Intelligent Pavement Assessment Vehicle for Structural and Functional Evaluation of Road Pavements

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ABSTRACT: Roads are generally designed and built based on strength characteristics or bearing capacity, but generally managed according to their functional condition, as strength has historically been difficult and expensive to measure on a routine basis. Until now, overall pavement condition has been largely determined using evenness, or IRI, which assumes that if a road is smooth, the pavement is not in a state of structural distress and has not exceeded its bearing capacity. However, experience shows that the inverse can also be true.

Having a complete dataset, incorporating information of the pavement below and at the surface, enables the road asset manager to better understand its condition. This dramatically improves decision making in managing the road network. Road agencies in North America, Europe, South Africa, China, Australia and New Zealand are now using Intelligent Pavement Assessment Vehicle (iPAVe) TSDD as a tool to collect pavement stiffness properties, at traffic speed, on a yearly basis, along with associated synchronized and simultaneous collected surface condition data.

Combining pavement structural and surface data, enables the identification and cause of pavement failure much easier, providing a powerful tool, in managing pavement condition and providing a solid background for robust infrastructure maintenance strategies. The unique capability of continuous high accuracy and high-resolution data enables infrastructure managers to pinpoint areas where pavement structure is deficient and subject to failure.

The collection of structural and surface condition data simultaneously, at traffic speed, provides a comprehensive assessment of infrastructure condition, enabling an effective and intelligent management of road infrastructure assets.

The paper presents: The ability and benefit of collecting structural (pavement strength) and functional (surface condition) in a single pass and how integrated structural and functional pavement characteristics can be presented in a user- friendly application. The paper also present how structural and functional data sets can be filtered to enable the identification of critical areas in road infrastructures.

KEY WORDS: infrastructure, condition, bearing capacity, functional characteristic, management, performance.

1 THE CHALLENGED ROAD INFRASTRUCTURE

A well-functioning road infrastructure is fundamental for societal growth, supporting the increasing population, urbanization, and development. It is of outmost importance that not only the development of the road infrastructure keeps pace with societal evolution, but also that of maintaining existing infrastructure at optimal cost levels. The capacity and quality of the road infrastructure is constantly challenged by increasing traffic, higher axel loading and demand for mobility. New scenarios for traffic patterns, truck platooning and autonomous vehicles requires add to the need for a paradigm shift in creating and maintaining the future road infrastructure. Furthermore, climate changes with higher temperatures, increasing stormwater incidents and rising ground water tables challenge the durability and structural life of the infrastructure and will require additional funding for maintenance and rehabilitation. (OECD ENVIRONMENT POLICY PAPER NO. 14 2018; Mollerup and Rohde 2016)

To overcome these challenges and providing an efficient road network infrastructure, often with stringent budget constraints, needs carefully planned and optimized maintenance strategies and solutions. Optimizing the maintenance strategies with limited budgets requires detailed and reliable condition data of the road infrastructure, i.e. data that reflects the road condition in relation to the functional surface and structure of the road both of which are constantly changing. With a significant increase in traffic and user expectations, the cost of temporary road closures is significant both financially and socially, so the need of performing road condition inventory surveys without interfering with the traffic flow is vital. Collecting road condition data under traffic is not new, although the discrete measuring of road surface characteristic and bearing capacity has been the tradition for decades.

Introducing a simultaneous and comprehensive structural and functional pavement survey methodology, provides comparable information on surface condition and bearing capacity. Integrated measurements also reduce the required time and resources for data collection and associated data analysis.

2 THE BENEFIT OF COLLECTING CONCURRENT STRUCTURAL (PAVEMENT STRENGTH) AND FUNCTIONAL (SURFACE CONDITION) DATA

Combining pavement structural and surface data, enables road engineers to carry out holistic analysis of distress mechanisms leading to the identification of cause and detection of possible pavement failure at an earlier stage than would be possible using separate data collection methods. This is thereby an essential and powerful tool, in managing the road infrastructure by providing a solid background for determination of a robust and cost beneficial maintenance strategy using correct maintenance solutions.

A comprehensive pavement assessment vehicle iPAVe TSDD is a fully integrated survey vehicle capable of collecting both structural and functional pavement condition data simultaneously and at traffic speed. It collects the following information:

- pavement strength through deflection measurement
- cracking
- longitudinal and transverse road profile
- pavement macro texture
- road geometry
- geospatial position

- digital imaging
- asset inventory and condition

The iPAVe TSDD can collect bearing capacity information of a road network at traffic speeds, and thus minimize the use of traditional stationary or slow-moving equipment such as Falling Weight Deflectometer (FWD) or Deflectograph. With a typical operating speed of up to 80 km/h, bearing capacity measurements can be performed without disturbing the traffic, as often seen when using stationary devices.

Depending on network characteristics, the iPAVe TSDD can collect approximately 70 000 lane kilometers of surface and structural condition data during a typical work year of 10 months. This compares very favorably to around 10 000 lane kilometers using an FWD and network survey vehicle combination that would otherwise be used. Furthermore, network level FWD testing is typically spaced at 200 m intervals, while the iPAVe TSDD provides continuous measurement, which can be delimited at intervals from 25 mm and upward. At 5 m spacing, the iPAVe TSDD could measure 14 million deflection points per annum, compared to around 50 000 for the FWD. For the FWD to generate the same coverage of testing, it would take around 280 years!

2.1 Deflection Measurements

The sensors used to derive the deflection measurements are 11 Doppler lasers positioned in front and behind the loading wheel to record the deflection basin in the longitudinal direction of the road. These lasers measure the instantaneous deflection velocity of the pavement, as the load (50 KN) is applied by the rolling trailer tyres on the rear axle.

2.2 Riding Quality

Continuous riding quality data, in the form of the International Roughness Index (IRI) standard, is derived from the digital laser profiler (DLP) which uses lasers and an accelerometer located above each wheel path to measure the roughness of the pavement.

2.3 Rut Depth Measurements

Continuous rut depth measurements are generated from the DLP equipment which establishes the transverse road profile to determine both the rut depth and the shape characteristics. The processing software allows for differentiation between general lane and wheel path rutting.

2.4 Texture Measurements

The surface macro texture is continuously measured using three (3) lasers i.e. one (1) in each wheel path and a third in between the wheel path for comparison purposes. The macro texture is reported in standardized terms of mean profile depth (MPD)

2.5 High Definition Road Surface and Spatial Imaging

The iPAVe TSDD is fitted with five digital imaging cameras to record high resolution images of the pavement and other road assets. The cameras are orientated to ensure that a wide field of view is recorded and are all calibrated for scale measurement and geospatial referencing.

Road surface information is used for the post rating of the road condition, whilst the spatial images provide essential information on roadside furniture, structures, signage, drainage, safety assets and road prism details.

2.6 Road Geometry

A Global Positioning Satellite (GPS) system provides accurate and synchronized coordinated spatial data of the vertical and horizontal road alignment

2.7 Automated Crack Detection

Automatic Crack Detection (ACD) using two (2) Laser Crack Management System (LCMS) is an integral component of the iPAVe TSDD. The laser units project a 4m wide laser line across the pavement with the laser image being captured by two 3D cameras mounted off-axis to the laser light source. The cameras interpret the distortions and each frame is analysed to determine the presence and type of cracking on the pavement surface.

3 COMPARING STATIONARY (FWD) AND TRAFFIC SPEED DEFLECTION MEASUREMENTS (TSD)

Over the years, many comparisons around the world have been made between FWD and TSD measurements, the comparison study methodologies were all different but all aimed to answer the same question i.e., “is the same structural information obtained by the two devices?” First of all, it is important to look at the differences between the two principles:

The FWD test, figure 1, is done stationary with intervals tailored to either project or network level, typically between 50 to 200meter intervals. FWD is currently the device with the longest history for structural evaluation and, therefore, the most commonly used device for deflection surveys, this despite the obvious drawbacks, particularly for network level assessment.

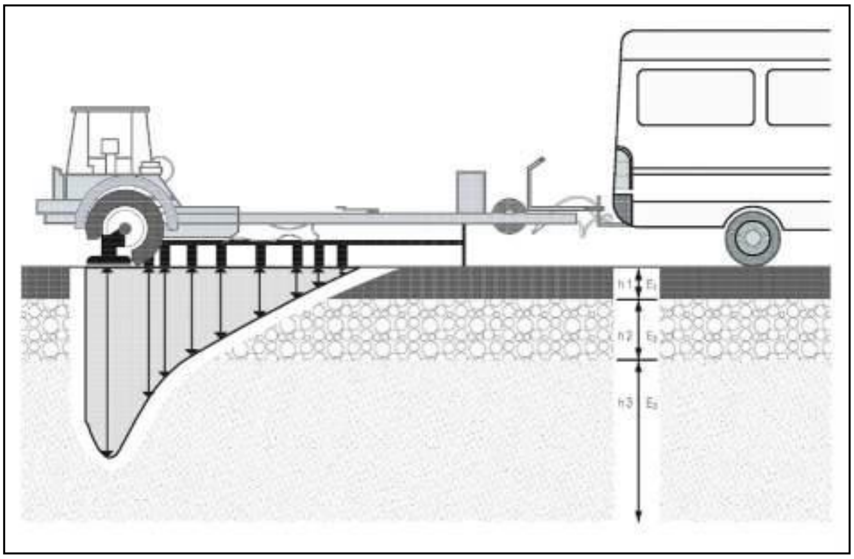


Figure 1: Falling Weight Deflectometer (FGSV, 2004)

The TSD, being an integral part of the iPAVe TSDD, shown in figure 2, is a significant improvement for measuring structural conditions at traffic speeds of up to 80 km/h. It uses a patented Doppler laser technology beam, also shown in figure 2, to measure the vertical displacement velocity at various offsets from the loaded wheel. The area under curve method (Muller and Roberts. 2013) is used to convert deflection slopes to a deflection bowl which represents the pavement's response to the wheel load of the iPAVe TSDD.

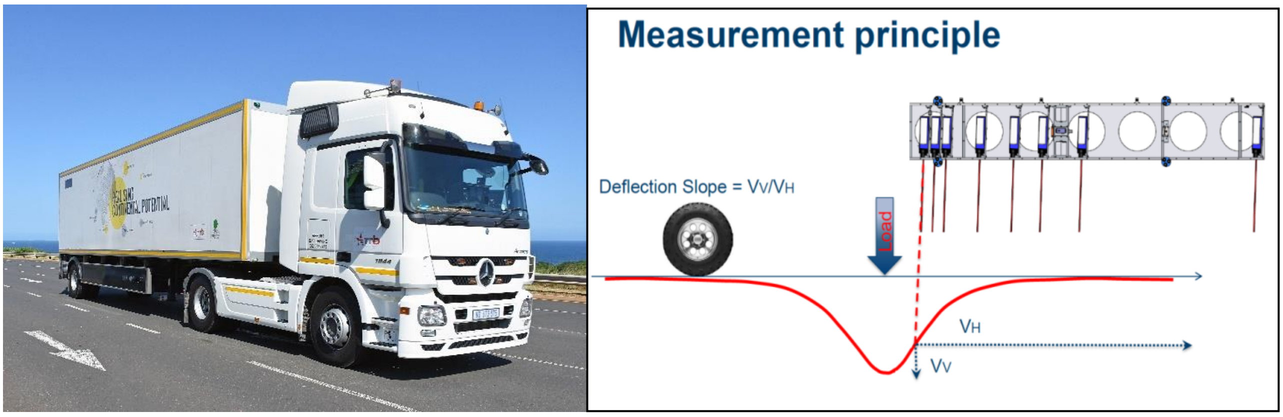


Figure 2: iPAVe TSDD (left) and Doppler laser beam (right)

The main difference between the FWD and the iPAVe TSDD is the loading mechanism of a static impulse type load and a rolling wheel, respectively. Because of the dynamic loading, iPAVe TSDD measured deflections can be influenced by surface irregularities such as surface distress and roughness (Flintsch et al, 2013). However, as dynamic forces induced by unevenness causes heavier loading on the pavement structure, resulting in lower structural serviceability, the influence of unevenness on the iPAVe TSDD measurements are seen as a true representation of actual conditions.

The deflection bowl of the FWD is produced from the physical measured deflection by geophones located at different distances from the load center and represents the magnitude of displacement caused by the impulse load of the FWD. load (typically 50 kN – European standard).

The iPAVe TSDD measures the horizontal traveling speed of the iPAVe TSDD and the vertical deflection velocity of the pavement surface in response to the iPAVe TSDD wheel load. The vertical pavement deflection velocity is divided by the horizontal velocity to derive the deflection slope or tangent at each laser. The combination of deflection slopes at each laser forms the deflection bowl as shown on the bottom right of figure 3. The slope of the deflection is thus a derivative of the pavement displacement (Ferne et al, 2009). This allows indices such as maximum deflection (D0), base layer index (BLI), middle layer index (MLI) and lower layer index (LLI) to be derived from the deflections.

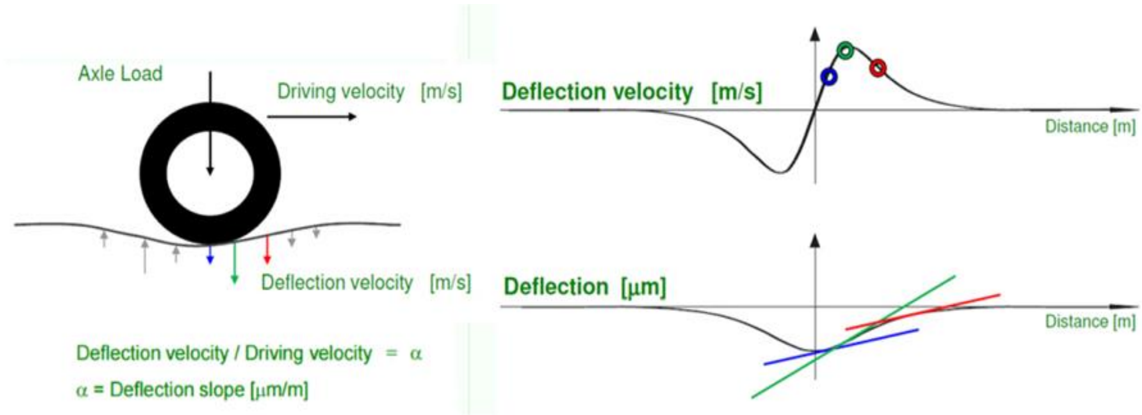


Figure 3: Concept of Deflection Slope

3.1 Pavement Layer Stiffness

The measured deflection bowl whether it is from an FWD or an iPAVe TSDD represents the pavement's ability to distribute the load from the traffic applied by the loading plate of the FWD and the dual wheel configuration on the iPAVe TSDD. The shape and the magnitude of the deflection bowl provides information of the pavement stiffness. However, to perform capacity and remedial analysis of a pavement, the characteristics of the individual layers needs to be determined, requiring knowledge of the individual layer thicknesses and to a lesser extent, the layer type. Traditionally the structural capacity of each layer is calculated using a "back-calculation" processes.

3.2 Are the Same Results Obtained With the FWD Compared to iPAVe TSDD?

Often, existing, and traditionally used equipment's are used as references for validating new methodologies, this although there are often fundamental differences between the old and new equipment. If we compare the traditional method of measuring pavement bearing capacity i.e., the FWD with the new approach, namely iPAVe TSDD, we need to look at the differences of the two methods. And in this case, there are some significant differences. Not only in the recording of the pavement deflections, where geophones are used with the FWD and Doppler sensors are used with the iPAVe TSDD, going from deflection recordings to recording vertical pavement surface speed, during loading. Also, the loading and the footprint of the loading is different, having a single circular loading plate for the FWD and a dual wheel configuration as used in reality on trucks, on the iPAVe TSDD. These differences cause different loadings, stress and strains and thereby different deflections of the pavement. Even though these differences are accepted, comparison of the two principles are done, and often with the FWD as reference.

The first question to be raised is how comparable are the actual deflections when measured? More importantly, what is the end result, i.e.

1) does the measurement inform the road engineer that the road is structural sound? and
2) how much capacity does it have? and
3) when will strengthening be required to extend its structural lifetime?

A study performed in South Africa (Visser and Tetley 2020), highlighted the comparisons between the FWD and the iPAVe TSDD by doing structural evaluation, as it would be carried out in a “real life” project level design on several test sections in South Africa. The back and forward calculations were undertaken using commercial software compiled for the analysis of FWD generated deflections.

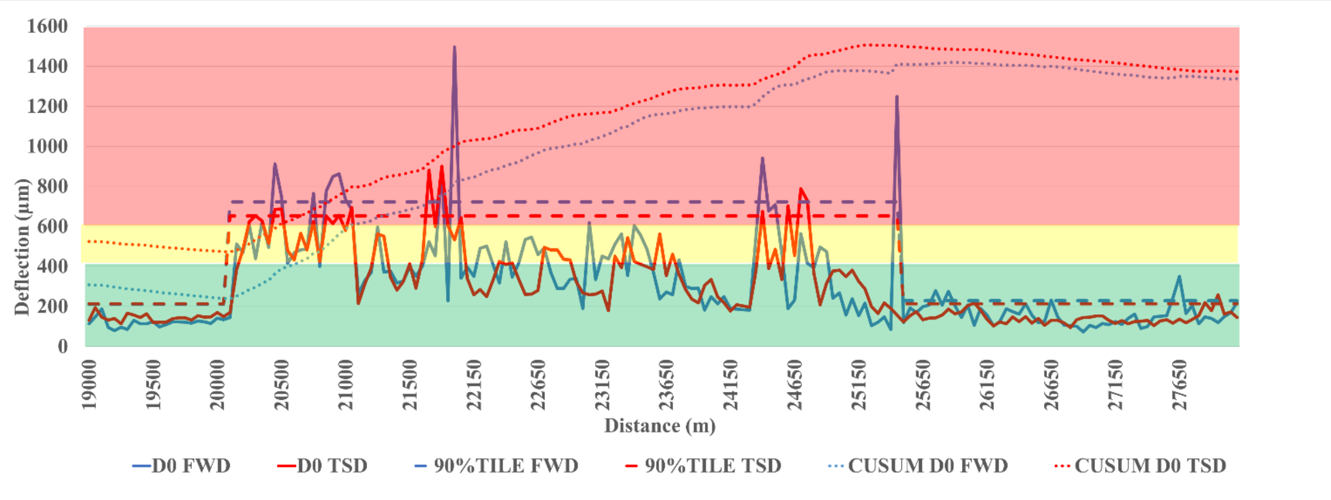


Figure 4: Comparison of FWD and iPAVe TSDD, max deflection and structural condition benchmarking (SAPEM ch. 10)

Figure 4, presents the actual and 90th percentile D0 values from the FWD and iPAVe TSDD, together with uniform section demarcation (cusum method) and benchmarking against deflection bowl parameter structural condition rating criteria as per South African Pavement Engineering Manual Chapter 10: Pavement Design. From the above, it can be clearly seen that the D0 values generated by the FWD and iPAVe TSDD are not identical but are comparable, with 90 percentile values for each method falling into the same condition limits with the uniform section turn points also coinciding.

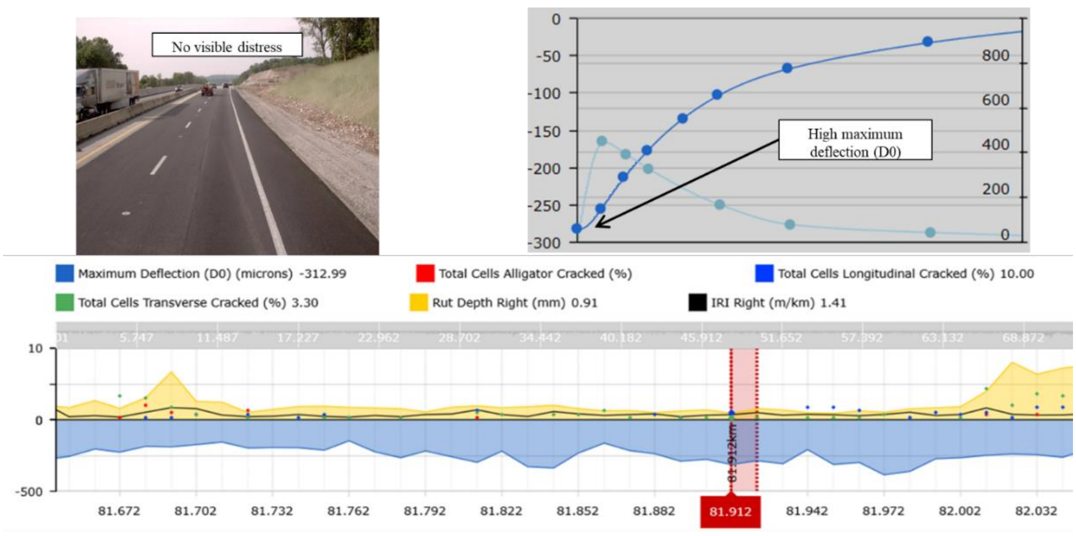
Test	Uniform Section	Back calculated Stiffness’s (MPa)					Capacity (MESA)
		Layer 1	Layer 2	Layer 3	Upper Subgrade	Substratum	
FWD	Section 1	6000	960	70	120	210	8,5
iPAVe TSDD	Section 1	5900	980	80	120	160	8,6
FWD	Section 2	750	160	40	100	120	0,1
iPAVe TSDD	Section 2	700	140	140	100	90	0,1
FWD	Section 3	6900	990	80	100	130	9,1
iPAVe TSDD	Section 3	6500	980	120	110	150	9,7

Table 1: Comparison of iPAVe TSDD and FWD derived layer stiffness moduli and estimated structural capacity

In order to assess the comparative back calculated layer moduli and subsequent bearing capacity evaluation, the deflections obtained from FWD and iPAVe TSDD were analysed using the Rubicon Toolbox computer software package – this program having been compiled for the analysis of FWD deflection measurements.
As showed in Table 1, despite using a design package intended for use with FWD data, there is very little difference between the mechanistic empirical analysis results that were derived from iPAVe TSDD and FWD measurements. This holds true for distressed and sound condition pavements. It is therefore evident that iPAVe TSDD technology could, in fact, be utilised for project level investigations as well as in network level surveys.

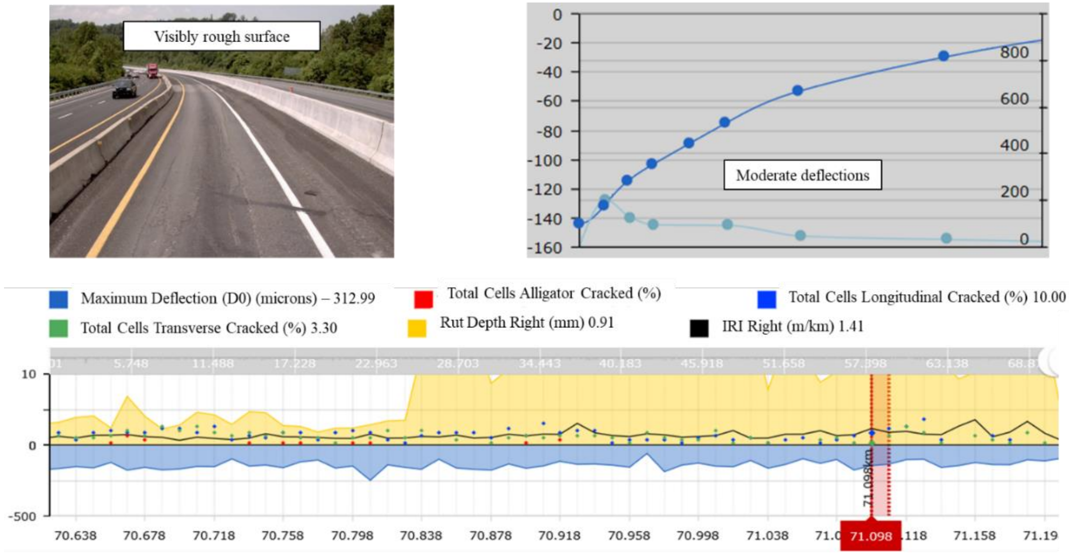
4 HOW CAN SIMULTANEOUS MEASUREMENTS OF STRUCTURAL AND FUNCTIONAL CONDITIONS STRENGTHEN THE EVALUATION OF PAVEMENT LIFE?

The need for actual bearing capacity measurements, particularly in network level assessment, is a subject of interest for many. Unfortunately, it has been a common belief that lack of structural capacity will always result in surface deterioration. This is not always the case as discussed below and, when it is, by the time structural inadequacy has manifested as surface distress , the structural condition is generally so poor that maintenance and rehabilitation is no longer possible and the road will require resource demanding rehabilitation. Seen from a financial and optimization perspective, the earlier the need for maintenance is detected, the more possibilities are available for remedial interventions and, therefore, structural assessments should be conducted to confirm the presence of structural deterioration before treatments are planned for such extensive deterioration. It is not uncommon for some administrations to delay treatments on some roads when such extensive work is required. Either way, the need for confirmation is an important part of appropriate treatment selection.
Not surprisingly, continuous structural capacity assessment, can reveal isolated/discrete portions of highways that may appear acceptable from the surface, but (for a multitude of potential reasons) are not able to provide the same structural support as adjacent portions of the same highway, as shown in the example in figure 5.
When the opposite occurs, where the pavement section exhibits extensive surface deterioration, as shown in figure 6, but provides a sufficient structural support, it can lead the administration to believe that substantial maintenance and repairs are required.



Filters: D0 > 250 μm; IRI < 3 m/km; Rutting < 5 mm; Total Cracking < 10%

Figure 5: High deflection and a smooth, even road surface



Filters: D0 < 250 µm; IRI > 3 m/km; Rutting > 10 mm; Total Cracking > 25%

Figure 6: Low deflection and a rough, uneven road surface

Pavement sections that exhibit extensive surface deterioration, may lead to the following, if corresponding structural assessment is not carried out:

a.) Treatments may be delayed as a result of the perceived deterioration being caused by structural inadequacy. If the surface continues to decline the result could be a rapid structural deterioration and ultimately structural collapse (by allowing water to infiltrate the pavement). This will likely lead to accelerated deterioration, regardless of whether structural issues existed initially or not.

b.) If an extensive treatment plan is decided (based on the surface deterioration) unnecessary expenditure would result, taking resources away from other road sections where it may likely be more appropriate to spend the maintenance effort.

When the surface is heavily deteriorated as shown in the example in figure 6, and the assessment reveals a road pavement with a sound structural capacity, the administration can optimize their maintenance budget by e.g.:

c.) Remove and replace the problematic surface layer and avoid more extensive unnecessary costly remedial measures.

d.) Use saved resources to investigate true cause(s) of surface anomalies.

The above examples clearly show that, regardless which case applies, continuous synchronized structural and surface data provides for a more detailed assessment within a project and/or network level scenario. Rather than assigning some “average” condition for treatment selection and design, discrete sections can be identified with greater confidence and accuracy. This ability offers the potential for isolating and treating areas of greater need. Project level decisions can now be made with ‘network level’ data thereby negating additional specialist procurement and providing road authority engineers with requisite information on which to base remedial design options. Such work can also be performed in advance of larger rehabilitation projects to produce a more ‘homogeneous’ structure for more cost-effective designs. Potentially, isolated repairs of this nature may even be performed (on their own) to proactively “buy some time” before additional work is needed.

5 CONCLUSION AND FURTHER INITIATIVES

Using comprehensive measurements (recording both surface characteristics and bearing capacity simultaneously) analysis provides the administrations the ability to detect present and forthcoming conditions at an earlier stage than has been traditionally possible. This provides a unique possibility for the administration to:

a) Proactively conduct spot repairs at precisely defined locations in advance of surfacing treatments, to improve treatment performance and optimize required thicknesses.
b) Proactively alter treatment forecasts and strategies to mitigate more extensive areas of structural concern, that currently are not identifiable e from the surface condition.

A newly published report by Samer W. K et al. 2020, shows the immediate benefit of using traffic speed deflection measurements but also the need for conducting comprehensive measurements for the decision making process, and that measurements and observations of pavement surface characteristics cannot stand alone. Implementing comprehensive and simultaneous pavement measurement data into road infrastructure asset management will greatly assist in overcoming the challenges of providing and efficient and safe road infrastructure that meets modern and future social expectations.

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