Continuous Deflection Measurements – The South African Experience

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***Abstract*—The intelligent Pavement Assessment Vehicle (iPAVe) may be described as a fully integrated survey vehicle capable of collecting both surface and structural pavement condition data at highway speeds. The iPAVe integrates the Traffic Speed Deflectometer (TSD) developed by Greenwood Engineering with additional Australian Road Research Board (ARRB) Hawkeye Systems which are controlled and processed using ARRB software. The Hawkeye System allows for measurement of road surface characteristics such as cracking, roughness, rutting, texture and geometry together with spatial information and digital imaging. Doppler lasers are used to measure the pavement deflection velocity, from which an integration technique is utilised to obtain a deflection bowl.**

The iPAVe has already proven itself on the international stage to be an improved method for network level assessments when compared to traditional methods. Its true benefits lay in the speed, efficiency and safety at which data can be collected.

The collected data is processed using the Hawkeye Processing Toolkit. This software allows for full data processing, analysis and management capabilities on all imaging, profile and deflection data collected. The efficient management of the collected data will assist road agencies in the development of an optimal maintenance and rehabilitation strategy.

In-house validation testing has been performed to monitor the iPAVe's performance over time and against Falling Weight Deflectometer (FWD) data. This comparison has shown a similar trend in deflection measurements as well as good repeatability.

This paper shall discuss the commissioning and operational challenges encountered in establishing a reliable and efficient operating methodology for the iPAVe.

Keywords—deflection measurement; pavement condition; integrated survey vehicle

I. Introduction

A Road Agency has the aim of managing a network with major emphasis being on determining the remaining useful life of a road network as well as the optimal maintenance and rehabilitation strategy. An accurate assessment of the reliable remaining life of a pavement requires knowledge of both the structural and functional condition. Traditional methods of determining pavement deterioration have primarily focused on surface condition. Structural condition assessments are usually based on stationary or slow-moving devices which can cause hazardous situations in normal traffic flow patterns.

The integrated Pavement Assessment Vehicle (iPAVe) is considered to be an advancement in pavement management since it is able to collect both surface and structural pavement condition data at speeds of up to 80 km/h. The iPAVe integrates the Traffic Speed Deflectometer (TSD) developed by Greenwood Engineering with the Australian Road Research Board (ARRB) Hawkeye Systems which are controlled using ARRB software. The Hawkeye platform is responsible for measuring road surface characteristics such as cracking, roughness, rutting, texture and geometry together with spatial information and digital imaging. Several high precision Doppler lasers are used to measure the pavement deflection velocity from which the deflection bowl is calculated using an integration technique.

The iPAVe is a much more practical method for network level testing when compared to traditional deflection testing using a Falling Weight Deflectometer (FWD). The iPAVe is significantly faster in collecting deflection data when compared to the FWD, which allows for large networks to be surveyed in a fraction of the time. It also provides a safer working environment by eliminating the need for stationary measurement and traffic control.

The iPAVe does however have certain surveying limitations. The equipment cannot be used on gravel roads as the dust can negatively affect the sensitive measuring equipment. The iPAVe is generally not used on projects where the lane width is less than 3.25m or the road length is less than 8km as experience has shown that these factors affect the turning ability of the iPAVe.

II. An Overview of the iPAVe

The iPAVe consists of several subsystems which when integrated result in a survey vehicle capable of collecting both surface and structural pavement condition data. The current iPAVe which is owned and operated by Automated Road Rehabilitation Business Systems South Africa (ASSA) integrates the *TSD 10* manufactured by Greenwood Engineering and the *Hawkeye 2000 Series* manufactured by ARRB. As of 2017 there are currently six iPAVe's which have been built by ARRB.

Both the TSD and Hawkeye equipment is housed within a semi-trailer manufactured by Brdr. Platz Karrosserifabrik A/S, Denmark. The semi-trailer is driven by a Mercedes-Benz Actros 1844 LS 4X2 truck. The TSD subsystem was manufactured and assembled by Greenwood Engineering in Brøndby, Denmark and was delivered to ASSA in March 2016. Once in Durban, a technical team from ARRB arrived to perform the installation and integration of the Hawkeye 2000 subsystem. These two main subsystems operate in tandem to successfully create an integrated survey vehicle. In addition, these two subsystems are supported by a myriad of electrical systems, power supply systems, sophisticated electronic control architecture, fan and cooling systems. A desktop computing system utilises proprietary software to create a Human Machine Interface (HMI) allowing for easy operator interaction with the iPAVe subsystems.

A rigid beam can be found inside the semi-trailer which is aligned longitudinally along the left side of the trailer chassis. Seven high precision Doppler lasers are attached within the beam. These lasers are positioned to measure the deflection velocity of the pavement surface at various offsets ahead of the loaded rear wheel and trailer. The offsets ahead of the load are as follows: 110mm, 210mm, 310mm, 610mm, 910mm and 1510mm. A reference laser is situated at an offset of 3510mm, where it is assumed that the pavement surface is unloaded and there is no vertical velocity response [1]. Fig. 1 provides the layout of the Doppler lasers.

The measurement beam ensures that the relative position and angle between the Doppler lasers remains unchanged. The beam is suspended by a servo system which keeps the distance between the Doppler lasers and the road surface constant to keep the lasers in focus. A gyroscope, accelerometer and inclinometer are mounted in the centre of the measurement beam. These sophisticated inertial sensors are used to remove the effects of the beam movement relative to the pavement surface.

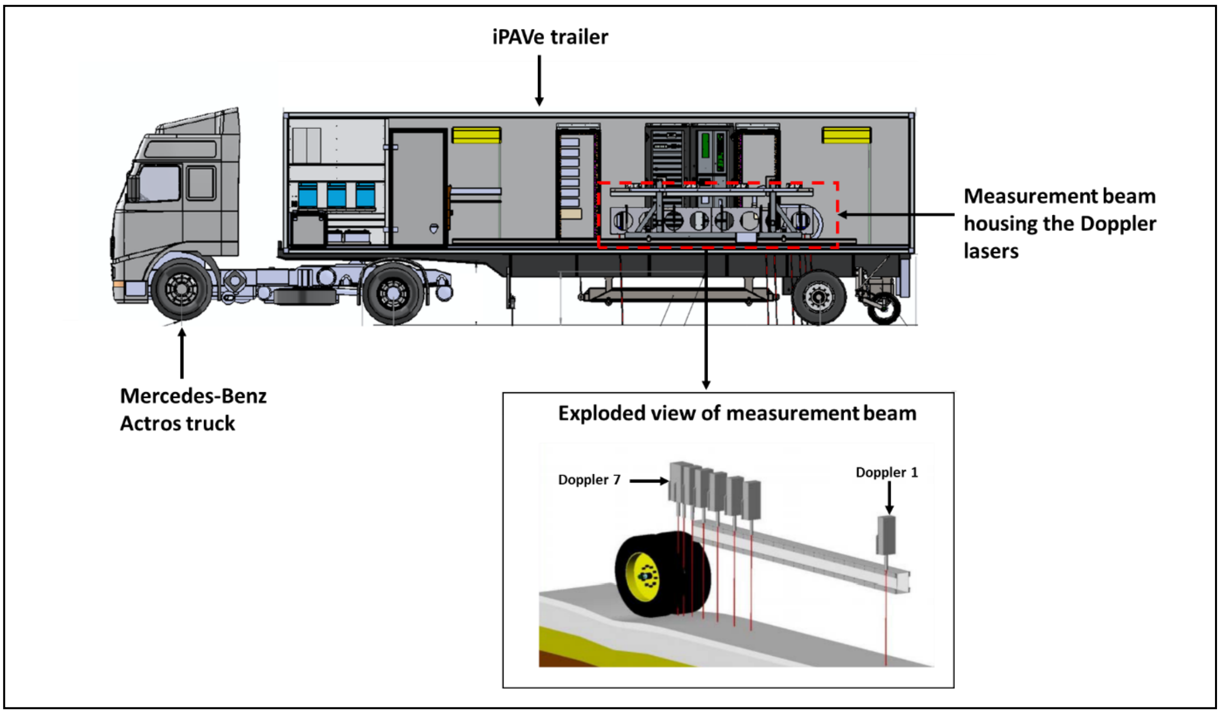

Fig. 1: Doppler laser arrangement

III. DEFLECTION MEASUREMENT PRICIPLE

The Doppler lasers are mounted approximately two degrees from the vertical plane so that the velocity measurement can be split into the vertical (V_V) and horizontal (V_H) components (see Fig. 2). The horizontal and vertical components allow for the calculation of the deflection slope (V_V/V_H) and consequently the deflection bowl. The Doppler lasers measure the pavement velocity by sensing the frequency shift of back scattered light from a moving surface.

The beam of the laser diode is split into two partial beams (a reference beam and a measurement beam) which are then superimposed again on the surface to be measured. This results in a three-dimensional space (measurement volume) which contains bright and dark fringes which are a distance Δs apart (see Fig. 3).

Since the light path length of the reference beam is constant over time, the movement of the pavement generates a dark and bright (fringe) pattern on the detector. The frequency of which is equivalent to the Doppler shift between the emitted and reflected light.

The modulation frequency of this fringe pattern is directly proportional to the velocity of the object. This reflected light is detected by a photodiode and the electrical signal digitally processed to determine the frequency and hence the speed [2].

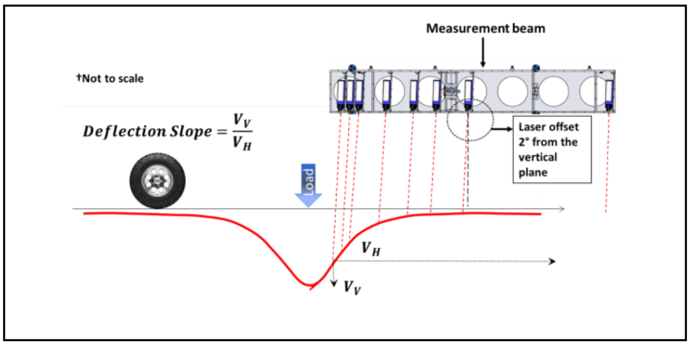

Fig. 2: Mounting arrangement of the Doppler lasers.

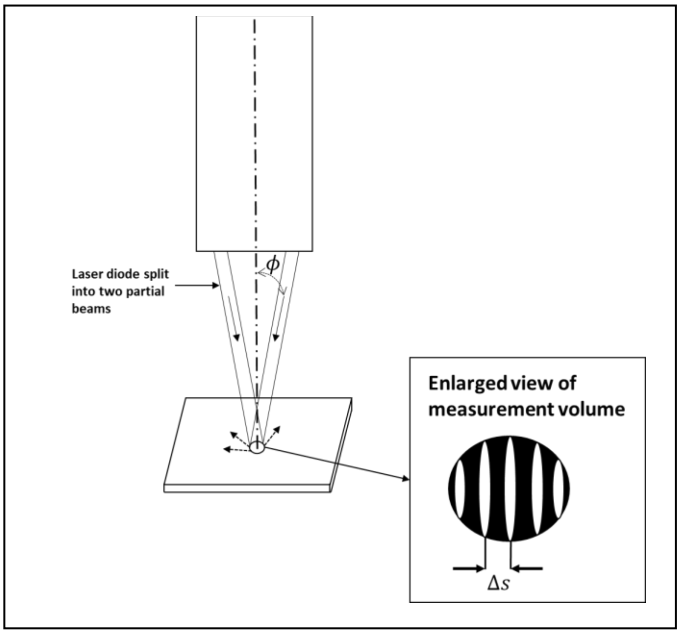

Fig. 3: Laser diode beam split into two partial beams.

IV. INTERPRETATION OF THE DEFLECTION VELOCITY

An important aspect when using the iPAVe is an understanding of the approach used to determine the deflection measurements from the measurements of vertical pavement velocity collected by the Doppler lasers. ARRB uses a numerical integration method based on the area under the deflection slope curve, known as the Muller – Roberts method [1]. Another approach has been developed independently which uses the method of curve fitting iPAVe measurements by optimising two constants. However, this paper will focus on the Muller – Roberts method.

A. A description of the Muller – Roberts method

The proposed methodology by Muller and Roberts fits a curve through a plot of deflection slopes measured by the iPAVe versus wheel offset. The deflection profile is then constructed by numerically integrating this plot working from a fixed point at or beyond the edge of the deflection bowl towards the wheel load. This use of a numerical method is an important departure from previous approaches. Constructing the deflection bowl in this manner highlights the contribution of velocity measurements further from the wheel to both the shape of the deflection bowl tail and the accuracy of maximum deflection predictions.

A typical curve fit of the deflection slope versus the wheel offset is given in Fig. 4. The grey shaded area shown on the curve is equal to the vertical pavement deflection (d_y) associated with the horizontal increment distance (d_x). The vertical deflection of the point on the ground is related to the average vertical velocity $(\overline{V_V})$ and the time period (d_t) as per (1).

$$d_y = \overline{V_V} dt \tag{1}$$

The horizontal displacement and the velocity of the iPAVe (V_H) can also be related to the same time period as per (2).

$$d_x = V_H dt \tag{2}$$

The above two equations can be combined via the common dt term to obtain (3).

$$d_y = \frac{\overline{V_V}}{V_H} dx \tag{3}$$

When a homogeneous deflection response across the wheel offset length is assumed, the above-mentioned concept can be extended across the entire plot. Therefore, the total pavement deflection (y_x) at any wheel offset can be determined by progressively adding up the vertical deflection increments for each horizontal increment, working from the edge of the deflection bowl up to the offset being considered. The deflection formula is given in (4) [3]. Fig. 5 shows a graphical representation of how the deflected pavement profile is obtained from applying (4).

$$y_x = \sum_{\infty}^{x} \frac{\overline{V_V}}{V_H} dx \tag{4}$$

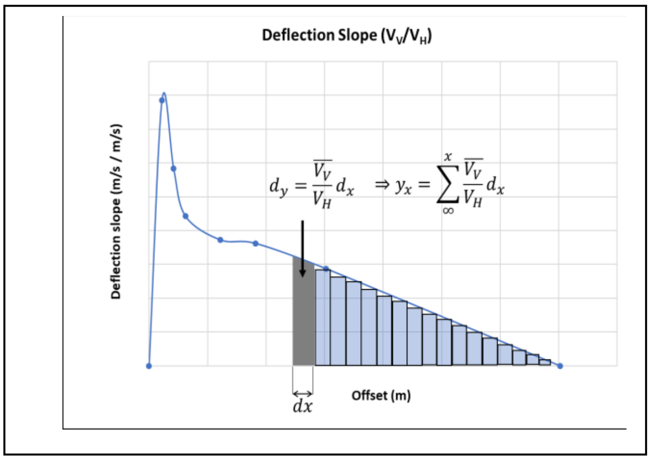

Fig. 4: Deflection slope versus offset.

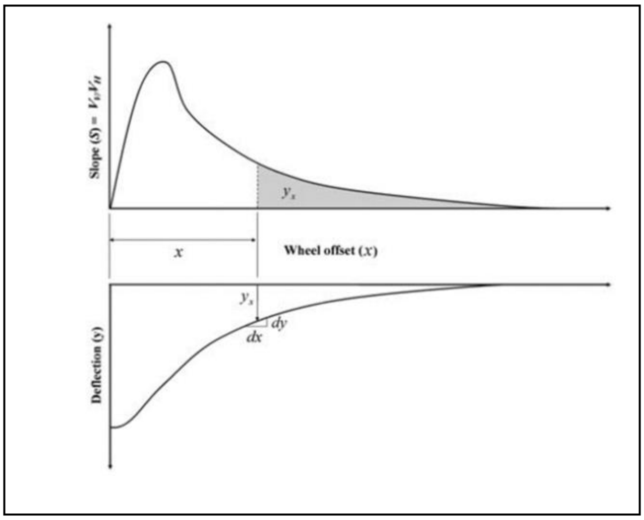

Fig. 5: The deflection profile can be obtained as the cumulative area under the Deflection Slope curve [1].

V. THE HAWKEYE 2000 SYSTEM

The Hawkeye System is integrated into the iPAVe and is responsible for measuring the condition of road surface characteristics such as cracking, rutting, roughness, texture and geometry. These surface measurements are coupled with spatial information and digital imaging.

A. Automatic Crack Detection (ACD) System

Two Laser Crack Management System (LCMS) laser units are integrated into the iPAVe to create an ACD system. The laser units project a 4m wide laser line across the pavement. The laser image is captured by two 3D cameras which are mounted off-axis to the laser light source. These cameras interpret the distortions to the straight laser line as variations in the vertical surface profile. Each frame is analysed to determine the presence of cracking on the pavement surface [2].

The ACD equipment is also used to measure a transverse profile in order to determine rut depth and rut characteristics. The processing software allows both lane and wheel path rutting to be measured using the string line and straightedge models [2].

B. Digital Laser Profiler (DLP)

The DLP is defined as a non-contact Class 1 inertial laser profiler which uses lasers and an accelerometer located in each wheel path to measure the longitudinal profile of the pavement. The roughness data is derived from these measurements [2].

C. Surface Texture

The Hawkeye System measures the macrotexture of the pavement surface using three non-contact lasers. The three lasers are situated in each wheel path and along the centre line of the iPAVe. The macrotexture is reported as Mean Profile Depth (MPD) [2].

D. Spatial Location

A Global Positioning Satellite (GPS) system provides accurate and synchronised spatial location Hawkeye data against GPS coordinates for export into asset management systems.

E. Digital Imaging

The iPAVe is fitted with five digital imaging cameras which are used to record digital images of the pavement and road assets. The cameras are orientated to ensure that points of interest are recorded in the camera's field of view. All cameras are located and calibrated for scale measurement which allows for the position of all visual assets to be referenced geospatially.

F. Hawkeye Processing Toolkit

The toolkit provides full data processing, analysis and management capabilities on all measured data collected by the Hawkeye 2000 System. The software also allows for full control and synchronisation of all raw and processed data streams collected.

VI. COMMISSIONING THE iPAVe

The commissioning process for the iPAVe involves calibration of equipment and benchmarking tests. Certain subsystems found in the iPAVe require calibration in set intervals in order to minimise measurement uncertainty by ensuring the accuracy of the measuring equipment. Calibration need not only be performed in set intervals but can also be performed when measurements appear questionable. Proper calibration of the equipment allows for the collection of valid and reliable data. The calibration of the Load Sensing System and the Doppler Lasers will be discussed in this paper.

Benchmark testing is performed to determine confidence in the equipment calibration, operational processes and stability of the entire system throughout a survey. The benchmarking exercise involves comparing deflection measurements from the iPAVe with measurements from a Falling Weight Deflectometer (FWD).

A. Calibrating the Load Sensing System

The Dynamic Load Sensing System requires calibration in order to provide reliable strain gauge data. The iPAVe has a front and a rear ballast. The ballasts are controlled by a hydraulic system which is used to attach and detach the ballasts from the iPAVe body. The rear axle mass is approximately 8700 kg when both ballasts are attached.

The calibration process involves measuring the iPAVe's rear axle mass for a combination of six different ballast positions. The rear axle mass is measured independently for both left and right-hand sides using calibrated weighing pads which have a measurement division of 0.5 kg.

The raw least significant bit (lsb) values for the left and right-hand side strain gauges are also recorded for each of the six ballast positions. The lsb is defined as the raw signal output as measured by the iPAVE's strain gauges.

A XY scatter plot of the rear axle mass versus the lsb can be plotted and a linear trend line in the form of $y = mx + c$ fitted to the data points. The line gradient (m) and y-axis intercept (c) provide values which are input directly into the calibration software. The different ballast loads considered as well as a sample XY scatter plot is shown in Fig. 6. Note that the regression (R^2) value can be used as an indication of the "goodness of fit" of the trend line to the data points. A R^2 value close to 1 indicates a "good" fit of the trend line.

B. *Calibrating the Doppler Lasers*

As previously discussed in Chapter III, the Doppler lasers are mounted approximately two degrees from the vertical plane so that the velocity measurement can be split into vertical and horizontal components as per Fig. 2.

Mounting of the Doppler lasers at an exact two degree offset from the vertical plane is a difficult task. Therefore, a correction factor is derived to account for any deviation from the two-degree offset requirement. An error in the offset angle as minor as 0.005 degrees can produce an error in the final results of up to 25% [4], [5]. Considering the sensitivity of the offset angle on the final results, it is natural that the laser calibration be as precise as possible. The calibration needs to be performed at regular intervals to ensure that the angles have remained unchanged during transit or from extended use.

C. *Comparison of iPAVe and FWD measurements*

The iPAVe allows for collection of deflection data up to the speed of 80 km/h and can generate over 36 million data points per hour at its highest operating speed [6]. It is important to note that the iPAVe applies the load of a real truck in traffic whereas the FWD uses a falling weight. This makes the pavement response under the iPAVe authentic compared to the response from the falling weight [7].

The iPAVe provides the advantage that it creates a wave like response in the pavement construction which is similar to that generated in traffic. During the load passage the principal stress and strain vectors rotate, something which is very different from what takes place when the FWD is used to obtain deflection data. An attempt to obtain an identical response between the iPAVe and FWD is therefore a mistake. The two response types are different in nature and this difference must be taken into account when the output is used in comparing deflection measurements [7].

The following data mining methodology is employed when comparing maximum deflections as measured by the iPAVe and FWD:

- Data and problem understanding
- Data preparation
- Interpretation of results
- Linear regression analysis

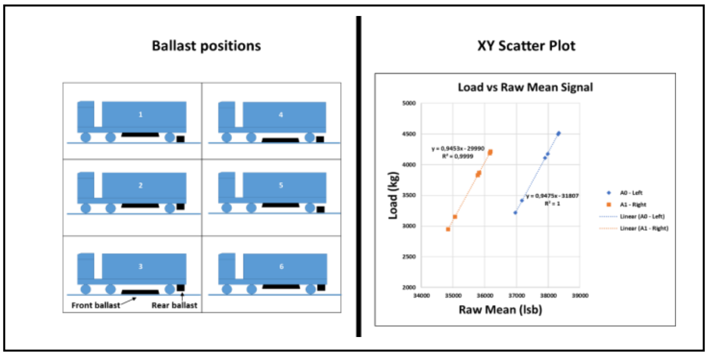

Fig. 6: Ballast positions and scatter plot created from measurements.

1) *Data and problem understanding*

ASSA has a predefined verification loop which is used to gather deflection data from both the iPAVe and FWD. The data sets compared in this document were obtained on the 8th of March 2017 and 17th of February 2017 for the iPAVe and FWD respectively. Since these measurements were performed on different dates it is possible that varying environmental and traffic conditions may have an influence when comparing the data sets.

The measuring interval for both the iPAVe and FWD surveys was set as 50m. In the case of the iPAVe, the deflection measurements are consistently reported in 50m intervals due to the use of precision lasers. The FWD measurement intervals will not be as precise when compared to the iPAVe due to the human element involved when bringing the vehicle to a stationary position to obtain a measurement.

2) *Data pre-processing*

Recall from Chapter VI that the rear axle mass of the iPAVe is approximately 8700 kg ≈ 85 kN. This mass is comprised of the trailer mass as well as the front and rear ballasts. The mass is biased slightly to the side of the measurement in order to obtain the maximum deflection response from the pavement. The iPAVe applies an approximate load of 50 kN to the side of the measurement.

In order to make a fair comparison of the maximum deflection values it is necessary to convert the data to an equivalent scale. The FWD obtains deflection measurements using a target load of 40 kN. The FWD measurements are scaled up to 50 kN such that the FWD measurements will be comparable to the load applied by the iPAVe. Multiplication of FWD deflection values from 40 kN with a constant of 1.25 provides the equivalent deflection at 50 kN $\left(\frac{50}{40} = 1.25\right)$.

The FWD displays measured deflections as positive values whereas the iPAVe displays measured deflections as negative values. The iPAVe deflections are multiplied by negative one in order to compare with the FWD data set.

The maximum deflection values for both data sets was normalised in the range from zero to one for easier comparison. The "Re-scaling method" was used for the normalisation approach and the formula is given in (5).

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \qquad (5)$$

Where:

x' = Normalised deflection value at measurement location

x = Original deflection value at measurement location

$\max(x), \min(x)$ = Maximum and minimum deflection values from the data set

3) Interpretation of results

The FWD and iPAVe normalised maximum deflections have been plotted against chainage in Fig. 7. It is not possible to perform an exact point to point comparison because the chainage is not exactly the same for the two data sets. However, in most instances the differences in the chainage for a given measurement point is less than one meter and will be considered as acceptable for the purposes of this comparison exercise.

As per the observation made by a previous author [6], it can be seen that the trend in FWD and iPAVe measured maximum deflections is usually the same. However, it is not possible to state that one machine consistently measures a higher deflection than the other.

It is important to recall at this time that the FWD deflection values are measured at discrete points by dropping a weight on the road surface causing the pavement to deflect. Whereas the iPAVe pavement deflection is measured using Doppler laser technology to provide a continuous stream of deflection values. Therefore, the iPAVe provides measurements which have been averaged over a 50m interval (which is equivalent to the chainage) and the FWD provides a pointwise measurement [8].

This difference in measurement techniques can be used to explain the high FWD measured maximum deflection at a chainage of circa 1.4km (refer to Fig. 7). It is possible that the FWD measurement may have been taken at a position where the pavement is locally “soft”. Furthermore, the environmental conditions may have been different when the FWD and iPAVe measurements were obtained since the surveys were performed on different calendar days.

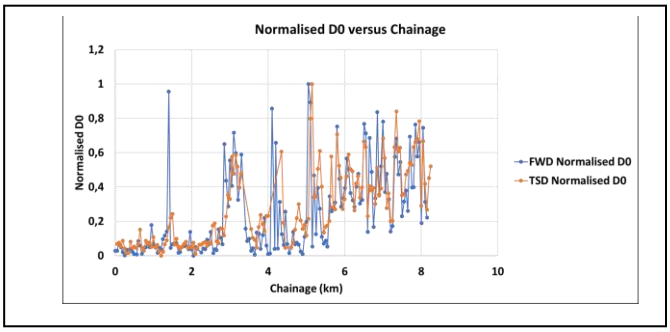

Fig. 7: A graph showing normalised FWD and iPAVe maximum deflections.

VII. Some Practical Challenges Experienced with the iPAVe

A. Hydraulic Generator

The iPAVe consists of a hydraulic power network which transmits mechanical power from a base machine to a motor housed within a hydraulic generator. The base machine in this application is a hydraulic pump attached to the truck which transfers mechanical power to a circulating hydraulic oil. The motor is integrated into the generator and can be used to produce electrical energy immediately when the generator is switched on. This hydraulic generator complements the electrical subsystems which provide electricity to the measuring equipment during a survey.

The iPAVe was initially plagued with repeating generator trips during a survey. After discussing the problem with Greenwood Engineering, it was concluded that when the truck engine was running and the generator switched off, the hydraulic pump still produces a small amount of circulating hydraulic oil flow, which in turn heats up the hydraulic oil. However, since the generator is switched off, the hydraulic oil was bypassing the oil cooler. The system would then trip and enter a protection mode to prevent the hydraulic oil overheating to a point at which the oil becomes damaged. The generator system was upgraded with a new oil cooler and some modifications to the hydraulic system to combat the problem.

B. Doppler Laser

One of the Doppler lasers unexpectedly failed during routine operation of the iPAVe. After unsuccessful trouble shooting attempts with Greenwood Engineering, a decision was taken to send the laser to the Original Equipment Manufacturer for diagnosis and repair. The repair process included a replacement of the prism and interferometer, as well as the alignment of the optics.

C. Computer Failure

A computer which serves as an integral component of the Hawkeye 2000 System unexpectedly failed during routine operation of the iPAVe. A diagnosis revealed that the motherboard and processor chip had suffered irreparable damage. The software associated with the Hawkeye 2000 System is currently only compatible with Microsoft Windows 7. This posed a challenge in sourcing replacement components as hardware compatibility with Windows 7 is being phased out by manufacturers. A compatible replacement computer was eventually sourced from Automated Road Rehabilitation Business Systems Australia. An additional computer has been ordered to serve as a standby to mitigate against future unexpected computer failures.

VIII. Conclusion

An overview of the pavement surface and structural measuring capabilities of the iPAVe has been discussed. The benefits of the iPAVe are in its ability to collect both surface and structural pavement data at speed, efficiency and safety, resulting in a much improved and practical method for network level testing.

The deflection measurement principle has demonstrated how the deflection bowl is obtained from pavement velocity measurements. This technique involves numerical integration of the deflection slope curve.

The Hawkeye 2000 System is integrated into the iPAVe and is responsible for obtaining the road surface characteristics such as cracking, rutting, roughness, texture and geometry. A processing toolkit is used for processing, analysing and managing the data collected by the Hawkeye 2000 System.

Calibration of the iPAVe is essential in order to minimise measurement uncertainty by ensuring accuracy of the measuring equipment. The commissioning process also involves comparison of iPAVe and FWD data to determine confidence in the equipment accuracy and calibration.

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