points System for surfacing condition index (CI_{SURF}) and pavement condition index (CI_{PAVE}) [Committee of Transport Officials (COTO), 2013]. Given that the automated method cannot rate certain distresses at this stage, i.e. surface patching, pumping etc, the manual assessments did not record these items even if they were present. The results of these evaluations are presented below in Figures 7 to 9.

The X-Y scatter chart allows a direct comparison between the automated visual assessment of the 10 road sections on the "X" axis, and the manual visual assessments on the "Y" axis. The dashed red line signifies a perfect correlation between automated and manual assessment whilst the blue dotted lines represent a -5% and +5% variance. The shaded boxes represent the various condition category limits, these being:

- Very Poor – Red <30
- Poor – Orange >30<50
- Fair – Yellow >50<70
- Good – Green >70<85
- Very Good – Blue >85

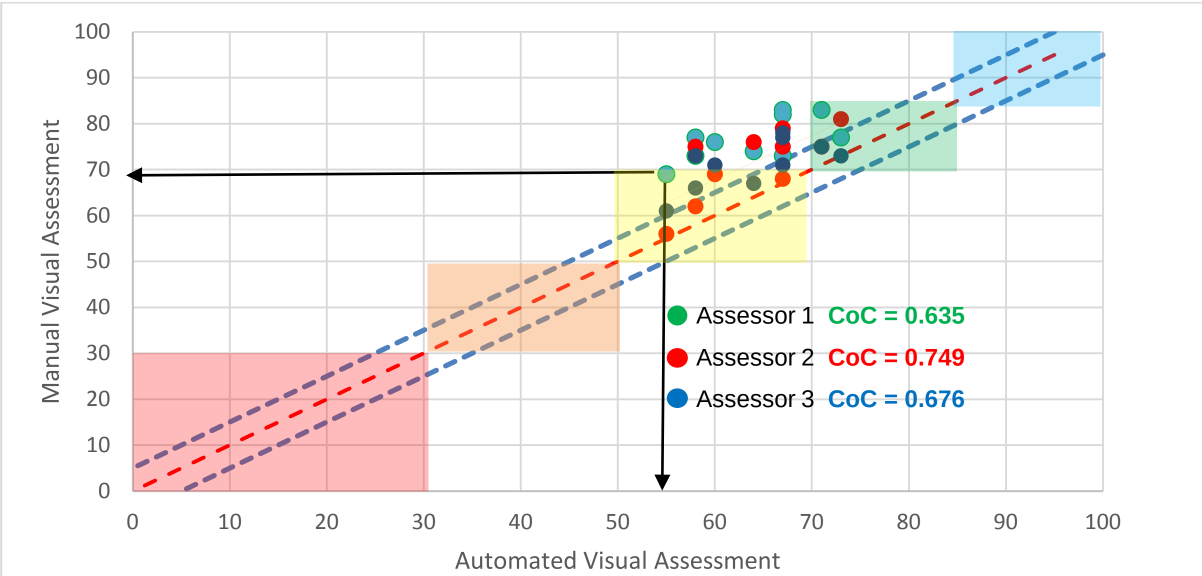

Figure 7: Automated Visual Assessment vs Manual Visual Assessment: VCI

Figure 7 illustrates the comparison between automated and manual VCI values for the 10 road segments, for example, Assessor 1 ratings returned a VCI value of 69 for road "X" whilst the SAVS generated VCI is 55. It can be concluded that whilst there is noticeable spread between the manual assessment VCI's and the values derived from the SVAS, over 50% are in the same condition category i.e. "Fair" and "Good" as denoted by the yellow and green shaded boxes.

In terms of coefficient of correlation (COC), the results are between +0.6 and +0.7 which denotes a measure of reasonable "positive" correlation. The VCI's calculated from the manual visual assessment of Assessor 2 gives the closest correlation to the automated VCI.

There is noticeable variance between the three manual assessments, particularly Assessor 1 and Assessor 2, and this highlights the previously discussed issue of subjectivity when undertaking visual assessments with people.

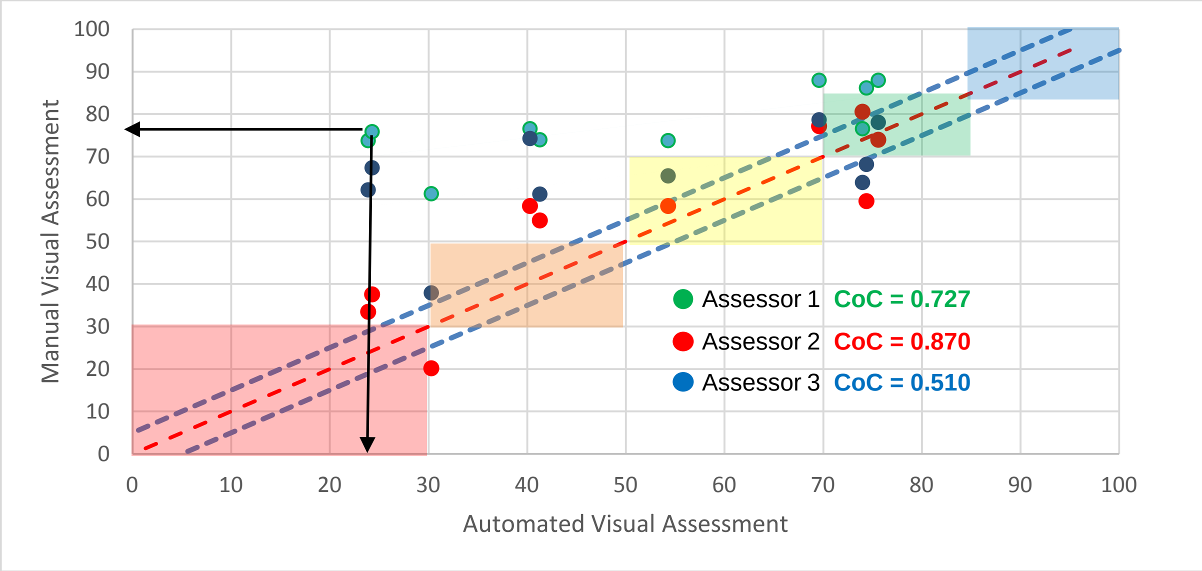

Figure 8: Automated Visual Assessment vs Manual Visual Assessment: CI_{SURF}

Using the deduct point method, it can be seen that the surface condition index is more dispersed than for the comparison of VCI values, with less correlation in terms of condition category matching at approximately 23%. On one section, the manual VCI is 77 whilst the automated value is 24 – as indicated by the arrows, This notwithstanding, there is a better correlation visually, particularly Assessor 2, and this is confirmed with improved coefficient of correlation values – with the exception of Assessor 3.

Once more, there is distinct variance between Assessor 1 and Assessor 2

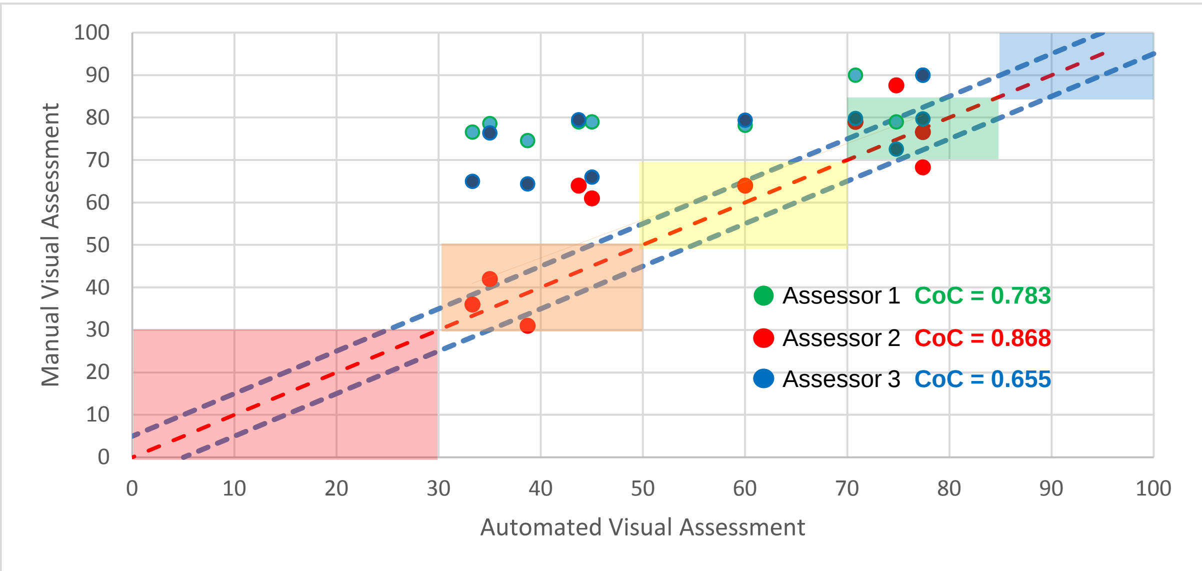

Figure 9: Automated Visual Assessment vs Manual Visual Assessment: CI_{PAVE}

In terms of the pavement (structural) condition index, there is a slight improvement over the surface index in terms of condition category matching, with around 33% of observations sharing either “poor”, “fair” or “good” condition categories.

The CoC values are reasonable for Assessors 1 and 2 being comparable to the surface condition values and there is a decrease in the variance of Assessor 3. As for Figures 7 and 8, Assessor 2 has the best correlation with the autonomously generated CI_{PAVE}.

In summary, it can be seen that whilst there is a noticeable variance between the indices derived from manual visual assessments compared to the autonomously generated values, with the former generally indicating a better condition, there is some correlation in terms of condition category matches and also trend.

Of interest is that the VCI comparison resulted in the best condition category correlation whilst the deduct points method indices have the better correlation in terms of correlation coefficient.

In terms of individual assessors, Assessor 2 has the best correlation to the automated results whilst Assessor 3 shows the most variance, Comparing the manual assessments with each other, there is a noticeable variance between Assessor 1 and Assessor 2 which again highlights the subjectivity of the manual assessment method.

Given the disparity between Assessors, a further correlation exercise was undertaken using the average indices for the three (3) Assessors and these results are presented in Figures 10 to 12.

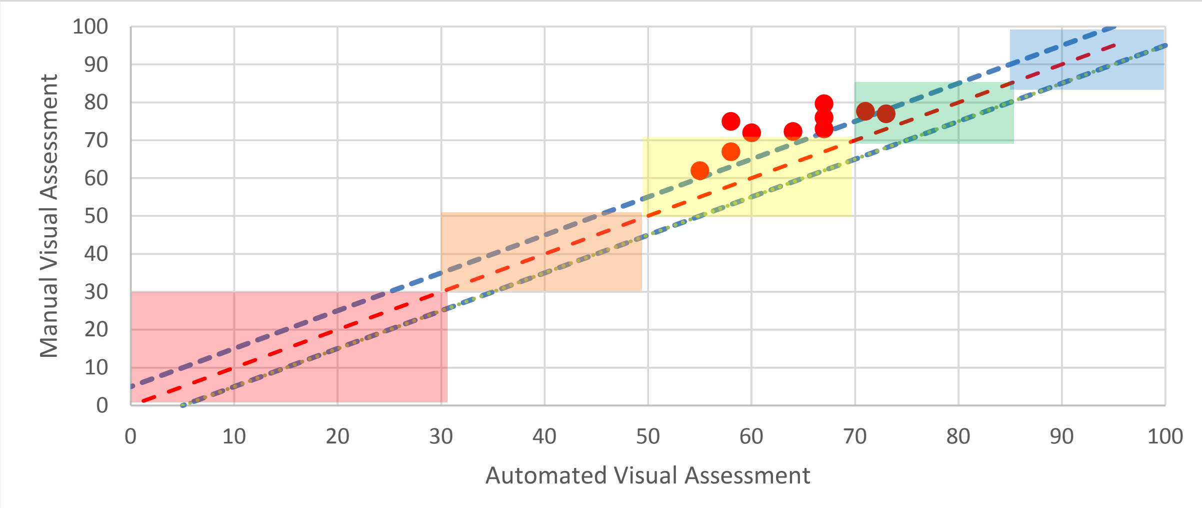

Figure 10: Automated Visual Assessment vs Average Manual Assessment: VCI

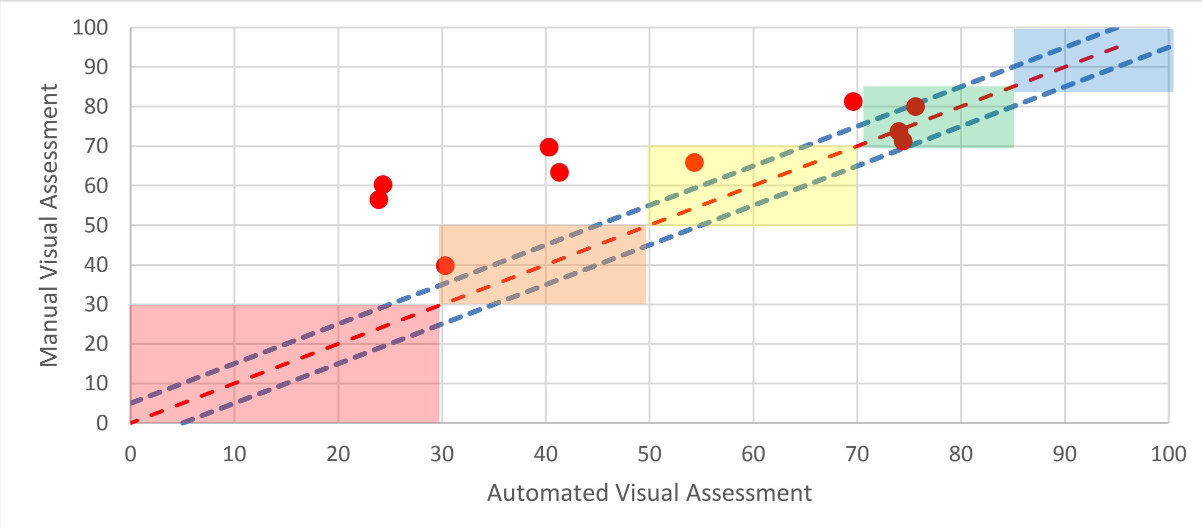

Figure 11: Automated Visual Assessment vs Average Manual Assessment: CI_{SURF}

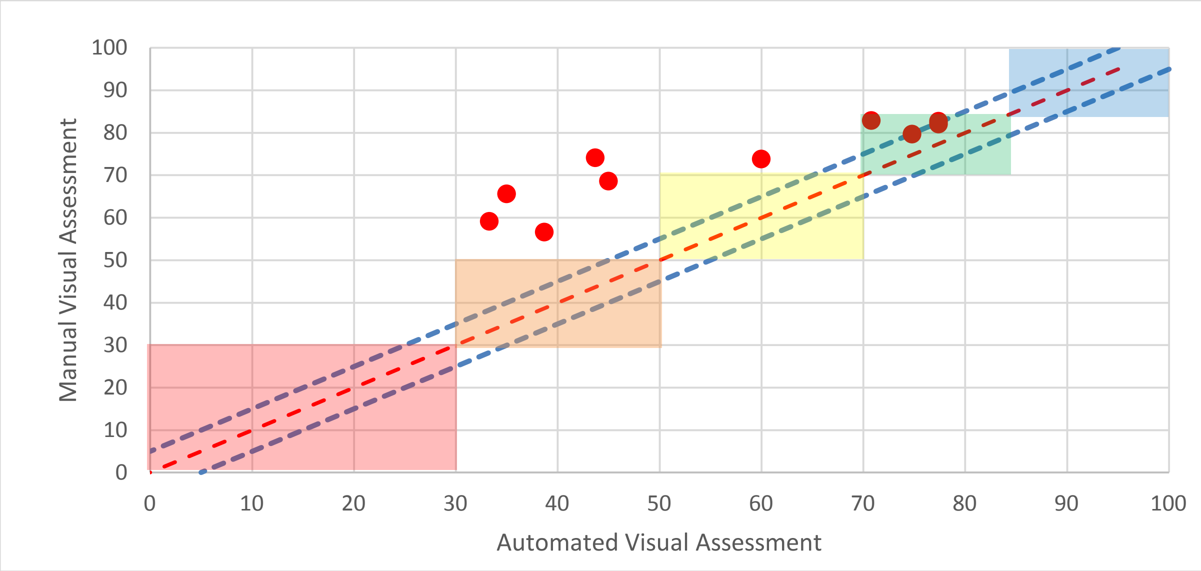

Figure 12: Automated Visual Assessment vs Average Manual Assessment: CI_{PAVE}

Using the average indices of the assessors, the trends are comparable with the individual ratings due to the high and low values negating each other.

Individual distress items have also been compared with examples being illustrated hereunder in Figures 13 to 16. The average degree of distress for the three visual assessors is plotted against the autonomously calculated degree.

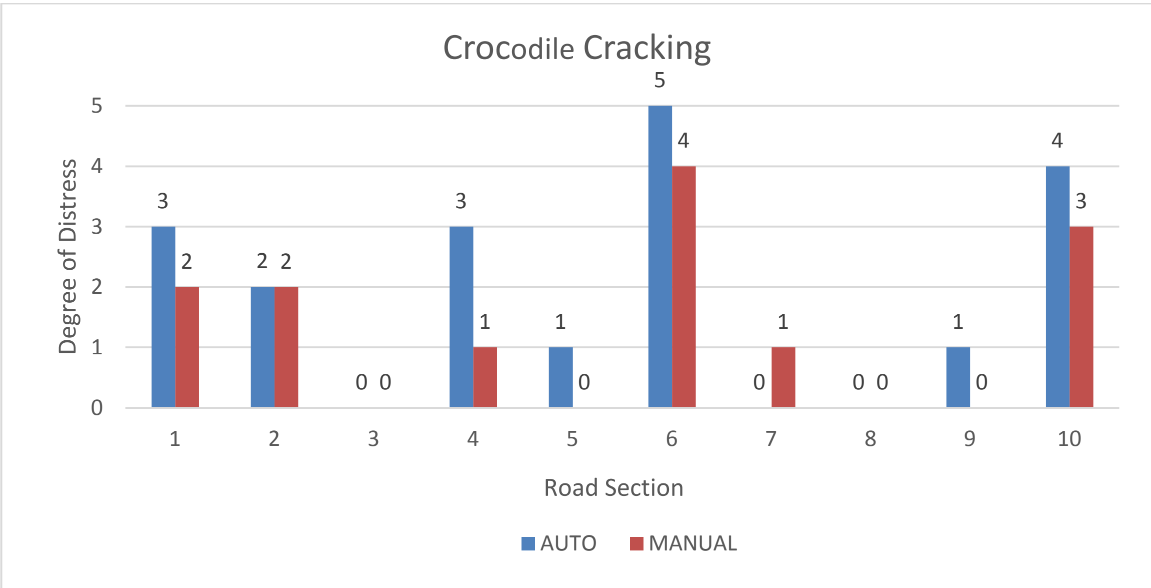

Figure 13: Comparison of automated and manual degree rating – Crocodile Cracking

In terms of crocodile cracking, there is a good correlation at the high and low degrees of severity with more disparity with the intermediate degree – as could be expected.

Given that the automated degree for rutting is generated from actual measurement, it is clear from Figure 14 that the manual assessments have underestimated the severity of this distress thus contributing to the automated assessment indicating a worse condition than the manual method – as previously observed.

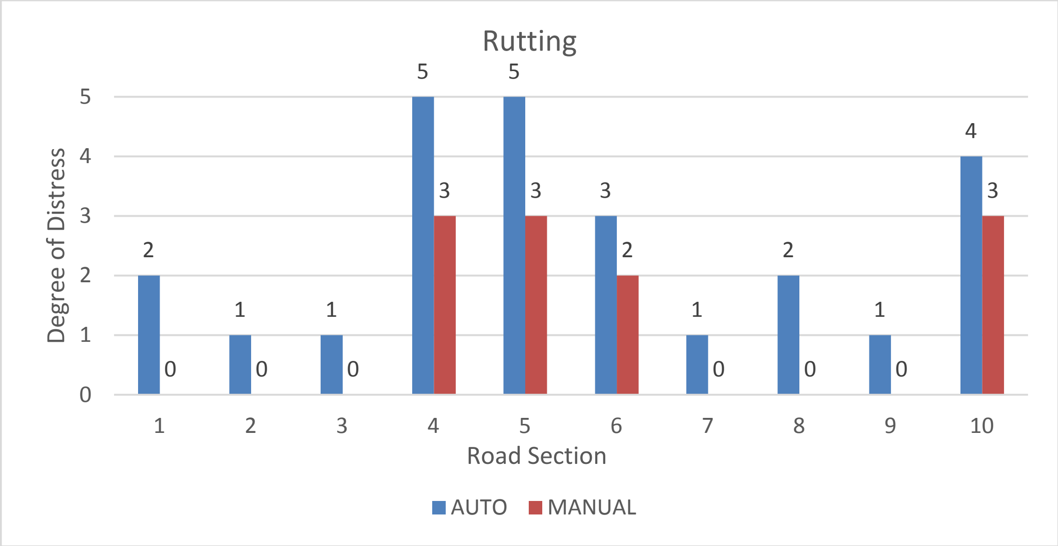

Figure 14: Comparison of automated and manual degree rating – Rutting

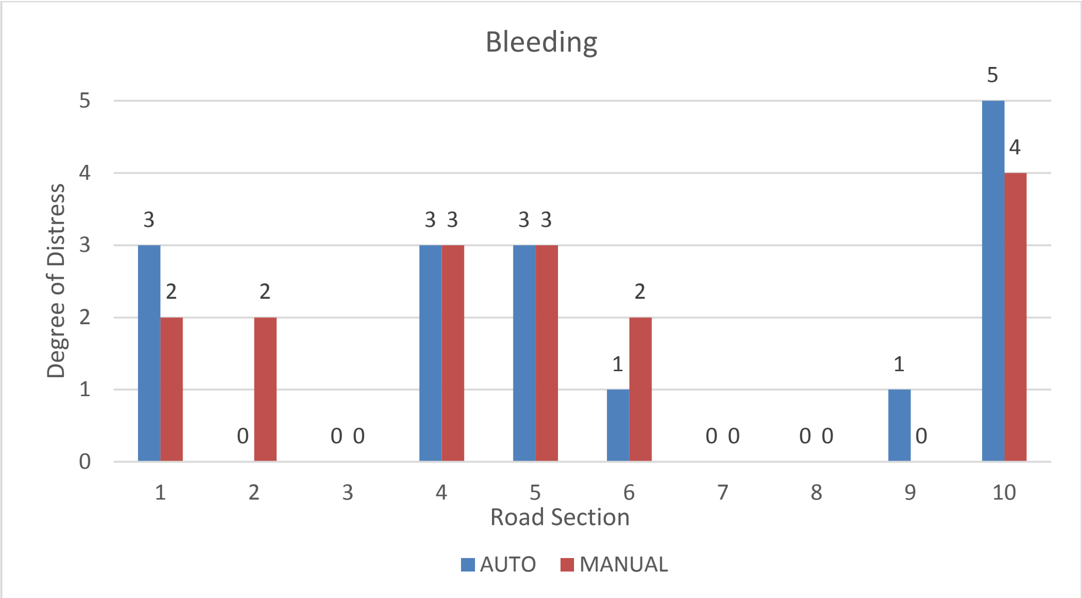

Figure 15: Comparison of automated and manual degree rating – Bleeding

The automated value for bleeding is derived from physical texture measurement. This distress item showed good correlation between the two methods of rating severity.

It is acknowledged that the sample size of the statistical study is inadequate to produce a definitive validation but it does provide substantiation that there is a reasonable comparability between the autonomous TMH9 visual assessment and the manual assessment which will provide essential input in further algorithm refinement and the production of a compilation of.

The degree for potholes is derived from actual depth and size measurement, which would suggest that the manual assessors may have been under scoring this distress item, again contributing to a better condition assessment compared to the automated rating.

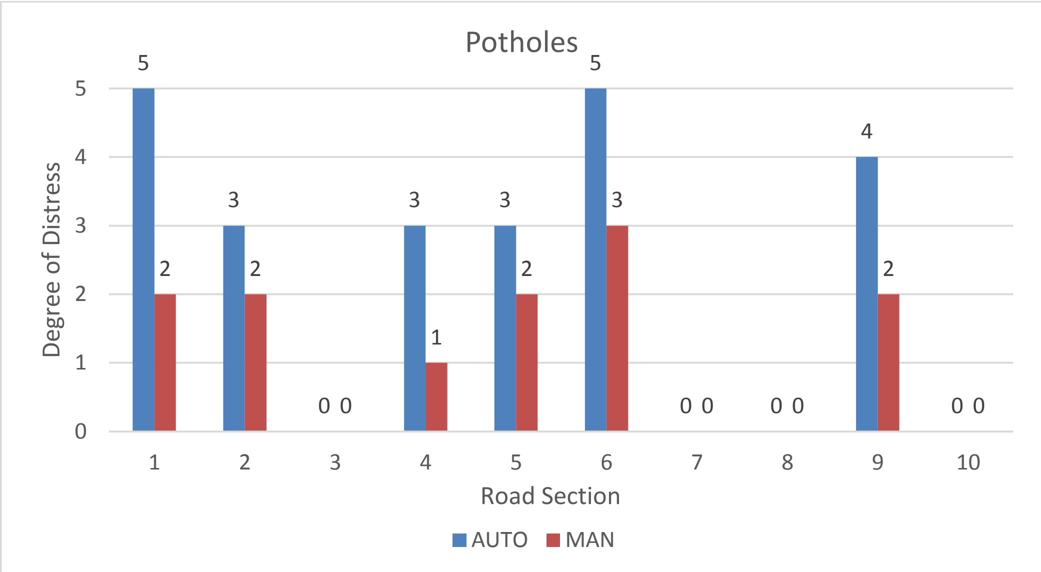

Figure 16: Comparison of Automated and Manual Degree Rating – Potholes

4. CONCLUSIONS

Despite the obvious benefits, the use of automated full spectrum road condition data collection for input to road asset management systems has not yet been widely adopted by road authorities in South Africa. With a few exceptions, current data acquisition methods are outdated and condition evaluation is based on subjective opinion.

This study was undertaken to establish and field test whether or not it is possible to automate the severity identification and extent of the standard TMH9 visual distress items using comparatively simple numerical algorithms rather than costly and labour-intensive machine learning processes. Work is still ongoing but the project to date has clearly shown that undertaking TMH9 compliant visual assessments by autonomous means is not just possible but is a reality.

The benefit of pavement evaluation automation is recognised worldwide with numerous papers, workshops and poster session presentations being included in the 2021 TRB Annual Meeting. A paradigm shift is clearly required in South Africa, with the automation of road condition data collection / evaluation being the obvious way forward. The adoption of this strategy will result in real benefits for road authorities, road users and the national fiscus including, inter alia:

- The implementation of automating the TMH9 visual assessment will eradicate subjectivity in the evaluation of road surface condition and result in road asset management outputs being based on fact rather than opinion.
- Integration and synchronization of individual data sets enables a more informed assessment of distress mechanisms.
- The above capabilities assist greatly in the identification of appropriate remedial actions and reducing wasted expenditure – even a 1% saving in a country's road maintenance budget will be significant.
- Significantly increased production compared to manual assessment methods. Will enable even large road authorities to undertake full spectrum evaluations in months rather than years.

- Real and meaningful improvement in safety conditions for assessment/testing personnel and the travelling public.
- In terms of TMH9 methodology, deflection data is not utilised in the identification of distress type, degree or extent but this notwithstanding, it is envisaged that TSDD technology could be used on the more important routes and roads – to provide deflection data input to the RAMS – with NSV's being used for the remainder of the road network.
- By using continuous distress measurement, it is possible to utilise data collected at network level in project level decision making and design – this rather than undertaking a second round of testing at the requisite project level spacing.

5. WAY FORWARD

As discussed previously, this investigation is ongoing and the following activities are envisaged in the completion of the study:

- Adjustment of "sensitive" algorithms highlighted in the study thus far.
- Evaluation of methods to enable autonomous identification and evaluation of the outstanding TMH9 distress items.
- Expansion of the field testing using experienced independent "expert" panel inspection visual assessors over widely differing road sections and surface types for calibration of the SVAS ratings.
- Study into the incorporation of continuous deflection measurements into the evaluation of structural distress items.
- Finalisation of algorithms and production of working models.

6. REFERENCES

Committee of Transport Officials (COTO). Draft TMH9. Standard Visual Assessment Manual: Parts A to E. Pretoria, South Africa. 2013.

Committee of Transport Officials (COTO). Draft TMH22. Road Asset Management Manual, March 2013: Appendix J-5.

Committee of Transport Officials (COTO). Draft TMH22. Road Asset Management Manual, March 2013: Appendix J-6.

Muller, WB & Roberts, J, 2012. Revised approach to assessing traffic speed deflectometer data and field validation of deflection bowl predictions. *International Journal of Pavement Engineering*: 14(4):388-402, Queensland, Australia.

National Department of Transport (2019). 'Overview: South Africa's road network'. [Online], Available at: http://www.transport.gov.za/roads.

SAPEM. 2014. South African Design Manual (SAPEM), Second Edition. March 2014. South African National Roads Agency SOC Ltd (SANRAL), Pretoria, South Africa.