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(Year 1 – 2014/2015)

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P40 Benefits of Traffic Speed Deflectometer Data in Pavement Analysis

SUMMARY

This report presents findings from the Year 1 study of the National Asset Centre of Excellence (NACOE) P40 research project. The objective of the project is to investigate the benefits of the Traffic Speed Deflectometer (TSD) data in pavement analysis at the project level.

The study indicated that the TSD can be a beneficial pavement evaluation tool that can be used beyond that of a network screening tool. Engineers can estimate the deflection basin based on TSD measurements from the Doppler laser, allowing a range of pavement analyses that utilise deflection basin data. Some examples include the CIRCLY and EFROMD forward and back-calculation software, that are widely used in Australia. This report presents ways that such tools could be used with TSD deflection measurements.

In this project, different case studies based on the 2014 collected data have been presented. These case studies identify different ways that TSD data could be used in project-level pavement evaluations. The findings show early promise to use TSD data for project-level applications. More validation studies are required to confirm these project-level applications.

During future work on this project, it is recommended that side-by-side testing of the TSD and other deflection testing devices be conducted. Limited 'ground-truth' experiments should be explored to improve the understanding of the surface responses under the TSD for comparison with traditional non-destructive deflection testing.

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1 INTRODUCTION

1.1 The Traffic Speed Deflectometer

The Traffic Speed Deflectometer (TSD) is a pavement evaluation device, manufactured by Greenwood Engineering in Denmark, which measures the pavement surface deflection at traffic speeds. ARRB Group acquired a TSD in 2014 and commenced deflection surveys in Queensland, New South Wales (NSW) and New Zealand.

The TSD has proven to be a valuable network assessment tool because of its high production rate while still maintaining measurement repeatability over a range of test speeds and road conditions. The raw data from the TSD was processed by the Greenwood Engineering software 'Profilograph for Windows' and deflection measurements are currently reported at a minimum reporting interval of 10 m.

Over 12 400 km of the Queensland road network were surveyed between April and August 2014. This provides a comprehensive evaluation of the pavement road assets, which would not be possible using traditional deflection measurement devices. In April 2015, the TSD commenced a second year of network surveying in Queensland.

1.2 Structure of Report

The P40 project – *Benefits of Traffic Speed Deflectometer Data in Pavement* Analysis, is part of a $3.2 million research program under the National Asset Centre of Excellence (NACOE) research agreement between the Department of Transport and Main Roads (TMR) and ARRB Group. The objective of the project is to investigate the benefits of the TSD for pavement analysis at the project-level. This is generally in line with the research direction of other international studies. FY 2014–15 is the first year of this project and the Year 1 findings are presented in this interim report.

The major tasks of this year include the following:

- Task 1: Literature review
- Task 2: Identify potential project-level applications
- Task 3: Draft interim report summarising findings
- Task 4: Scoping for Years 2, 3 and 4.

A literature review has been conducted in Year 1, the findings from domestic and international studies are presented in Section 2. The literature review found that limited information on theoretical TSD surface deflection was available. As a result, some preliminary numerical modelling using the Australian principal pavement design software, CIRCLY, was conducted and is presented in Appendix A. The second key objective is to evaluate if the TSD has the potential to be used for project-level studies in Queensland. It was found that the device, together with appropriate analysis techniques, can be used to supplement existing evaluation tools. An assessment of using TSD for project-level applications is presented in Section 3. Three TSD case studies are presented to support the discussion. Finally, a summary and proposed future work are presented in Section 4.

2 OVERVIEW OF TSD AND USAGE

2.1 Introduction

2.1.1 Overview of Deflection Testing

The TSD is a relatively new deflection device. At the time of this report, only eight TSD devices had been manufactured by Greenwood Engineering of Denmark. There are two versions of the device, a first-generation device and a second-generation device. This report evaluates the second-generation device, which is the version owned and operated by ARRB Group. It should be noted that regular system upgrades and modifications are being made by the TSD manufacturer and owners. Two main sources of literature summarise the international experiences in using TSD:

- Austroads publications
- Deflection at Road Traffic Speed (DaRTS) workshops.

It is generally agreed that the TSD is providing valuable information for asset management purposes.

The non-destructive measurement of pavements has a long history. The development of the Benkelman beam in the early 1950s was followed by the introduction of many other deflection measuring devices. The purpose of these non-destructive deflection testing devices is to determine the structural capacity of a pavement by measuring the pavement response (i.e. surface displacement or deflection) caused by a pre-determined load.

Non-destructive deflection testing can be categorised according to the type of loading that is applied to the pavement. Two main categories include static and dynamic loading. Dynamic loads can be grouped as follows:

- moving loads
- steady-state vibration
- impulse.

The TSD is one of the recent deflection equipment that provides ‘pseudo-continuous’ deflection measurement at 10 m interval. The TSD is the only production line deflectometer variant that is capable of testing at 70–80 km/h. Table 2.1 lists the measurement and loading characteristics of different deflection measuring devices.

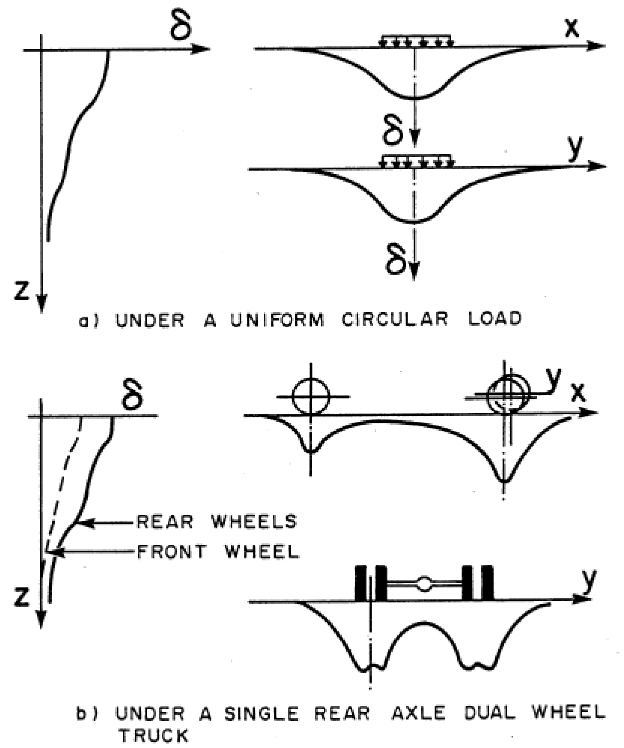
Table 2.1: Measurement and loading characteristics of different deflection measurement devices

Deflection device	Measurement	Load type	Direction of load	Speed
Benkelman Beam	Displacement	Wheel	Unloading	Creep
Deflectograph	Displacement	Wheel	Loading	Creep (≈ 3.5 km/h)
Curviameter	Velocity	Wheel	Unloading (+small loading)	20 km/h
Falling Weight Deflectometer	Velocity	Damped impact load via plate	Stationary load	Stationary
Rolling Weight Deflectometer	Change of height	Wheel	Loading	Variable (80 km/h, typical)
Rolling Dynamic Deflectometer	Velocity	Wheel	Loading	5 km/h
TSD	Velocity	Wheel	Loading	Variable (80 km/h, typical)

The falling weight deflectometer (FWD) is a common deflection testing device for project-level studies in Australia and around the world. Because of its popularity, FWDs are often used to compare with other deflection measurement devices. When comparing the TSD with the FWD, the loading is different for the two devices. Figure 2.1 illustrates the general shape of the deflection basin measured under a circular loading plate (i.e. FWD) and the deflection basin under a truck with front and rear axles. Even from a static analysis standpoint, the deflection bowl is different, as the truck loading is influenced by both the front and rear axles as well as the left and right wheel loadings.

The TSD would have a similar deflection shape under a rear axle dual-wheel truck as shown in Figure 2.1. It is noted that there is a reduction in deflection value mid-point between the two dual wheels. This has been observed by ARRB Group and other international TSD operators.

Figure 2.1: Typical shapes of deflection influence lines

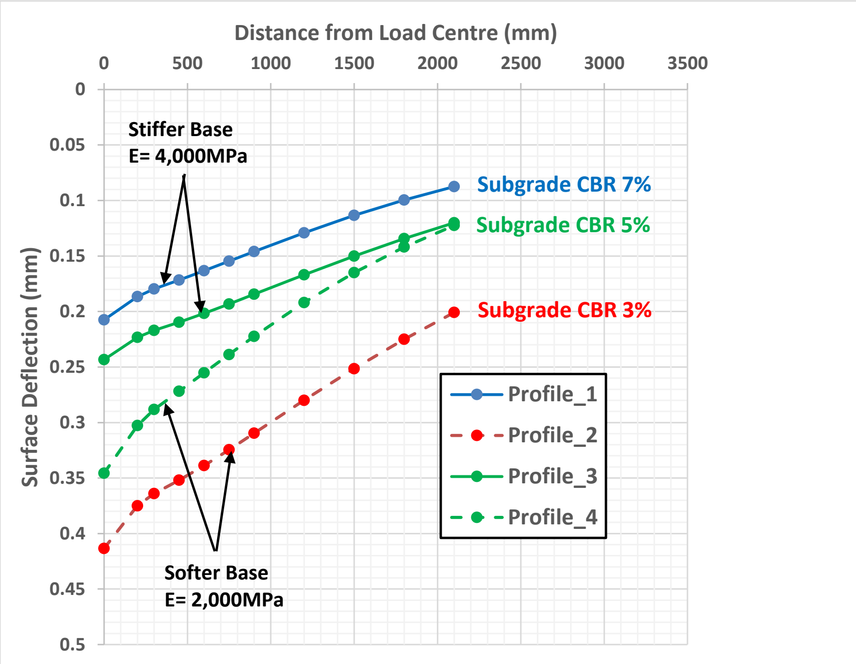


Source: Horak (1987).

2.1.2 Analysis of NDT Results

In simple terms, a higher deflection corresponds to a weaker pavement. Figure 2.2 illustrates the change in surface deflection for different pavement profiles. While different deflection equipment do produce different results, the general trend and interpretation method of deflection basin remains applicable across different testing devices. Pavements that are weak in the base and subgrade layers will have the highest deflection. The inner part of the deflection basin indicates the response of the top base layer (i.e. a stiff base layer will have a slower rate of deflection reduction with increasing distance from the load centre). For a base of the same stiffness, a weak subgrade increases the value across the entire deflection basin (i.e. the deflection basin shifts downwards).

Figure 2.2: Relationship between variation of stiffness moduli in base layer and subgrade



Four types of deflection analyses are typically conducted using the deflection basin:

- analysis based upon the maximum deflection (i.e. deflection at zero offset from the loading point, D_0)
- analysis that uses deflection basin parameters (i.e. curvature, surface curvature index, base curvature index, deflection ratio, AREA… etc.)
- cluster analysis
- back-calculation of pavement layer moduli (i.e. a set of elastic moduli that best match the theoretical and measured deflection basin).

The maximum deflection is a commonly used indicator as it gives an indication of the overall strength of the entire pavement system, although the indicator fails to distinguish whether the weakness lies within the pavement structure or subgrade. Deflection basin parameters quantify the shape and relative magnitude of different parts of the deflection basin, so that the interpretation can be narrowed down to a specific part of the pavement system.

Similar to the maximum deflection value, guidelines given on deflection basin parameters are specific to deflection equipment and pavement types. Examples of some commonly used deflection basin parameters are presented in Table 2.2.

Table 2.2: Typical deflection basin parameters used for pavement evaluations

Parameter	Formula	Measuring device
Maximum deflection	δo	Benkelman beam Lacroix deflectograph
Radius of curvature	$R = \dfrac{r^2}{2\delta_0\left(\dfrac{\delta_0}{\delta_r} - 1\right)}$ r = 127 mm	Curvaturemeter

Parameter	Formula	Measuring device
Spreadability	$R = \frac{\left[\frac{(\delta_0 + \delta_1 + \delta_2 + \delta_3)}{5}\right]100}{\delta_0}$ $\delta_1 \ldots \delta_3$ spaced 305mm	Dynaflect
Area	$A = 6\left[1 + 2\left(\frac{\delta_1}{\delta_0}\right) + 2 * \left(\frac{\delta_2}{\delta_0}\right) + (\frac{\delta_3}{\delta_0})\right]$	FWD
Shape factors	$F_1 = \left(\frac{\delta_0 - \delta_2}{\delta_1}\right)$ $F_2 = \left(\frac{\delta_1 - \delta_3}{\delta_2}\right)$	FWD
Surface curvature index	$SCI = \delta_0 - \delta_r$ r =305mm or 500mm	Benkelman beam Road rater FWD
Base curvature index	$BCI = \delta_{610} - \delta_{915}$	Road rater
Base damage index	$BDI = \delta_{305} - \delta_{610}$	Road rater
Deflection ratio	$Q_r = \frac{\delta_r}{\delta_0}$ Where $\delta_r \cong \delta_0/2$	FWD
Bending index	$BI = \frac{\delta}{a}$ Where a = Deflection Basin	Benkelman beam
Slope of deflection	$SD = \tan^{-1}(\delta_0 - \delta_r)/r$ Where r = 610 mm	Benkelman beam

Source: Horak (1987).

Back-calculation of layer moduli is the most complex analysis method. The method offers the maximum flexibility in terms of data interpretation and can be applied to a range of loading configurations and pavement types. Furthermore, the back-calculated layer moduli can be used as the input to the Austroads general mechanistic procedure (GMP) for subsequent pavement rehabilitation analysis (Austroads 2011). It is important to note that results from the back-calculation process often give non-unique solutions (i.e. multiple sets of layer elastic moduli can be obtained from a single measured deflection basin). Engineering judgement is often required to select the appropriate solutions for subsequent analyses.

2.1.3 TSD Doppler Lasers and Conversion to Deflection Basin from Velocity Data

The TSD uses multiple Doppler lasers to measure the surface displacement at different offsets from the rear dual-axle. The standard output from the Doppler laser is expressed in terms of deflection velocity slope (i.e. Vv/Vx) – vertical velocity over horizontal velocity.

Researchers have developed different ways to interpret the TSD data, which include:

- the Euler Bernoulli model
- the integration of the slope data approach to obtain a deflection basin (Muller and Roberts 2013)
  This method is also known as the area under the curve (AUTC) method.
- the Pedersen model (Pedersen 2011).

In this study, the integration of slope data approach has been adopted because the limited deflection results show reasonable agreement with the available FWD data.

2.1.4 Factors Affecting Measured Pavement Surface Deflections

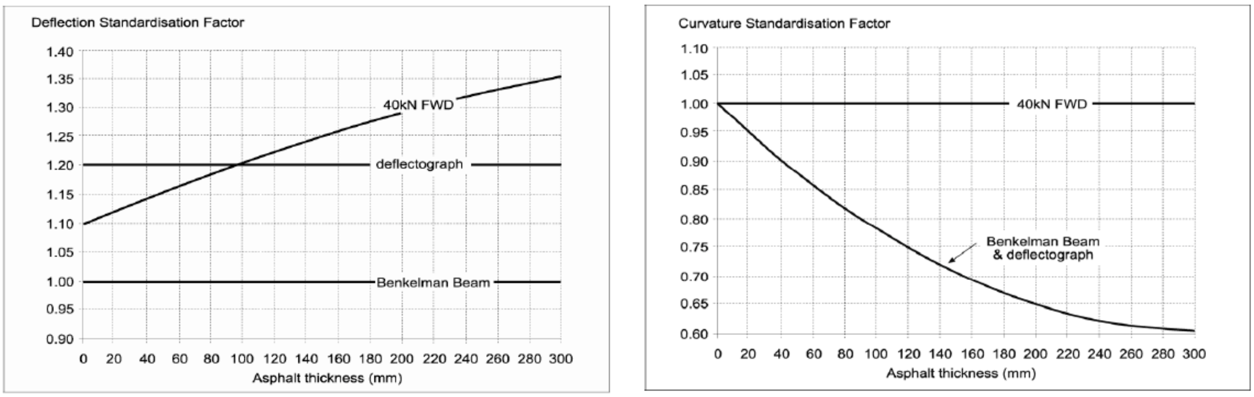
A layered pavement system can be a complex structure consisting of various civil engineering materials. Most pavement materials behave non-linearly under load and these materials can change depending on moisture and temperature conditions. For example, hot mix asphalt is a pavement material that is temperature and load-frequency dependent (i.e. its response will be different depending on the type and magnitude of the loading applied). Some of the factors which influence deflections are listed below:

- loading related – magnitude, wheel configurations, load duration/frequency
- environmental related – temperature and moisture content
- pavement condition related – uniformity of construction and distress level such as rutting, roughness.

For traditional deflection equipment, Part 5 of the *Guide to Pavement Technology* (Austroads 2011) provides presumptive standardisation factors for deflection and curvature functions, as shown in Figure 2.3.

All deflection measuring devices attempt to simulate truck loading and measure the pavement response at the surface. Different devices apply different loadings and measure the pavement surface response using different techniques to determine the pavement's structural response.

Figure 2.3: Austroads presumptive deflection and curvature standardisation factors



(a) Deflection Standardisation Factor (b) Curvature Standardisation Factor

Source: Austroads (2011).

2.2 Discussion in Recent Austroads Reports

Since the 2009–10 TSD trial in Australia, there have been a number of reports prepared by ARRB Group for Austroads. These Austroads publications are listed as follows:

- AP-R395-12, *Review of the Traffic Speed Deflectograph – Final Project Report* (Austroads 2012a)
- AP-T217-12, *Benefits and Risks of Investing in Network Level Deflection Data Collection* (Austroads 2012c)
- AP-T246-13, *State-of-the-art Traffic Speed Deflectometer Practice* (Austroads 2013)
- AP-T280-14, *Traffic Speed Deflectometer: Data Analysis Approaches in Europe and USA Compared with ARRB Analysis Approach* (Austroads 2014a)

- AP-T279-14, *Traffic Speed Deflectometer: Data Review and Lessons Learnt* (Austroads 2014b).

Both AP-R395-12 (Austroads 2012a) and AP-T217-12 (Austroads 2012c) focus on the interpretation of the TSD data collected during the first trial. The studies also look into the feasibility of commissioning the ARRB Group to operate the TSD in Australasia. The trial results suggest that the equipment has good repeatability over a range of pavement conditions and speed environments. Whilst the deflection slope parameter and other derivatives have traditionally been used in Europe for strength assessment, the AUTC method appears to show early potential as a way to convert the Doppler laser measurement to estimate maximum deflection (D_0). Kelley and Moffatt (Austroads 2012a) pointed out that the TSD can be used as a screening tool to identify weak sections within a road network.

Kelley and Moffatt (Austroads 2012a) also reported that the Transport Research Laboratory in the United Kingdom (TRL) was using 1 m as the standard reporting length for their research on the TSD, which is a higher resolution than the current Greenwood Engineering software allows (i.e. a minimum interval of 10 m). Even at the early stage, it was noted that the correlation between TSD and the FWD is dependent on the pavement type and thickness. Their study also pointed out the distinct difference in loading configuration between a FWD (impulse load on circular plate) and TSD (weight of truck transferred to the pavement through the dual-wheel axles).

In AP-T246-13 Moffatt and Martin (Austroads 2013) summarised the DaRTS workshop discussion that was held in London in 2012. This was the first workshop where traffic speed deflectograph operators came together to share their learnings and experience. The majority of the European practise is to use the TSD as a network screening device. The UK has been using the TSD as a screening tool for pavements that can potentially be classified as long-life. It was noted that the dynamic load measurement from the instrumented axle group improves the deflection data collected in Australia. Other studies include the combining of multiple field measurements in Germany (e.g. TSD, GPR and cores) and TRL investigated the use of TSD to assess load transfer efficiency across joints of rigid pavements and using the TSD to estimate critical pavement deflection/strains based on a pavement model.

In AP-T279-14 (Austroads 2014b), Roberts et al. document a network-level review and comparison of deflections in the same wheel path captured by the FWD and the Danish TSD during the 2009–10 pavement trials in Queensland and NSW. Detailed discussion of the AUTC method was also presented. It was noted that this was the first attempt to establish the link between the maximum deflections (D_0) measured by the FWD and the TSD. Correlations between the D_0 from the AUTC method and the measured FWD were presented.

In AP-T280-14 (Austroads 2014a) Moffatt et al. detailed the discussions of the 2013 DaRTS workshop. Greenwood Engineering organised a TSD comparison trial where the first generation TSD from Denmark and the second generation TSDs from Italy, Poland and South Africa participated. Generally, good repeatability for soft and stiff sections over a range of test speeds were reported. This trial reinforces the good repeatability nature of the TSD. It is also worth noting that a change in results were recorded by the Italian and Polish devices either side of the lunch break. Some possible factors such as temperature, wind direction and strength, as well as the accuracy of distance-measuring equipment were considered. It was concluded that the most possible explanation was due to progressive cooling and/or heating of system components over the lunch break. Insufficient data was collected during the trial to allow identification of the exact cause. In the meanwhile, TRL was working on improving the deflection correction and analysis procedures as well as the comparison study against deflectograph data. It is worth noting that the pavements tested in UK are mainly bound pavements. A US field trial to compare the Rolling Wheel Deflectometer (RWD) and TSD were also conducted during the period.

2.3 International Experience

2.3.1 DaRTS Workshop

There have been three DaRTS workshops held. The date and locations were:

- 18 June 2012 (London, United Kingdom)
- 27 June 2013 (Trondheim, Norway)
- 19 September 2014 (Blacksburg, Virginia, USA).

A detailed summary of the discussions at the DaRTS workshops held in 2012 and 2013 have been previously reported in other Austroads publications (Austroads 2013, Austroads 2014a). Detailed summaries of these workshops are provided in Table B 2 and Table B 3.

The third DaRTS workshop was held in conjunction with the 2014 Pavement Evaluation conference held in Virginia, USA. Many advances in the research study has been undertaken since the second DaRTS workshop. A summary of the presentations from the workshop is presented in Table B 4. A few highlights are listed as follows:

- A TRL study in 2013 explored the potential of using TSD on continuously reinforced concrete pavement (CRCP) construction. Even though it shows promise, the reporting intervals adopted were 0.1 m.
- TRL highlighted the fact that a robust equipment-calibration procedure is essential. For example, it is essential to have a fully focused and calibrated TSD Doppler laser.
- SANRAL from South Africa has built a fully instrumented site with a range of embedded sensors to monitor the surface and sub-surface motion. The fundamental differences between the FWD and TSD means that a ‘ground-truth’ reference is required.
- Federal Highway Administration (FHWA) and University of Texas at El Paso conducted field experiments at the Minnesota Department of Transportation (MnRoad) facility with different pavement types. Surface motion was recorded using geophones and accelerometers.
- University of Nevada presented the new dynamic analysis software ‘3D-Move’ which shows early promise. Side-by-side field testing between FWD, RWD and TSD was conducted. Back-calculated layer moduli from FWD were used as inputs to 3D-Move. It is noted that the software only has a model for isotropic materials.

3 POTENTIAL PROJECT-LEVEL APPLICATIONS

3.1 Introduction

In the early stage of ARRB Group's TSD acquisition, it was determined that the TSD is a cost-effective device for network assessment. The TSD collects pavement strength and condition data at traffic speeds. A deflection basin can be computed through integration of the area under a slope velocity graph (Muller & Roberts 2013).

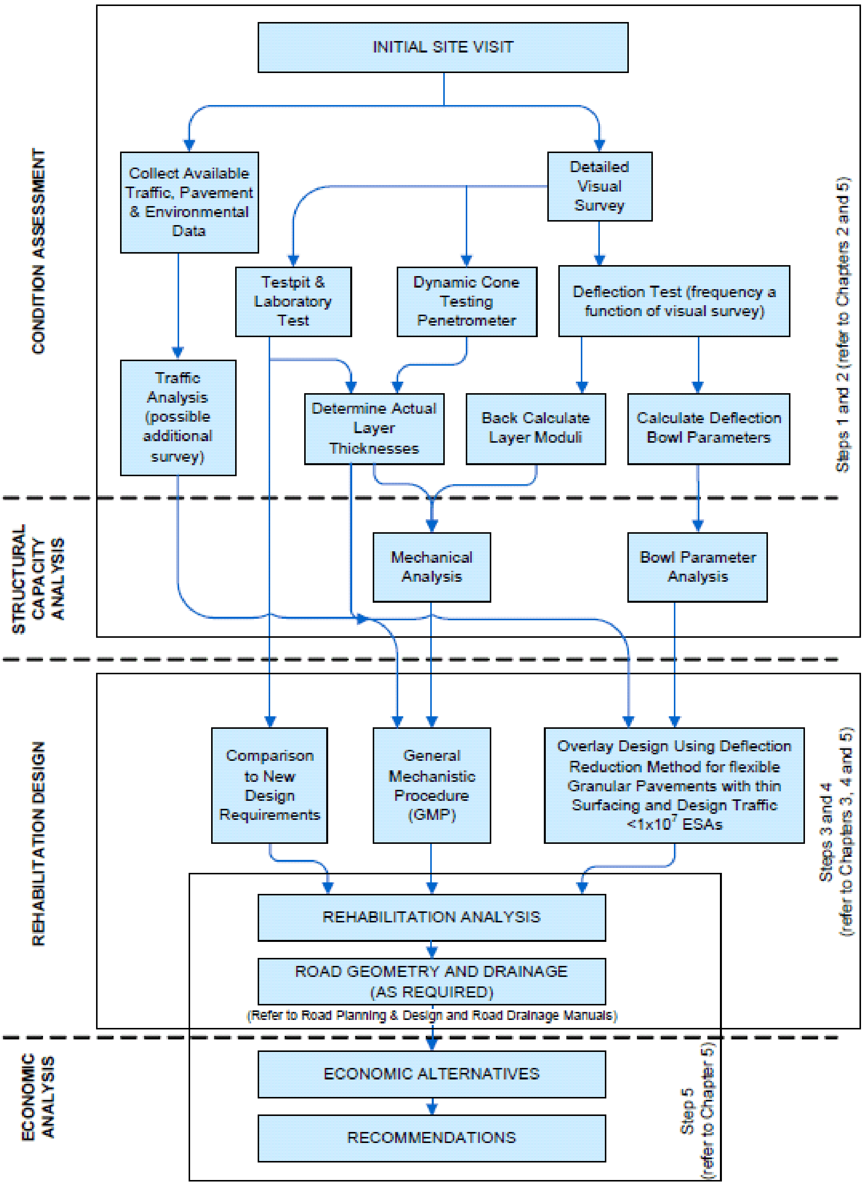
Expressing the TSD data as a deflection basin provides the opportunity to compare the deflection basin with that of other devices and potentially allows for the use of the current pavement analysis methodologies. Information provided by modern deflection testing devices goes beyond maximum deflection and curvature readings. An experienced designer can make reasonable assumptions of the pavement condition based on the shape of the deflection bowl. This study focuses on examining how TSD measurements can be applied and integrated into current pavement analysis practices. It is expected that as additional information on the operation and calibration procedures for TSDs becomes available, the accuracy of the pavement analyses should improve.

Figure 3.1 outlines a typical pavement rehabilitation process. Structural analysis can be carried out using bowl parameter analysis and/or mechanical analysis. In this section, some interim measurement correlations of TSD and FWD measurements will be presented along with identified limitations. The section will also present an assessment of the TSD for different pavement analysis applications.

3.2 Comparison of Theoretical Deflection Basins

Early in the project, it has been recognised that limited theoretical modelling work has been conducted to find out the theoretical surface deflection under a TSD. Some numerical analysis work using CIRCLY has been conducted this year and is presented in Appendix A. While the CIRCLY is a linear elastic model and can only consider static loading, this provides a good start to provide an indication of the expected TSD surface deflection bowl when different parameters of the pavement structures were changed. The analysis found that the theoretical deflection is different between the TSD and FWD, with the extent depending on the pavement types that were tested (i.e. granular pavement shows the largest differences are located near the wheel load, while the differences between the TSD and the FWD are expected to be minimal in a stiff pavement, such as a pavement with cement treated base).

Figure 3.1: Flow chart illustrating a typical pavement rehabilitation process



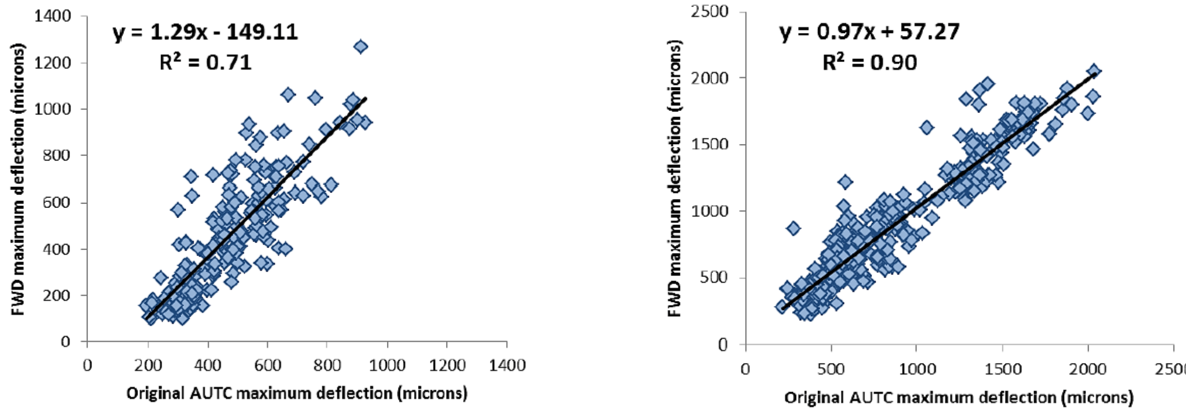
Source: Department of Transport and Main Roads (2012).

3.3 Interim Measurement Correlations

Correlations between different pavement deflection devices are important so that the existing knowledge can be used when interpreting TSD data. Presumptive correlations between FWD, deflectograph and Benkelman beam were published in the *Austroads Guide to Pavement Technology*: Part 5 (Austroads 2011).

As part of this study, published correlations from the literature as well as the 2014 TSD and FWD comparison work in Queensland are reported. In general, the TSD and FWD measurements reported were not taken at the same time. Other operational factors such as Doppler laser calibration and the evolution of analysis methods over time should also be taken into consideration. Due to the factors mentioned above, this interim correlation requires further validation and should be treated with caution. Roberts et al. (Austroads 2014b) presented correlations between the FWD and the Danish TSD system used in the 2009–10 Australian Trial (Figure 3.2). The Danish TSD used only three Doppler lasers. Another relationship determined by Muller & Roberts (2013) is presented in Figure 3.3.

Figure 3.2: Maximum deflections reported by the TSD (AUTC method) and FWD

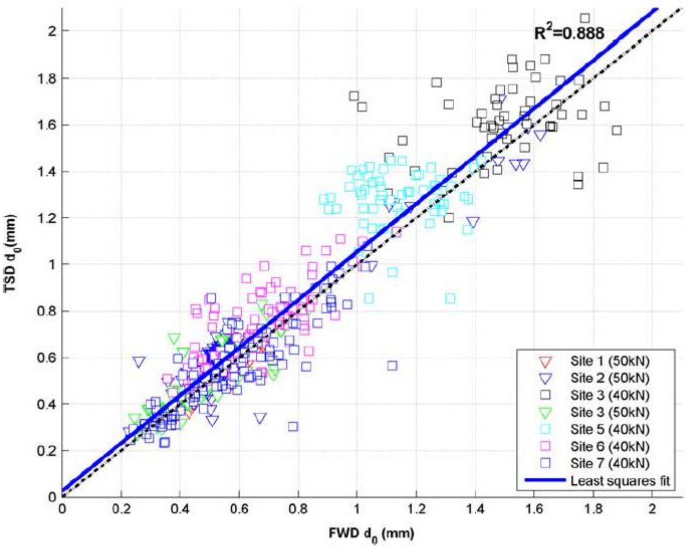


(a) NSW sites during the 2009–10 TSD trial

(b) Queensland sites during the 2009–10 TSD trial

Source: Austroads (2014b).

Figure 3.3: Maximum deflections reported by the TSD and FWD



Source: Muller and Roberts (2013).

As part of the NACOE research project, both TSD and FWD deflection data were collected on a granular pavement along the Centenary Highway. The deflection profiles are shown in Figure 3.4, and the correlation between the TSD and FWD measurements is shown in Figure 3.5.

Figure 3.4: FWD and TSD deflection profiles along Centenary Highway

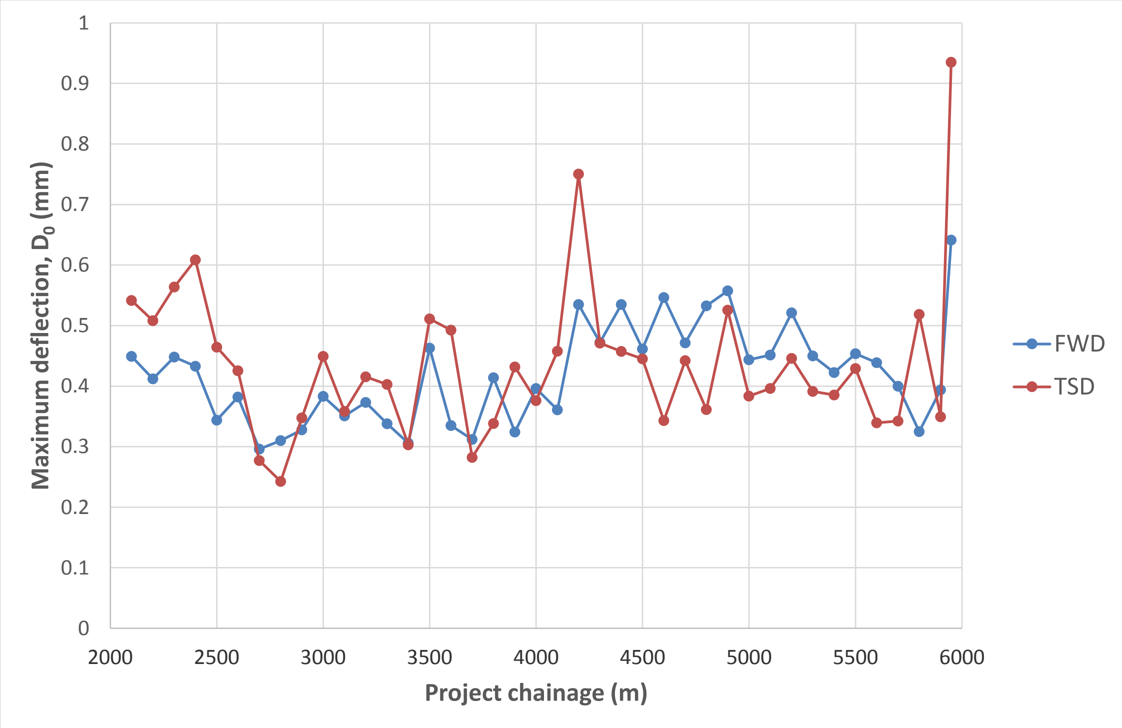
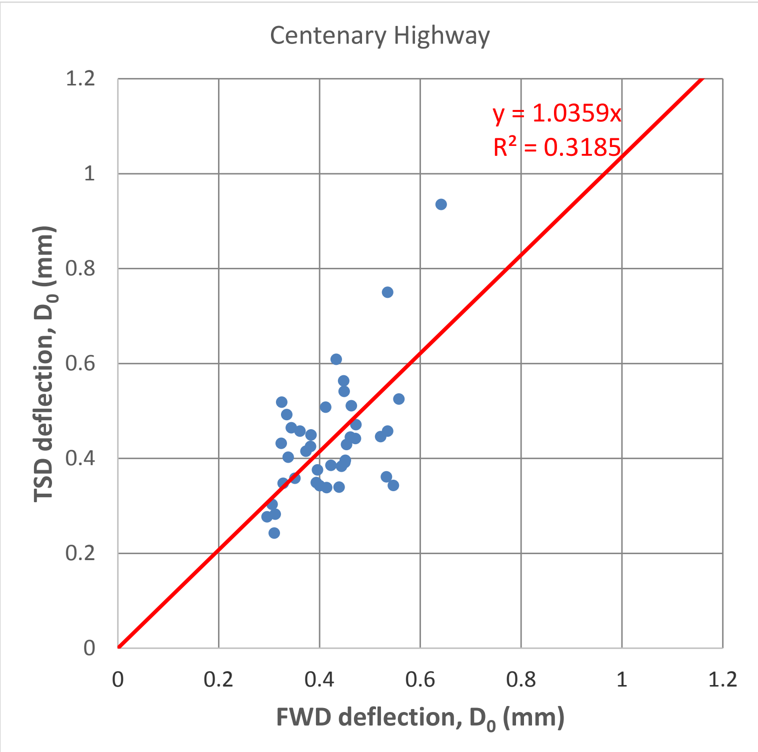


Figure 3.5: Comparison of maximum deflection measured using the FWD and TSD along Centenary Highway



As part of the NACOE research project (P2 – *Stabilisation Practices in Queensland*), four sections of the Bruce Highway, namely 10L, 10M, 10N and 10P, were tested using the FWD. These results have been compared with the TSD data collected in 2014. The 10L and 10M sites consist of cement modified base, while the 10N and 10P sites contain foamed bitumen stabilised base. The pavement thickness profiles and location information for each site are summarised in Table 3.1.

The deflection profiles and correlation plots for the sites are shown in Figure 3.6 to Figure 3.13.

Table 3.1: Pavement profile of selected stabilised pavement sites along Bruce Highway

Highway	Location	Start chainage (m)	End chainage (m)	Pavement thickness profile
10L	51 km south of Townsville	36+150	37+700	Sprayed seal 200 mm cement modified base 185 mm cement-bound subbase 300 mm stabilised subgrade
10M	Near Ingham	118+700	119+700	Sprayed seal 300 mm cement modified base 150 mm granular subbase 150 mm select fill
10N	112 km south of Cairns	123+987	123+037	Sprayed seal 250 mm foamed bitumen stabilised base 300 mm granular subbase 300 mm select fill
10P	Near Gordonvale	64+175	65+225	Sprayed seal 250 mm foamed bitumen stabilised base 100 mm granular subbase Natural subgrade

Figure 3.6: FWD and TSD deflection profiles along Bruce Highway (10L)

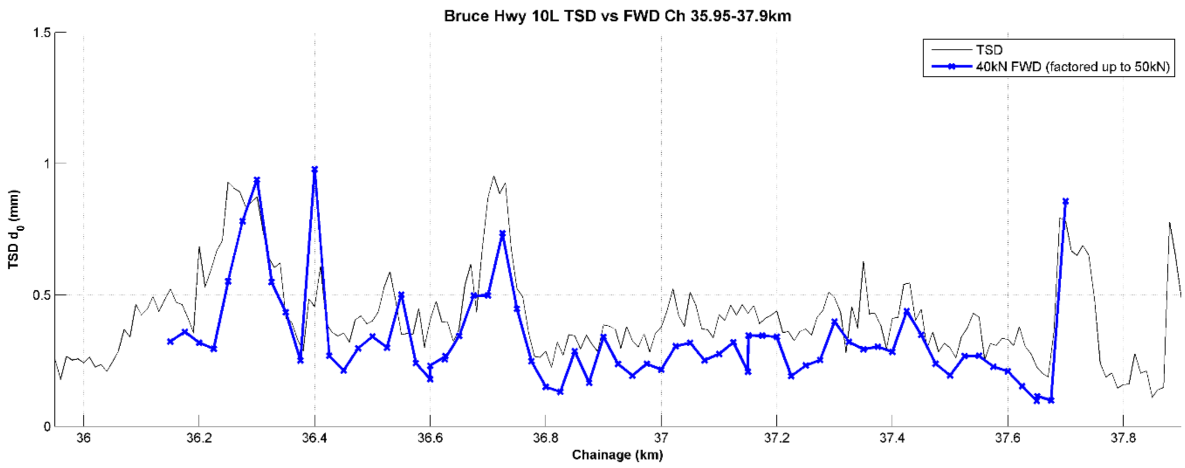


Figure 3.7: Comparison of maximum deflection measured using the FWD and TSD along Bruce Highway (10L)

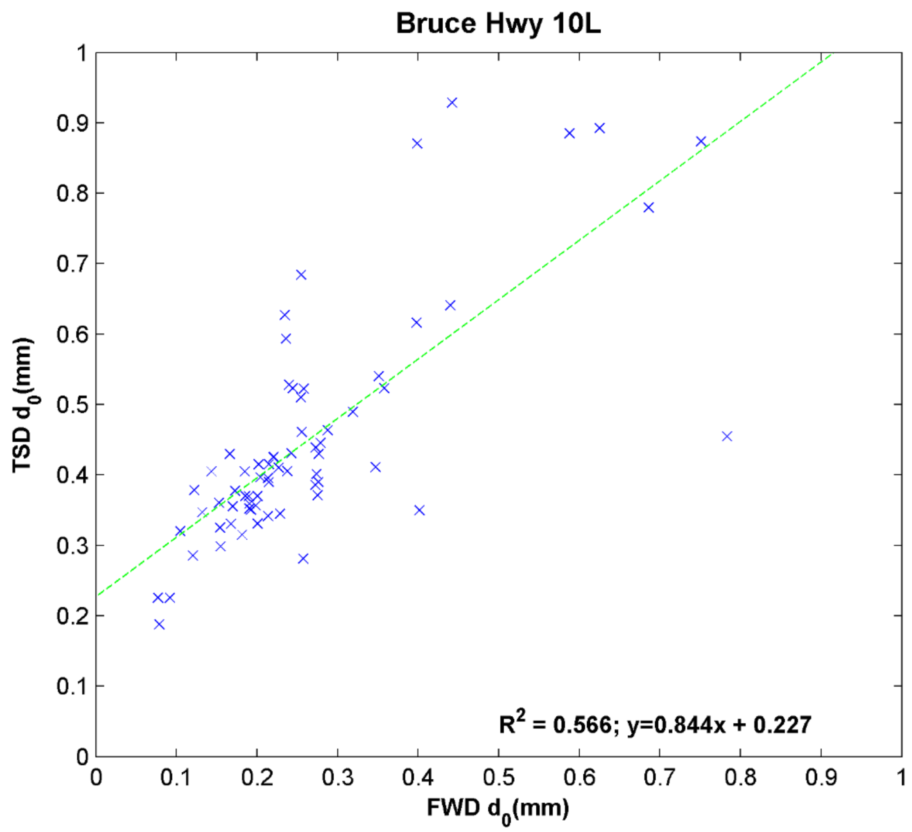


Figure 3.8: FWD and TSD deflection profiles along Bruce Highway (10M)

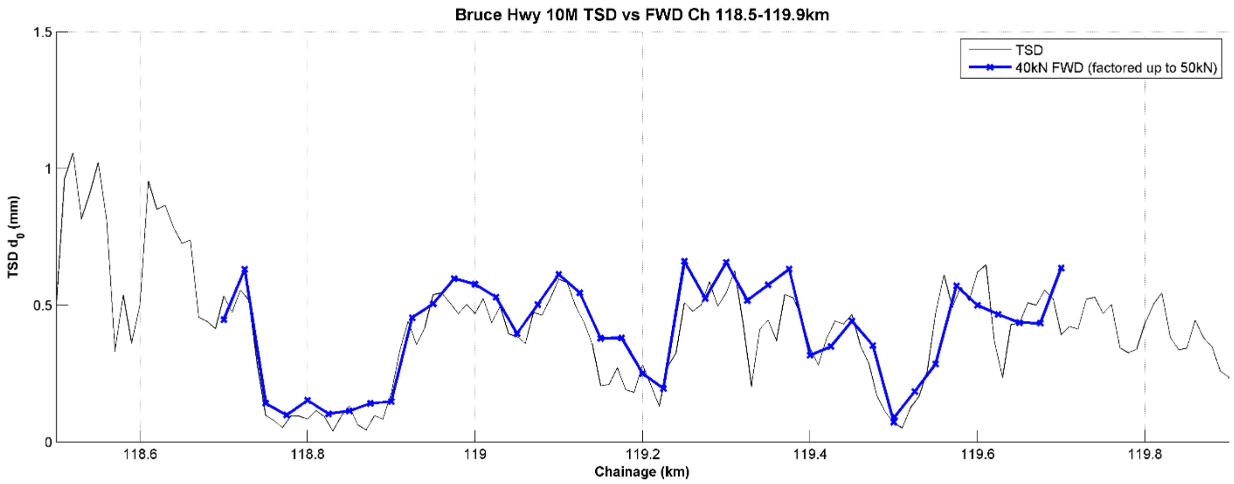


Figure 3.9: Comparison of maximum deflection measured using the FWD and TSD along Bruce Highway (10M)

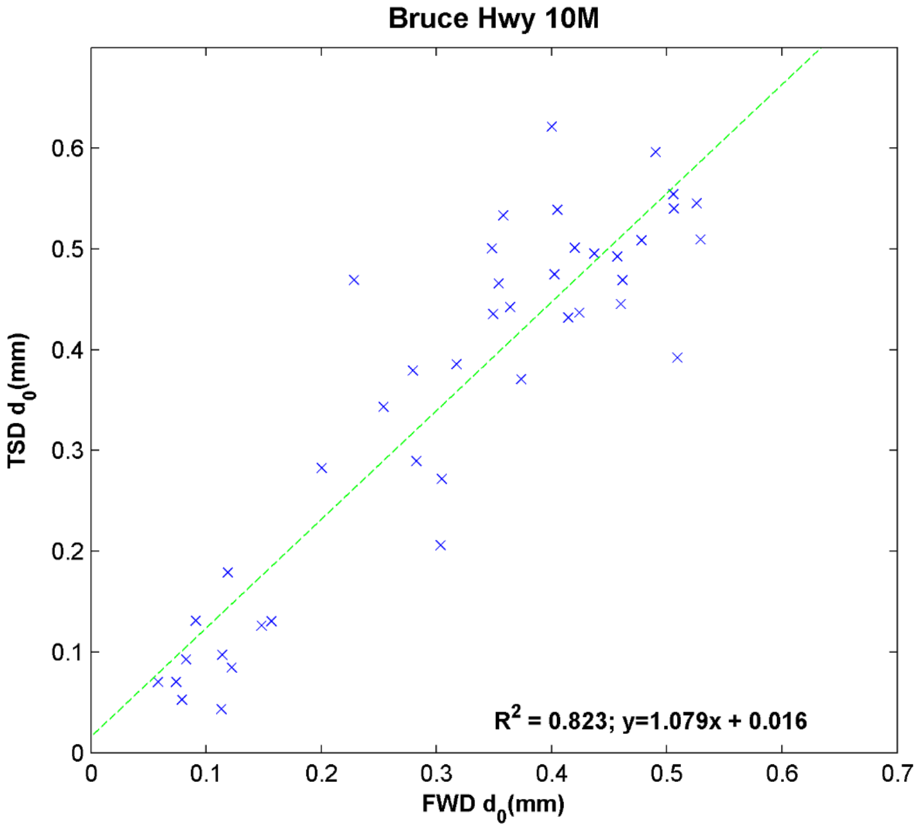


Figure 3.10: FWD and TSD deflection profiles along Bruce Highway (10N)

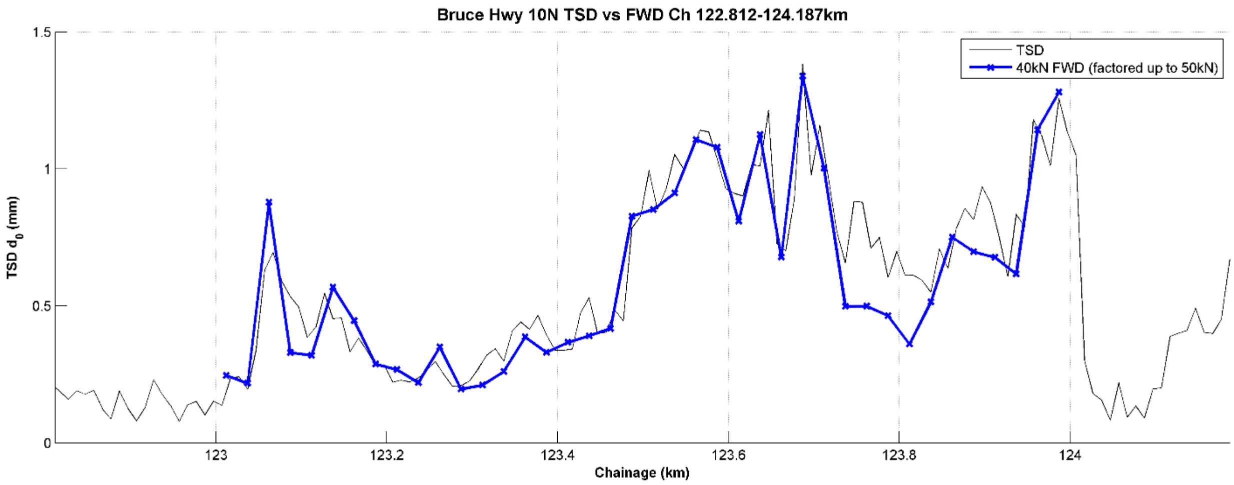


Figure 3.11: Comparison of maximum deflection measured using the FWD and TSD along Bruce Highway (10N)

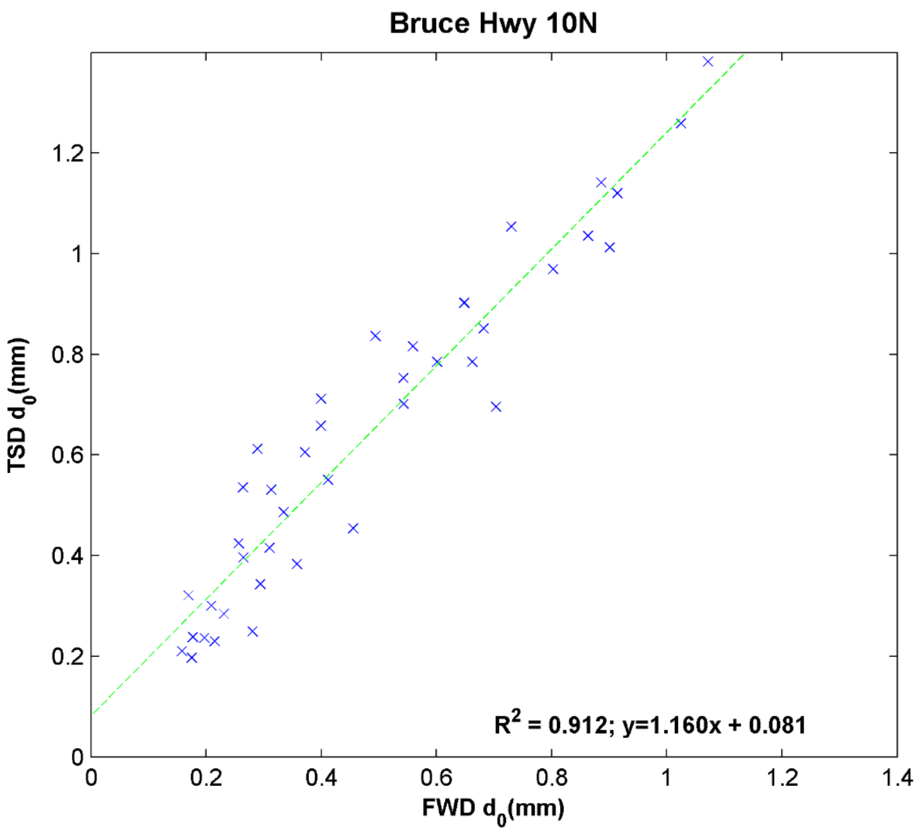


Figure 3.12: FWD and TSD deflection profiles along Bruce Highway (10P)

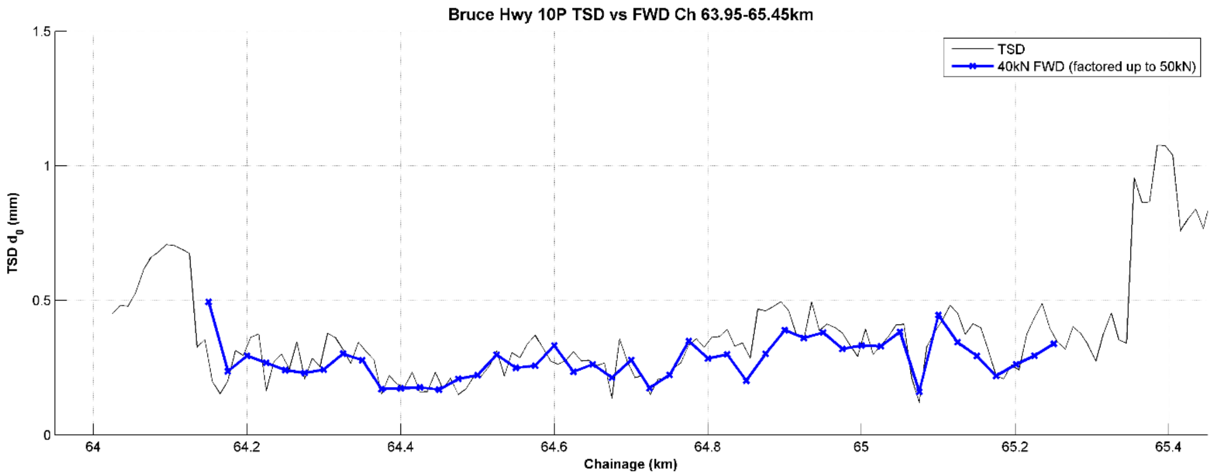
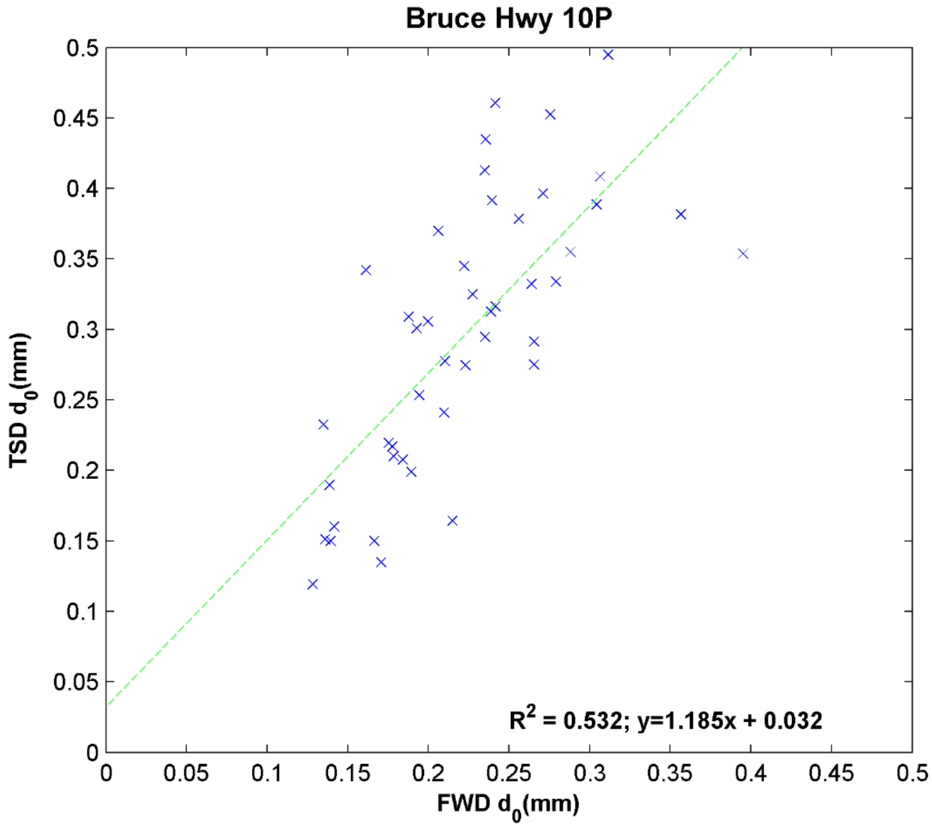


Figure 3.13: Comparison of maximum deflection measured using the FWD and TSD along Bruce Highway (10P)



A regression analysis was conducted on data from each site presented above. The correlations are summarised in Table 3.2 and should be treated as interim relationships until more robust side-by-side comparisons can be completed.

Table 3.2: Correlations of FWD and TSD data collected in 2014 and in the 2009–10 trial

State	Year of data collection	Road	Pavement type	Regression equation	Coefficient of determination (R^2)
NSW	2009–10	Various	Unknown	FWD = 1.29 TSD – 149.11 (FWD and TSD as 0.001 mm)	0.71
Queensland	2009–10	Various	Unknown	FWD = 0.97 TSD – 57.27 (FWD and TSD as 0.001 mm)	0.90
Queensland	2014	Bruce Hwy. (10L)	Cementitious bound	TSD = 0.844 FWD + 0.227	0.566
Queensland	2014	Bruce Hwy. (10M)	Cementitious bound	TSD = 1.079 FWD + 0.016	0.823
Queensland	2014	Bruce Hwy. (10N)	Foamed bitumen stabilised	TSD = 1.160 FWD + 0.081	0.912
Queensland	2014	Bruce Hwy. (10P)	Foamed bitumen stabilised	TSD = 1.185 FWD + 0.032	0.532
Queensland	2014	Centenary Hwy.	Granular	TSD = 1.0359 FWD	0.319

3.4 Technology Assessment for Pavement Applications

A state-of-the-technology review on different moving deflection devices was conducted by researchers in the USA (Rada et al. 2011). The study highlighted that structural adequacy can be an important pavement performance indicator when making pavement rehabilitation decisions. The study also identified various attributes that moving deflection devices need to have before being used for a range of pavement applications. Moving deflection devices considered include the Texas RDD, ARA RWD and UK TSD (a first-generation TSD). The four pavement applications in Rada et al. (2011) are listed as follows:

1. identification of pavement changes or anomalies
2. determination of overall pavement structural capacity indicators or indices at network level
3. determination of structural capacity of individual pavement layers at the project level
4. determination of the number of joints or transverse cracks and load transfer efficiency.

Rada et al. (2011) identified key attributes that are required for each pavement application listed in Table 3.3.

Table 3.3: Device attributes for different pavement applications

Device attributes	Pavement application			
	1	2	3	4
(a) **Precision of deflection measurements** – repeatability in multiple surveys	✓	✓	✓	✓
(b) **Accuracy of deflection measurements** – closeness to the actual or true values		✓	✓	✓
(c) **Distance between deflection measurements** – spacing of subsequent deflection readings	✓	✓	✓	✓
(d) **Reporting measured deflections** – statistical methods to report characteristic values	✓	✓	✓	✓
(e) **Measuring deflection basins** – deflection basin at multiple radial distance per test point			✓	
(f) **Layer moduli analysis capabilities** – software for determining layer moduli from the collected data			✓	
(g) **Monitoring of applied load** – load measurement capability	✓	✓	✓	
(h) **Operating speed** – operate at higher speeds than the FWD, preferably at the posted speed limit	✓	✓	✓	✓
(i) **Ancillary data** – such as air, pavement surface temperatures, accurate geospatial positions	✓	✓	✓	✓

Source: Rada et al. (2011).

In the Rada et al. study, the accuracy (i.e. closeness to the actual or true values) was not studied, however, it was noted that accuracy would have a major impact in the final decision on the applicability of the devices for project-level applications. The study also carried out an assessment on the ability of each device to meet the stated attributes. It should be noted that the study is based on the first-generation TSD, which is different from the second-generation TSD owned by ARRB Group. A number of improvements have been made in the second-generation TSD. A comparison of the ARRB second-generation TSD is presented in Section 3.4.8.

3.4.1 Precision, Distance between Measurement and Statistical Reporting

Measurement precision was being assessed in subsequent TSD trials and calibration exercises. For example, trial test sites located in NSW and Victoria were used to confirm the repeatability of the TSD in multiple surveys (Austroads 2014b).

The current post-processing software provided by Greenwood Engineering Profilograph (v1.3.229) limits the minimum reporting intervals to 10 m. In comparison, the earlier version of the software allowed operators to process data at a 0.1 m interval.

At a 10 m interval spacing, the TSD can be used for project level investigation, as inferred in the extract from the *Pavement Rehabilitation Manual* Clause 2.8.10.2 (Department of Transport and Main Roads 2012) below:

> The most commonly used test intervals for project level investigations for non-rigid pavements vary between 25 m (e.g. in urban areas or short lengths) and 50 m (e.g. for rural areas or long lengths), though this may be reduced to as low as 5 m for sections of high distress or of very short length. The maximum test interval for (non-rigid pavement project level evaluation should generally not exceed 50 m.

3.4.2 Accuracy of Deflection Measurements

The accuracy of the TSD deflection measurements refers to the comparison of TSD against a true deflection measurement (i.e. the actual pavement surface displacement). As discussed previously in this report, many factors can influence the surface deflection measurement. This generally varies with pavement types, speed or frequency of loading, temperature and seasonal variation.

One method to check the accuracy of the TSD is to compare it to other known deflection equipment. This assumes that all variables remain constant. Such side-by-side comparison allows a correlation between two deflection devices to be developed. This approach accounts for all the inherent differences between two deflection devices by simplifying them into a single parameter.

However, the more robust method to validate the accuracy of a device is to compare it with the true pavement surface motion. This is usually done by embedding sensors on the road surface and comparing the reported deflection value to the true surface motion measured.

The DaRTS workshop in 2014 reported two research groups (one in USA and one in South Africa) which have instrumented pavement sites to improve the understanding of TSD measurements. This allows TSD measurements to be compared with the true deflection measurements.

3.4.3 Measuring Deflection Basins

The ability to measure the deflection basin at multiple offsets from the load provides insight into the structural response of the pavement. However, TSD measurements are also expressed in terms of velocity slope and other parameters, such as the SCI_{300} provided by the processing software from Greenwood Engineering. The AUTC method proposed by Muller and Roberts (2013) provides a deflection at multiple offsets. This is a familiar representation, which provides compatibility with existing pavement evaluation and design methodologies. Another approach is to retain the velocity slope data for the subsequent analysis. This approach has traditionally been adopted in Europe.

3.4.4 Layer Moduli Analysis Capability

The current Austroads mechanistic pavement design method relies on CIRCLY to determine critical strains at different layers. In conducting rehabilitation designs, this calculation requires elastic moduli as inputs that are typically determined through a back-calculation process.

For project-level studies, deflection from FWD is typically used. As part of this year’s study, attempts have been made to back-calculate layer moduli using TSD deflection data collected on existing pavements that contain a bound layer (i.e. foamed bitumen stabilised base or cement modified base). This is presented in Appendix C.3 of this report.

There are many different back-calculation software programs available. Each program uses different solution-searching algorithms and different stress-strain relationships. The calculation error between different programs can be reduced by using the same stress-strain computation engine in the forward and backward modelling processes.

EFROMD developed by ARRB Group uses the same stress-strain engine as the CIRCLY. Among all the back-calculation software that are available world-wide, EFROMD is the only one that is fully compatible with the forward model within CIRCLY. Furthermore, EFROMD is capable of modelling multiple loading points and therefore can be used to model the dual-tyre-loading configuration of the TSD (whether it be a half or full axle, or the entire TSD trailer unit).

3.4.5 Monitoring of Applied Load

The ARRB TSD has dynamic load cells installed in the rear axle. At this point, the dynamic load has not been used when analysing the TSD deflection. It is recommended that the slope or deflection reading should also be normalised using the measured applied loading.

3.4.6 Operating Speed

The nominal operating speed of the ARRB TSD is currently limited to 80 km/h. However, consideration is being given to investigate the feasibility of increasing the nominal speed to 90 km/h.

Testing undertaken in Australia and South Africa studied the effect of operating speed on TSD measurement. It was found that TSD measurement is fairly stable when operating between 30 to 80 km/h.

When considering the effect of operating speed, the key quality control parameter used at the moment is the data-rate at which the Doppler laser information is obtained. Experience indicates that when the data rate drops below a certain threshold limit, the quality of the deflection results are reduced.

3.4.7 Ancillary Data

During the operation of the ARRB TSD, the measurement of other ancillary data such as air temperature, pavement temperatures and geospatial locations are important. During the deflection survey, the TSD collects information on pavement roughness, rutting, texture, cracking and road geometry. In addition to high-quality surface imagery to monitor the condition of the pavement surface, the TSD can also collect information on roadside assets such as signs, guardrails, furniture, etc.

3.4.8 Assessment of the ARRB TSD for Project-level Applications

Based on the attributes identified above, a subjective assessment of the ARRB TSD (second-generation TSD with Hawkeye system installed) was conducted and is summarised in Table 3.4. Areas of further study are also identified.

Table 3.4: Assessment of the ARRB TSD against the identified pavement application attributes

Device attributes	Section of this report	Pavement application			
		1	2	3	4
(a) **Precision of deflection measurements** ▪ repeatability in multiple surveys	Section 3.4.1	✓	✓	✓	×
(b) **Accuracy of deflection measurements** ▪ closeness to the actual or true values	Section 3.4.2		?	?	×
(c) **Distance between deflection measurements** ▪ spacing of subsequent deflection readings	Section 3.4.1	✓	✓	✓	×

Device attributes	Section of this report	Pavement application			
		1	2	3	4
(d) **Reporting measured deflections** ▪ statistical methods to report a characteristic values	Section 3.4.1	✓	✓	✓	×
(e) **Measuring deflection basins** ▪ deflection basin at multiple radial distance per test point	Section 3.4.3			✓	
(f) **Layer moduli analysis capabilities** ▪ software for determining layer moduli from the collected data	Section 3.4.4			?	
(g) **Monitoring of applied load** ▪ load measurement capability	Section 3.4.5	✓	✓	?	
(h) **Operating speed** ▪ operate at higher speeds than the FWD, preferably at the posted speed limit	Section 3.4.6	✓	✓	✓	✓
(i) **Ancillary data** ▪ such as air, pavement surface temperatures, accurate geospatial positions	Section 3.4.7	✓	✓	✓	✓

Notes:

✓ Likely to be met based on the limited data and case studies that are available.

? Further study is required.

× Not meeting the attribute requirement.

Based on the assessment above, the ARRB TSD can meet the first two pavement applications, namely, the identification of homogenous sections and the determination of overall structural capacity indicator (i.e. expressed as the maximum deflection and other deflection basin parameters).

The TSD differs from traditional deflection testing equipment in a number of aspects as discussed earlier in the report. As a result, the current design requirements for traditional devices may not be appropriate for the TSD. Adjustments to these parameters are expected to be developed as more data becomes available.

It has been shown that the ARRB TSD can possibly be used in project-level and network-level investigations, subject to more validation study.

3.5 Summary of TSD Case Studies

As part of this project, several case studies were conducted to explore the potential project-level application of TSD data. A list of the three studies is shown in Table 3.5. Detailed discussion of each case study is are presented in Appendix C.3.

Table 3.5: TSD case studies and potential project-level application

Case studies	Reference	Potential project-level applications
Centenary Highway	Appendix C.1	▪ Identification of pavement changes ▪ TSD vs FWD comparison
Landsborough Highway (13E)	Appendix C.2	▪ Identification of changes in pavement treatments ▪ Forward modelling using CIRCLY to match TSD bowl
Bruce Highway (10P and 10M)	Appendix C.3	▪ Back-calculation of elastic modulus of base layer using EFROMD3

In summary, the first case study on Centenary Highway is a granular pavement where deflections were measured using the FWD and the TSD. The TSD continuous profile shows the variability of pavement strength along the highway. Furthermore, a comparison of the results from both devices are presented. It is noted that the correlation of the maximum deflections are weak and 'side-by-side' comparison should be undertaken in future years. The second case study used TSD deflection to identify changes in pavement treatments as well as the estimation of layer moduli through forward modelling to match the measured deflection basin. Lastly, the third case study presented two stabilised sections along Bruce Highway (i.e. one with a foamed bitumen stabilised base layer and the other with a cement modified base layer). The base layer in each section was back-calculated from the TSD and FWD measurements and both show linear trends. The loading pattern of the TSD has been adopted when undertaking the back-calculation using EFROMD3, and the value obtained shows a linear trend with the moduli obtained through back-calculation of the FWD data.

The above are a few examples demonstrating the applications of TSD on real-life projects. At the simplistic level, the number and spacing interval of TSD deflection readings allow delineation and changes generally align with the locations of different pavement treatments. Forward modelling was used and the moduli obtained appear to be reasonable. More complicated analysis such as the back-calculation of pavement layer moduli should be investigated in the future.

4 SUMMARY, LESSONS LEARNT AND SCOPING FOR FUTURE YEARS

4.1 Summary

This report presents findings from the Year 1 study of the NACOE P40 – *Benefits of Traffic Speed Deflectometer Data in Pavement Analysis* research project. The objective of the project is to investigate the benefits of the TSD for pavement analysis at the project-level. The completed tasks for this year are as follows:

- a literature review on TSD
- theoretical analysis of the TSD deflection basin using Australian pavement analysis software (i.e. CIRCLY and EFROMD)
- evaluation of the TSD for a range of pavement assessment applications
- presentation of interim correlations between TSD and FWD measurements
- presentation of case studies using recently collected TSD data and exploration of different data applications
- identification of current limitations and gaps in knowledge
- determination of project scope for future years.

The study indicated that the TSD can be a beneficial pavement evaluation tool that can be used beyond that of a network screening tool. Engineers can estimate the deflection basin based on TSD measurements from the Doppler laser. This provides a range of pavement analysis tools for routine pavement analysis. Some examples include the CIRCLY and EFROMD forward-calculation and back-calculation software, that are widely used in Australia. This report presents ways that such tools can be used with TSD deflection measurements.

Fundamental differences (such as loading type, loading speed, measurement and analysis technique) in deflection devices are expected to result in different maximum deflections and deflection basin shapes. Correlations developed between different devices are limited and should not be extrapolated to other pavements without further study. These correlations should be validated as the operational and calibration aspects of the TSD continues to improve over time. It is essential that future study should include 'side-by-side' comparison of different deflection measurement devices, and where possible, 'ground truth' measurement obtained from instrumented sections to improve understanding of TSD measurements. Detailed project information such as 'as-constructed' pavement details are also essential.

In this project, different case studies using the 2014 collected data have been presented. These case studies identified different ways that TSD data can be used in project-level pavement evaluations. The findings show early promise to use TSD data for project-level applications, subject to more robust validation study in future years.

4.2 Lessons Learnt and Current Knowledge Gaps

4.2.1 Key Learnings

Key learnings in this year are listed below:

- The TSD has been seen as a network-assessment tool. This study found that TSD measurements could potentially be used for project-level applications. In the case studies presented, the TSD accurately identified changes in pavement treatments. A framework was provided to demonstrate ways to use current pavement analysis tools (e.g. CIRCLY and EFROMD) to analyse TSD deflection data. More sophisticated analytical tools, which incorporate the dynamic effect of the TSD load should be explored in the future.
- The TSD currently only measures deflection along the outer wheel path of a lane, which limits its potential usefulness for pavement rehabilitation analysis. In the future, upgrades such as measurements along the inner wheel path and increasing the number of Doppler lasers could be considered.
- The TSD has a minimum reported spacing of 10 m. This spacing is adequate for project level studies on flexible pavements and does limit the use of TSD for assessing load transfer at joints of concrete pavements.
- Analysis using CIRCLY shows that the influence zone (i.e. extent of the deflected pavement surface) varies across different pavement types. For stiff pavements, the distances to zero residual deflection are much further than in a granular pavement. This should be taken into consideration in future calibration procedures.
- Since the TSD owned by ARRB Group has dynamic load cells installed, the deflection measured by the TSD should be normalised based on the dynamic load applied.
- The TSD applies a 'real truck' load on the pavement at traffic speed. The simulation of real loading and the production efficiency of the device are two significant benefits of the TSD device.
- Doppler sensor calibration remains the top operational priority. Correlation with other deflection equipment and 'ground-truth' experiments are important for improved understanding of the TSD device. These calibrations need to be addressed in future years to facilitate increased adoption of the TSD technology.

4.2.2 Learnings from the Recent Austroads Asset Task Force Meeting

A year after the TSD commenced data collection in Australia, a workshop was organised by the Austroads Asset Task Force in Brisbane on 28 April 2015. The workshop included representatives from TMR, Roads and Maritime Services (RMS), South Australia, New Zealand Transport Agency and staff from ARRB Group. The workshop summarised lessons learnt and the current state-of-the-technology of the TSD from various perspectives including the TSD operator (ARRB Group), road agency users (TMR and RMS) and researchers actively involved in TSD development.

The key topics of discussion at the workshop are summarised in Table 4.1.

Table 4.1: Summary of lessons learnt and current knowledge gaps

Category	Issues	Solutions identified (if any)
OPERATIONS		
Equipment/maintenance	Equipment improvements e.g. cooling unit, distance measurement instruments, synchronisation of geospatial data etc.	Faulty sub-components were either replaced or modifications made. Greenwood Engineering has adopted some of these modifications and retrofitted components in other TSDs.
Calibration	1. Limitations of current Greenwood Engineering calibration procedure. 2. Doppler sensor focus. 3. Effective field calibration procedure is necessary. This requires identification of sites that are flat, uniform, provide low deflections and have proper cross fall.	Need further improvements to the field calibration procedure. This would allow the TSD operator to undertake calibration of equipment across different states. The Doppler laser requires regular calibration to maintain accuracy. Properly focused Doppler laser affects the data rate. Calibrations are repeated at known sites and are being monitored. Additional information from Greenwood Engineering on the background of the calibration process in their software would be beneficial.
Data rate dropout	For the TSD to provide reliable results, the data rate needs to be maintained above a certain threshold level. A significant drop in data rate (e.g. in the case of over a wet or shiny fresh asphalt surface) usually leads to a drop in reported deflection value.	Properly focused Doppler laser can minimise data rate dropout.
Dynamic force measurement	The current analysis does not take into account the dynamic load measurement.	Observations so far indicate that the variation in measured dynamic force is insignificant over the 10 m reporting length, which is within 4% error.
Measurement repeatability	Deflection and individual sensor readings show good short-term repeatability at a range of operating speeds.	
TSD operating speed	Currently, the TSD is limited to an operation speed of 80 km/h.	ARRB Group will investigate the possibility of operating at 90 km/h.
ROAD AGENCY USERS		
Draft test method for TSD	Standard operating criteria need to be established to provide a baseline for subsequent years.	ARRB Group is in the process of drafting a test method to document the current testing procedure.
Productivity	Long distance of non-survey mileage accumulated.	Improve planning of survey route to optimise the testing circuit.
ANALYSIS TECHNIQUES		
Zero velocity assumption at zero offset	Measurement indicated that at zero offset from the centre of the dual-tyres single axle group, the velocity measurement is not equal to zero.	Consider the use of additional Doppler laser sensors, and/or move beam behind the dual-wheel assembly.
D_{900} sensor	There is a check in place to limit the D_{900} value to no larger than two-thirds of the D_{600} sensor measurement.	Improvement of the current analysis technique or including additional sensor in the future should be considered.

4.3 Scoping for Future Years

Building on the knowledge and data collected in Year 1, the TSD shows early promise for pavement analysis although an improved understanding of the technology is required. Future works proposed for Year 2 of this project are summarised in Table 4.2.

Table 4.2: List of tasks proposed for Year 2 of this study

Task	Description
Task 1: Refine project scope	Hold meeting with TMR to discuss project scope at the beginning of Year 2.
Task 2: Design experimental plan	It is envisaged that trial sites will be selected and confirmed with TMR based on the attributes to be studied. Some of the trial sections will be instrumented to provide a 'ground-truth' comparison. In addition, a sub-network will be selected for application in an asset management system.
Task 3: Conduct experiment	Set up and conduct experimental work. This will include a side-by-side comparison of several deflection devices. Site instrumentation work will form part of the experiment to better understand the operational characteristics of the TSD. The experimental work will be split across Year 2 and Year 3 of this project.
Task 4: Analyse data from experimental work	Collect data and analyse on selected sites.
Task 5: Compare Year 1 and Year 2 TSD data	For a selection of pavement sites and sub-networks, TSD deflection collected in Years 1 and 2 from the Queensland network will be compared.
Task 6: Draft interim report summarising findings from Year 2	The deliverables at the end of financial year 2015–16 will be presented in a draft interim report, which will be incorporated in the final year report.
Task 7: Scoping for Years 3 and 4	Based on the experimental findings and subsequent analysis, undertake scoping work for Years 3 and 4.

In this study, it has been demonstrated that the TSD can be more than a network assessment tool. Early work shows that it has fairly good linear correlation with a FWD, a common deflection testing device used for project-level works. Some of the interim correlations presented in this report should be validated with 'side-by-side' equipment validation, and in the future, compare it with 'ground-truth' surface deflection measurement. These future works will increase confidence in wider adoption of the technology by the pavement engineering community.

Limited analysis using CIRCLY and EFROMD3 shows some early promise of applying traditional analysis techniques to this technology. This should be considered as the first step to improve understanding of the TSD measurements, to support the empirical observations in the field with mechanistic models. However, the question remains whether current static analysis can adequately model a moving wheel load of a TSD at 80 km/h. Other dynamic analysis packages such as 3D-Move developed in the USA could be explored to account for the effects of dynamic loading on measured surface deflections.

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APPENDIX A NUMERICAL MODELLING OF TSD LOADS

A.1 Introduction

The response of pavements under traffic load can be complex and often cannot be adequately modelled using currently available tools. However, it is important to use the available mechanistic tools to provide some guidance for interpretation of TSD measurements. Mechanistic tools also provide another way to compare the pavement responses from different deflection testing devices.

A.2 Modelling TSD Load and Comparison with a FWD

A.2.1 CIRCLY – Multi-layer Linear Elastic Theory

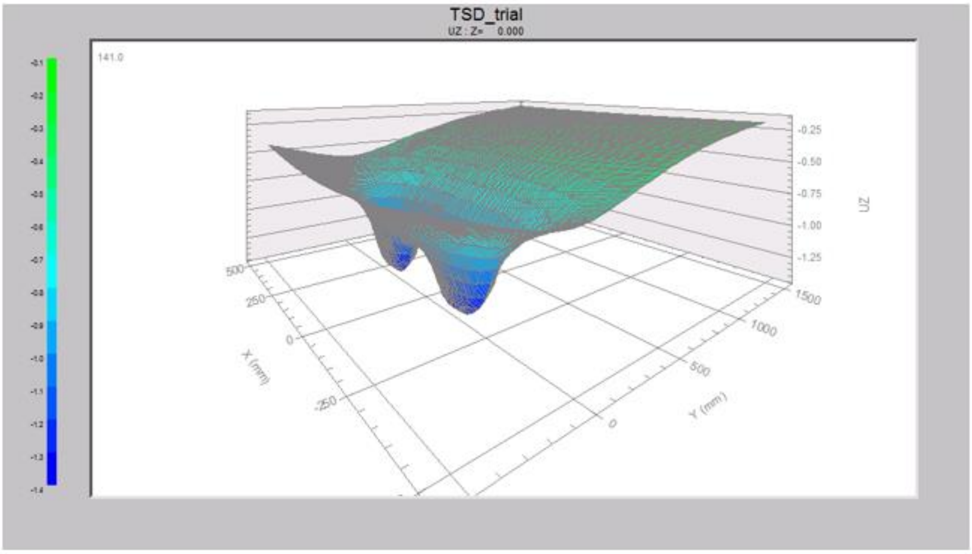
There are multiple mechanistic analysis software programs available to model the surface pavement response from a static loading. For the preliminary analysis, CIRCLY, the widely used software in Australasia, was adopted. For decades, CIRCLY has been incorporated into the current Austroads mechanistic-empirical design approach. Even though the software is based on a linear elastic model and does not directly take into account the material non-linearity and dynamic loads, the results from CIRCLY provide a good baseline to improve the understanding of TSD measurements.

Surface deflection profiles were computed for the TSD and the FWD on a granular pavement as shown in Figure A 1. The configuration of the granular pavement is listed in Table A 1. Both devices applied a nominal 50 kN load with the FWD loading distributed over a 300 mm diameter circular loading plate and the TSD loading spread over the two dual tyres for each half of the rear axle. Based on this preliminary computation, it is expected that for this particular granular pavement, the measured maximum response from both devices will be different.

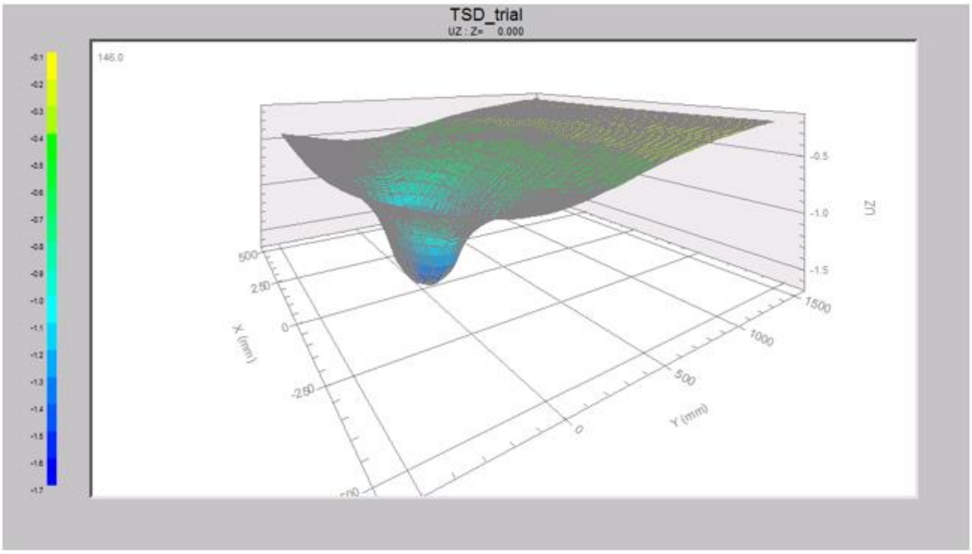
Table A 1: Pavement profile of granular pavement

Material	Anisotropy (Ev/Eh)	Austroads sub-layered (Austroads 2012b)	Thickness (mm)
Granular base (E = 350 MPa)	2.0	Yes	200
Granular subbase (E = 150 MPa)	2.0	Yes	400
Subgrade CBR 5% (E = 50 MPa)	2.0	No	Infinite

Figure A 1: Computed surface deflection of a TSD and FWD loading over a typical granular pavement



(a) Typical TSD deflection (Uz = vertical displacement) profile

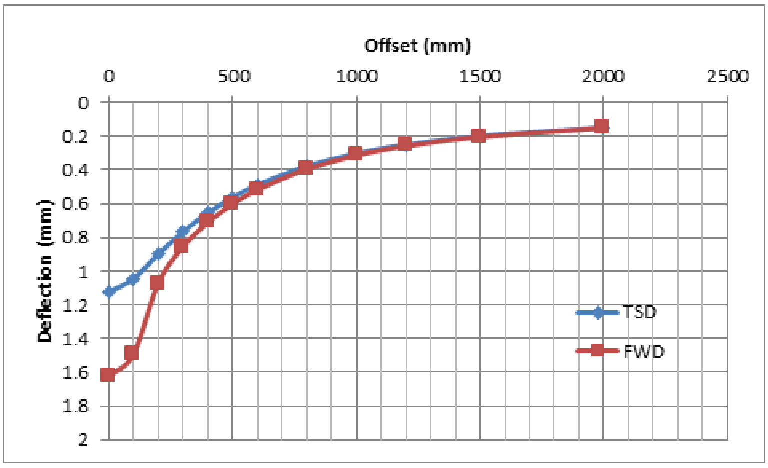


(b) Typical FWD deflection (Uz = vertical displacement) profile

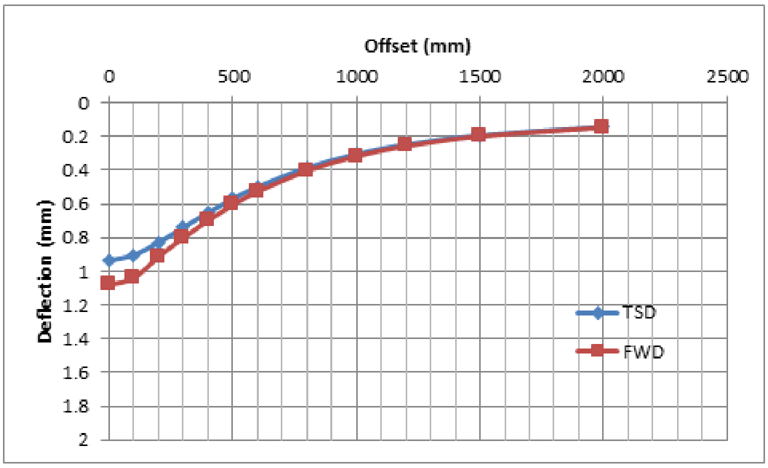
Similar to the above analysis, theoretical surface deflections of the FWD and TSD for different pavement types are shown in Figure A 2 and Figure A 3. Observations from the analysis are as follows:

- For a granular pavement, the theoretical surface deflections are expected to be different between a TSD and FWD. In a static analysis of flexible pavements, the deflection bowls from the two devices are more similar in stiffer pavement structures (i.e. full depth asphalt and cemented treated base pavements) than in a flexible granular pavement structure.
- The full TSD trailer can be modelled in CIRCLY, as shown in Figure A 3. The stiffer pavement structure has a flatter bowl and therefore the zone of influence from the front and rear axle of the TSD trailer may extend further into the centre of the trailer. These aspects need to be considered in the selection of the location for calibration of the Doppler Laser. It is anticipated that at a 3.5 m offset from the rear axle, the residual deflection is negligible.

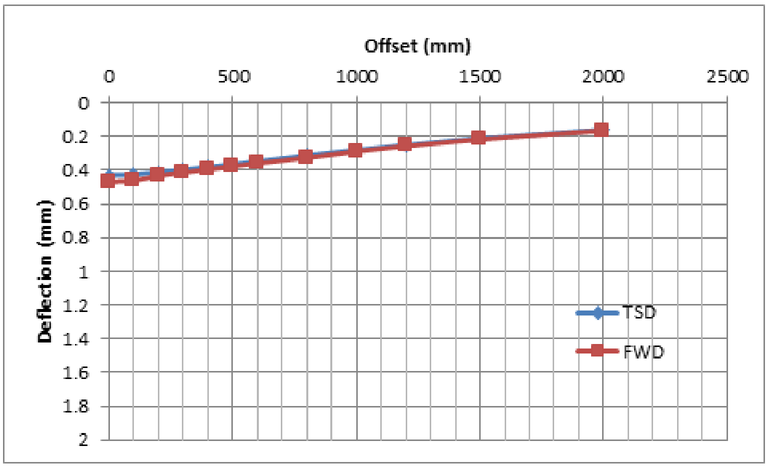
Figure A 2: Computed deflection profile for different pavement types using CIRCLY



(a) Granular pavement

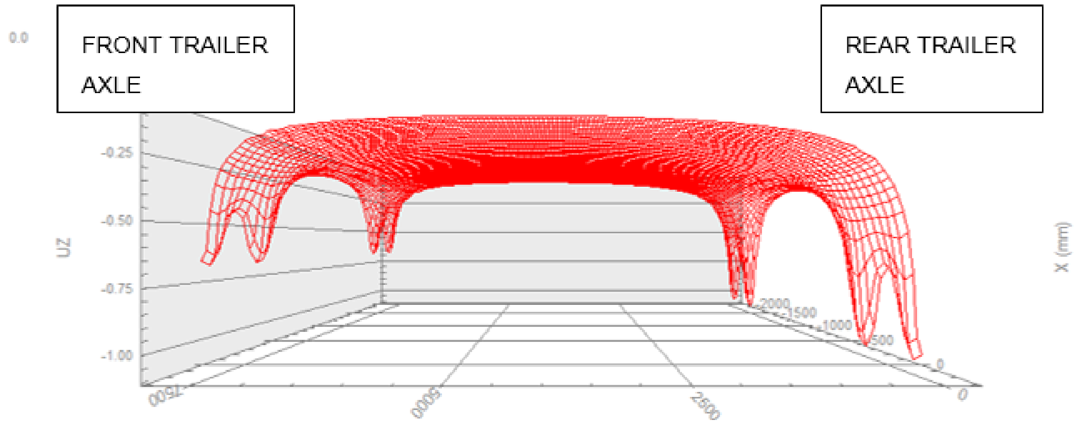


(b) Full depth asphalt over granular working platform

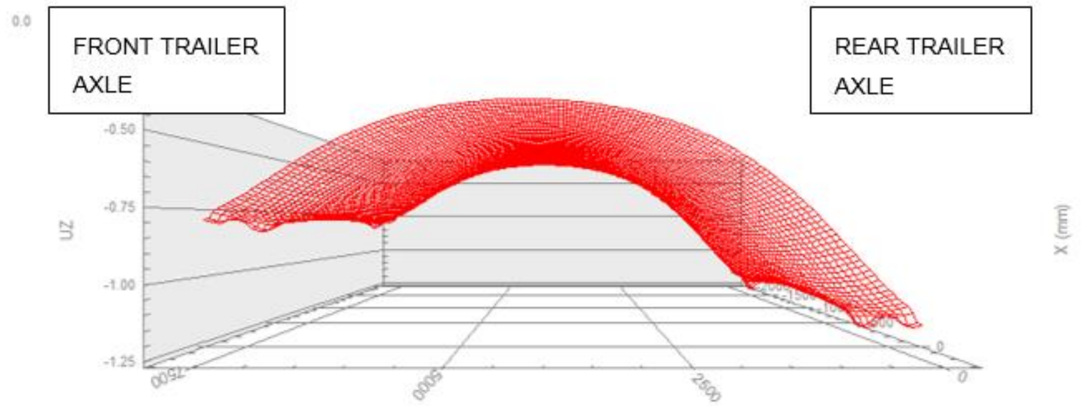


(c) Cement treated base over granular working platform

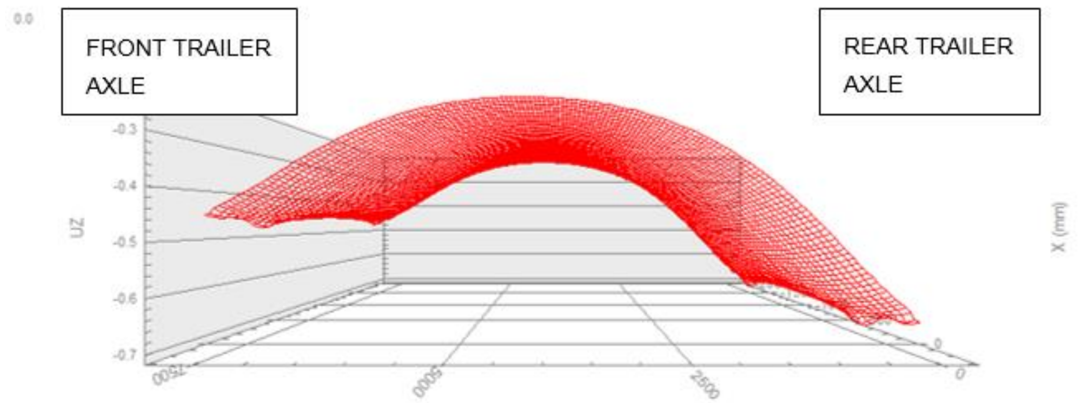
Figure A 3: Deflection contour of the TSD trailer computed using CIRCLY



(a) 300 mm granular pavement



(b) 300 mm asphalt pavement



(c) 300 mm cement treated base pavement

APPENDIX B SUMMARY OF RELEVANT LITERATURE

This appendix is a brief summary of relevant literature reviewed during this study. Table B 1 summarises work on TSD as reported in different Austroads publications. Subsequent discussion during meetings held at the DaRTS 2012, DaRTS 2013 and DaRTS 2014 workshops are presented in Table B 2, Table B 3 and Table B 4.

Table B 1: Austroads publications related to the TSD

Publication	Topics	Details
AP-R395-12 (*Review of the Traffic Speed Deflectograph – Final Project Report,* Austroads (2012a))	Australian TSD trial 2009–10	Summary of TSD use on NSW and Queensland road networks over the 2009–10 Australian summer. 18 000 km of road network scanned
	TSD operation	TSD technology is effective and capable of measuring a pavement's response to load at traffic speeds up to 80 km/h.
	Design application	Shows considerable promise as an input into the design of granular overlays on existing granular pavements. The use of TSD data for design of flexible overlays on other flexible pavement types is not considered currently possible.
	Repeatability	Studies on mainly asphalt pavements encountered in Denmark and the UK indicated the TSD can provide reliable and repeatable measurement of the deflection response to pavement loading.
	Pavement types – full depth asphalt	European arterial, highway and motorway flexible pavement structures almost exclusively contain significant amounts of asphalt and the use of unbound materials within pavement structures is largely limited to foundation layers.
	Deflection parameters – D_0 and SCI_{300}	Early attempts to estimate maximum deflection from TSD data proved unreliable; however, the Danish Road Directorate (DRD) found that by using the TSD-SCI_{300} model and only selecting test samples generating a TSD-SCI_{300} over 50 it could produce a reliable TSD-D_0 estimate suitable for the RTA's purpose.
	Repeatability	TSD shows very good repeatability in the short-term under the same operating and environmental conditions (i.e. vehicle speed and temperature).
	Material properties – effects of speed	It is known that the stiffness of asphalt is dependent upon the speed of loading, with higher stiffness realised at higher loading speeds. The effect on surface deflections caused by changes in asphalt stiffness would depend on the thickness of the asphalt in the tested pavement.
	Reporting length	TRL has recently advised that 1 m is now their base reporting length for surveys as whilst the data still contains some noise, a longer length (and an increased averaging/smoothing of data points) risks losing information useful for some applications. Noted that the latest Greenwood Engineering software does not allow reporting intervals below 10 m.
	Dynamic load	Strain gauges were attached to the rear axle of the Danish TSD to measure wheel loads for a previous DRD/BASt) TSD study. These gauges remain on the DTSD and were used to obtain dynamic wheel loads for the Danish TSD at the NSW trial sites.
	TSD testing speed	It was considered important to be able to replicate the testing in Australian conditions for both asphalt and spray sealed granular flexible pavements, some testing at different survey speeds (40, 60 and 80 km/h) was undertaken in the trials.
	TSD-D_0 correlation	In the limited testing of the RTA trials, the modelled TSD-D_0 has shown excellent correspondence to the Deflectograph maximum deflection, D_0, and a lesser but still strong correlation to FWD D_0.

Publication	Topics	Details
AP-T217-12 (*Benefits and Risks of Investing in Network Level Deflection Data Collection,* Austroads (2012c))	Cost of network strength assessment	A study to illustrate the cost-effectiveness of a traffic speed deflectograph to assess long length of road network. The cost of measuring pavement deflection using a FWD device varies depending on the measurement spacing adopted, while the cost of using the TSD depends on the level of its utilisation.
	Network strength assessment	TMR (Queensland) – screening to define 'weak' road segments is the most likely first application. Department of Transport (DOT) Northern Territory – screening is seen as the prime function of network deflection data. The two main drivers for network-level assessment of pavement strength found from the survey in order of preference are: (i) as a screening tool to identify and locate weaker and inadequate pavements for further detailed investigation; and (ii) for estimation of pavement rehabilitation and reconstruction budgets.
	Benefits of TSD data collection	Potential for a higher quality deflection data collection with very short sampling intervals (20 mm) along the road network to give a better understanding of structural conditions and improved decision making. A non-destructive test that simulates the impact of real heavy vehicle traffic on pavements.
	Risk of TSD data collection	One of the prime concerns is the relationship of TSD estimated deflection data to the deflection data produced by the FWD. This is a concern where the FWD deflections have been used historically to estimate the remaining pavement service life from traffic loading. However, this may not be a long-term concern once ongoing network surveys are in operation.
	Integration method – TSD vs FWD	Preliminary results using the integration method of the velocity slope data appears promising, although the physical nature of the TSD and FWD deflection tests is distinctly different as FWD testing involves a stationary impact test load and TSD testing involves a wheel load moving at highway speed.
	Survey respondents – opportunities identified from network level strength assessment	Survey respondents identified opportunities from network strength assessment as follows: ▪ as a screening tool to identify the weak and vulnerable pavements ▪ estimation of major rehabilitation and reconstruction budgets ▪ estimation of heavy vehicle pricing or charging for axle mass increases above current legal or agreed limits ▪ for calibration of road deterioration models ▪ as a basis for project-level design of rehabilitation and maintenance works.
	Future work	Survey respondents indicated future work can include: ▪ development of relationships between TSD and FWD deflections ▪ the influence of collecting deflection data at speeds less than 70 km/h on the reliability of the data collected under these conditions in urban areas ▪ Doppler lases of the TSD could be located at the positions closer to the wheel load and be progressively spaced further away ▪ inclusion of Doppler lasers in both inner and outer wheel paths.
AP-T246-13 (*State-of-the-art Traffic Speed Deflectometer Practice*, Austroads (2013))	DARTS workshop held in the UK in June 2012	Summary of discussion at the DaRTS workshop 2012 (Table B2).

Publication	Topics	Details
AP-T279-14 (*Traffic Speed Deflectometer: Data Review and Lessons Learnt*, Austroads (2014b))	FWD and TSD	A correlation study of the maximum deflection measurements from the FWD and TSD. This correlation confirmed that the TSD can differentiate between weak and strong pavement structures for typical Australian and New Zealand flexible pavements. It was noted that the correlation between the FWD and TSD measurements varies across the NSW and Queensland sites.
	AUTC method	The development of the AUTC method provides a basis for replacing the TSD manufacturer's estimate of vertical deflections, and therefore confirms that the TSD can give a reliable means for obtaining equivalent FWD deflection data that is understood by practitioners.
	TSD assessment for Australasia	As part of this project, extensive assessments of Australian TSD data were made using the available data from NSW and Queensland. The assessment focused on issues relevant to TSD data on flexible sprayed seal granular pavements which are often characterised by high macrotexture, occasionally high roughness and a number of measurement issues, such as repeatability, speed sensitivity, reporting length and accuracy.
AP-T280-14 (*Traffic Speed Deflectometer: Data Analysis Approaches in Europe and USA Compared with ARRB Analysis Approach*, Austroads (2014a))	DaRTS workshop held in Norway in June 2013	Summary of discussion at the DaRTS workshop 2013 (Table B3).

Table B 2: Summary of discussions from the 2012 DaRTS workshop

Topic	Discussions
Distinction between network-level and project-level deflection assessment	The purpose and use of deflection data for network and project-level: **Network-level:** Serviceability, structural strength. Asset evaluation, set budget levels, derive performance indicators, identify schemes, and set priorities. **Project-level:** Maintenance/rehabilitation treatments, confirm priorities.
Australian experience	Entire network-level surveys are not routinely conducted. TSD measurement could resolve traffic management and non-continuous issues. It is anticipated that FWD measurement (project-level) will still be needed for small, low speed areas. FWD produces a precise full deflection bowl for use in back-calculation, which is a key element of Austroads general mechanistic procedure. Accounting for dynamic load measurements (from axle strain gauge data) improves deflection measurement from multiple runs. The integration approach to TSD analysis was discussed with workshop participants.
Belgian experience	The curvimeter meets the current Belgian needs for assessing the pavement at the project-level. This process is similar to the Australian overlay design method used to estimate remaining service life.
Danish experience	Denmark previously used SCI_{300} (D_0-D_{300}) measured by a FWD as an indicator of bearing capacity of a road. It was expected that by end of September 2012 the TSD data will be used instead of the FWD data.

Topic	Discussions
German experience	Nine sites were tested with TSD, GPR and field cores. The aim was to see if a combination of these technologies could be used to determine the thickness of thick asphalt pavements across the network. Maximum FWD deflection data provided some match to layer thickness. However, SCI_{300} measured from the FWD and TSD provided contradictory rankings of pavement 'strength'.
Italian experience (ANAS)	ANAS has been investigating the use of the TSD to assess new pavement construction. The parameter IS200 and IS300 obtained from the FWD has been used in the past. Parallel testing has been conducted using both the FWD and TSD data to gain confidence in using the TSD for this purpose.
UK experience	The Highways Agency (HA) in UK has been using the TSD as a screening tool to identify pavements that could potentially be classed as long-life. Other than the main traffic lanes, the device was also used to survey the entire length of hard shoulders on the motorway network, allowing identification of shoulder areas that would need upgrading to be able to withstand full traffic loading. Possible approach for using the TSD as a tool to estimate critical deflection/strains based on a pavement model was discussed. The strain would be correlated with network condition. Some early trials were conducted to investigate using the TSD data to assess rigid pavement performance. Early results show promise for determining load transfer based on TSD measurements. In particular, the ability of the beam to reposition sensors to either side of the load presumably lead to a more direct assessment of load transfer.
USA experience	It was noted that near-continuous deflection data has only recently become a practical reality and issues of reporting interval and frequency of collection are still yet to be resolved.

Source: Austroads (2013).

Table B 3: Summary of discussions from the 2013 DaRTS workshop

Topic	Discussions
TSD comparison trial in Denmark	TSD machines from Denmark, Italy, Poland and South Africa participated in a comparison trial (over three days). The trial involved comparing results from the different machines at four different speeds on two sections of road which were denoted as 'soft' and 'stiff' sections. This was supplemented by FWD deflection testing carried out every 5–10 m. The length of drying period required after rain was also assessed. TSD machines tested on both weak and strong pavement sections showed good repeatability over a range of test speeds between 20 to 80 km/h. It was noted that regular sensor calibration is important.
Australian experience	ARRB acquired a second generation TSD for pavement strength measurement. It was noted that, overall, the AUTC approach achieved TSD deflection bowls closer and more consistent with conventional FWD bowls. This does not imply that the response from the TSD and FWD should always match, as the pavement structure can affect the responses from different deflection devices and therefore the correlations between them.
Belgian experience (BRRC)	The French-designed Curvimeter is used to estimate consumed and remaining capacity.
German experience	The BASt conducted trials to show good spatial repeatability of the measured dynamic load.
South African experience (SANRAL)	The acceptance testing of SANRAL's second generation TSD shows high repeatability of deflection measurements that are generally independent of testing speed (between 20–80 km/h), pavement roughness, pavement stiffness and surface texture. The SANRAL machine has nine Doppler lasers. It was found that the old firmware applies a 25 sample moving average filter and removing this part of the processing algorithm produced less noisy results. The firmware upgrade has been made for all TSD owners. Comparison between the TSD and FWD demonstrated that a direct one-to-one correlation does not exist. Differences in contact pressure patterns were believed to be one of the possible reasons. More instrumented pavement sections are being built.
UK experience	TRL is to conduct further research for HA in UK. This includes improving deflection correction and analysis procedures; comparison with deflectograph data, study of TSD data on strain under bound pavements. Furthermore, this includes evaluation of joints in rigid pavements using a second generation TSD.
USA experience	Field trials to be conducted by the FHWA using a RWD and TSD device.

Source: Austroads (2014a).

Table B 4: Summary of presentations at the Pavement Evaluation 2014 conference, and discussions at the 2014 DaRTS workshop

Topic	Discussions
Evaluating the performance of new and in-service pavements in Italy using high speed non-destructive testing (Drusin 2014)	ANAS has used the TSD for final approval of work since 2009 and for the determination of pavement bearing capacity. Performance indicators include IS200 and IS300, which are corrected and reported to standard conditions (14 °C). Measurements are continuously recorded but averaged every 10 m by applying a 12 tonne loaded wheel travelling at 80 km/h.
How do first and second generation TSDs compare – results of a UK trial (Ferne 2014)	Different trials were carried out to compare the first and second generation TSDs. TSDs from different organisations are often configured with different sensor offset spacings. Short term repeatability is good, although long term repeatability requires further investigation. The slope measurement from the sensor at a 300 mm offset is often used by TRL. It was highlighted that a robust methodology for calibrating and quality auditing surveys is essential if meaningful measurements are to be collected.
Network structural surveys in the UK – current status and future European developments (Ferne et al. 2014)	In 2007, TRL studied the use of TSD slope measurement at 100 mm offset and did a correlation study with FWD load transfer efficiencies (LTE) over a 20 m long road with jointed concrete pavement. The measurement was undertaken at a travelling speed of 10 km/h. In 2013, TSD surveys on CRCP construction were carried out. The study indicated promising results but further investigation is required. The reporting intervals of the measurements are 0.1 m. TSD showed responses to joints in thin concrete pavement that correlated with LTE from the FWD. Furthermore, early results from a feasibility study on the use of the TSD to assess the condition of thick in-service concrete pavements showed promise.
Evaluation of the TSD in Germany (Jansen 2014)	BASt has conducted evaluation of both first- and second-generation TSDs. TSD evaluation among ‘rolling devices’ showed good results. Discussion about considering uneven loads and dynamic loads has to be undertaken. A comparative study in 2014 was undertaken using the second generation TSD equipment. The pavement comprised 29 cm of asphalt base over 15 cm of cement stabilised subbase, and unbound lower subbase. The reported D_0 value showed TSD had a lower magnitude than the corresponding FWD measurement.
Verification of TSD measurements using instrumented pavements in South Africa (Kannemeyer et al. 2014)	A site acceptance test was carried over a range of parameters (speed 20–80 km/h, roughness IRI 0.8–6.0 m/km, deflection D_0 0.1–1.5 mm, macro texture depth (MPD) 0.7–3.0 mm). Comparison between the TSD vs the FWD indicated similar deflection patterns, however, it appeared that there was a shift in sensor position. In general, the FWD measurement was higher than the TSD D_0 measurement. It was noted that although the FWD has been around for some time, it cannot be a ‘true’ reference measurement for accepting TSD measurement. Some factors such as the constructed FWD basin is an artificial composition of the peak measurement from the FWD sensor time history. Furthermore, the FWD rubber buffer between the drop weight and the loading frame is temperature sensitive and has been reported to have an effect on the pulse duration. Instrumented sections were built with a range of embedded sensors. MDD showed the ‘pinching’ effect of the 100 mm sensor. This effect was more significant in a granular pavement than a full depth asphalt pavement. Measurements suggested that for speeds between 30–80 km/h, TSD measurements represented an ‘elastic’ response. For test speeds below 30 km/h, the surface deflection increased exponentially due to visco-elastic behaviour of material. Deflection at the reference sensor 3.5 m is not zero, but the slope is close to zero. It is crucial to have a properly focused and calibrated TSD Doppler laser. TSD is not just a network deflection scanning tool.

Topic	Discussions
Network level structural evaluation with the TSD device – overview of TSD testing with seven state DOTs (Katicha 2014)	Presented the on-going study of using the TSD for network level structural evaluation in seven state DOTs. The objective is to incorporate TSD results into pavement management system (PMS). A number of topics for further investigation were identified, such as: 1. the selection of appropriate deflection parameters for DOT's decision making 2. estimation of structural number (SN), remaining service life, surface curvature index (SCI), strain in asphalt layer 3. applicability of TSD measurement for CRCP and JCP.
Road scanning v2.0: Preliminary results from updated TSD and NM-GPR technologies (Muller 2014)	The use of the TSD and noise-modulated GPR in combination for pavement assessment was investigated.
Evaluation of accuracy and precision of highway speed deflection devices (Nazarian 2014)	The objective was to assess, evaluate and validate the capability of RWD and TSD for pavement structural evaluation at the network level. The testing was conducted at the MnRoad facility with a variety of pavement and sensor types. Time histories from In-ground sensors were collected using geophones and accelerometers. The TSD results were averaged over 10 m intervals, while the RWD measurements were averaged over 15 m intervals. Coefficient of variation (COV) measurements for a range of deflection levels were reported for different sensor offsets. Higher deflection levels generally corresponded to lower COV values. It was also reported that at higher IRIs, the COV was also lower for TSD measurement. Further study and investigation is required.
Investigation of applicability and use of a pavement response model with high speed deflection devices (HSDDs) (Siddharthan et al. 2014)	FHWA project DTFH61-12-C-00031 used a range of field deflection data to calibrate the results from the finite element model, 3D-Move. Consideration is given to address vehicle velocity, non-stationary loading as well as normal and shear forces. Calibration using field data formed part of the project. During the field testing, FWD, RWD and TSD were used. The layer moduli were back-calculated from FWD and used as inputs for 3D-Move. The computed displacements were then compared with the measurements made in the field using geophones.
Network level pavement structural evaluations – a way forward (Sivaneswaran 2014)	Assessed a range of traffic speed deflection devices to determine if these devices meet minimum requirements for structural evaluation of pavements at the network level.
TSD acceptance testing in Australia (Wix 2014)	Presented the acceptance testing results from commissioning ARRB Group's TSD in Australia.

APPENDIX C DETAILS OF CASE STUDIES

Three case studies illustrating potential project-level applications of TSD data are presented below:

- Centenary Highway – comparison of FWD and TSD deflection data on a new heavy-duty unbound granular pavement
- Landsborough Highway – evaluation of TSD as a tool to identify changes in pavement treatments at a flood-restoration project
- Bruce Highway – examination of using TSD data in back-calculation analyses for pavements containing cement treated or foamed bitumen stabilised layer.

C.1 Heavy-duty Unbound Granular Pavement – Centenary Highway

The project is a TrackStar Alliance partnership between the Queensland government and local contractors. The road section comprises base and sprayed seal trial sections including approximately 4.65 km of the northbound alignment between project chainages 1530 and 6180. The trial pavement consists of a double seal, HSG base and Type 2.3 subbase constructed over the existing subgrade. The pavement works were initiated in June 2013 and completed in October 2013.

FWD and TSD data were both collected in 2014. The maximum TSD and FWD deflection along the Centenary Highway is shown in Figure C 1. The deflections are also plotted against each other in Figure C 2.

Figure C 1: Maximum deflection measured using a FWD and TSD along Centenary Highway

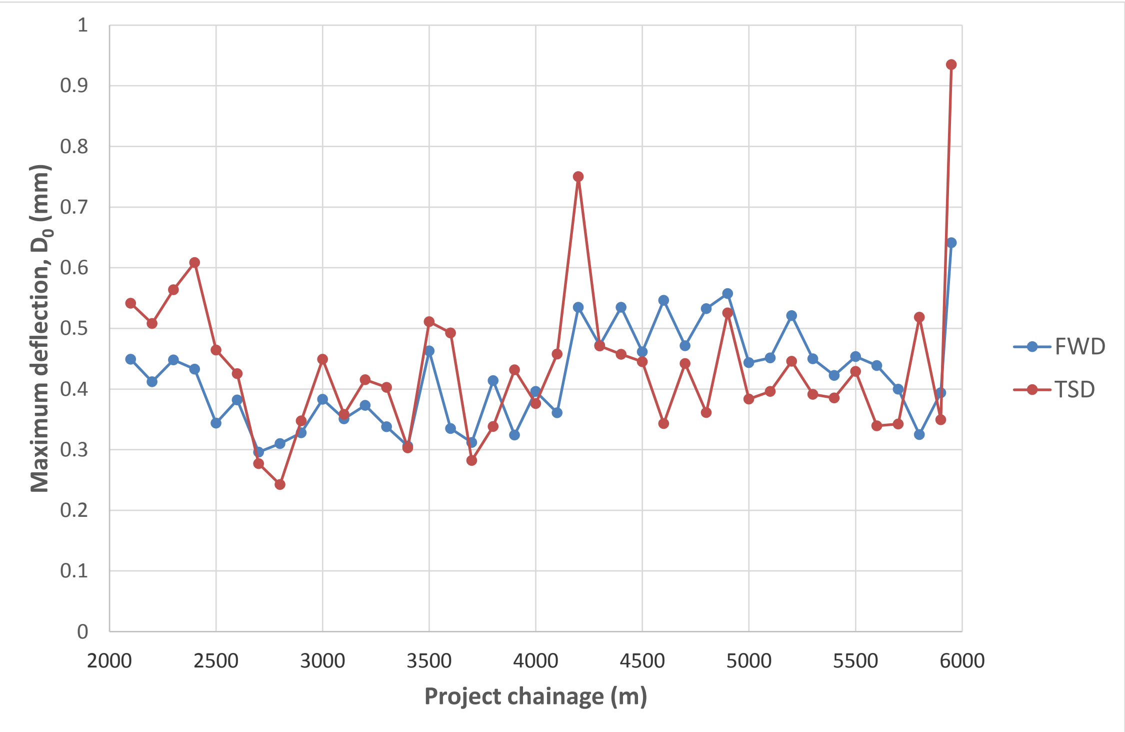
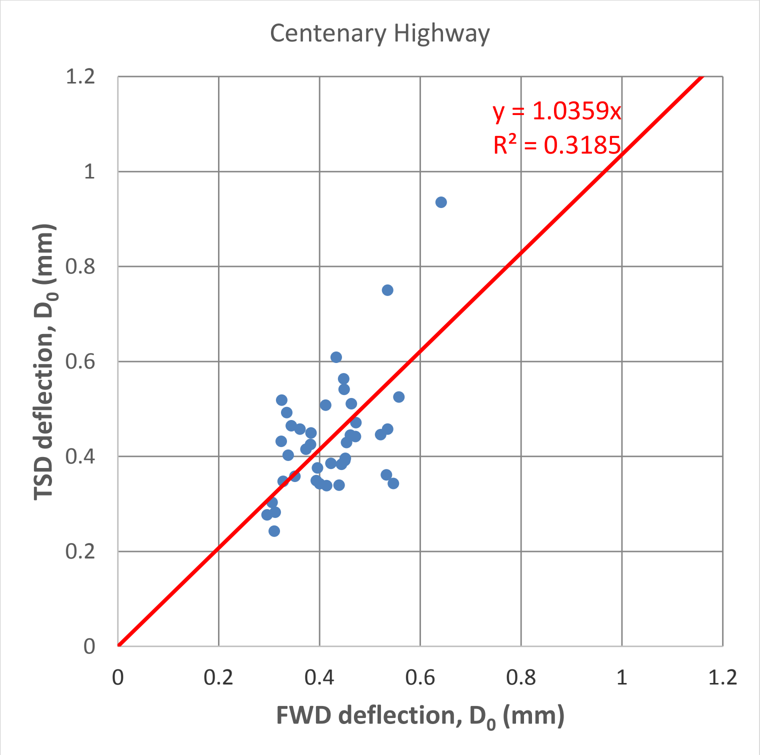


Figure C 2: Measurement correlation between a FWD and TSD along Centenary Highway



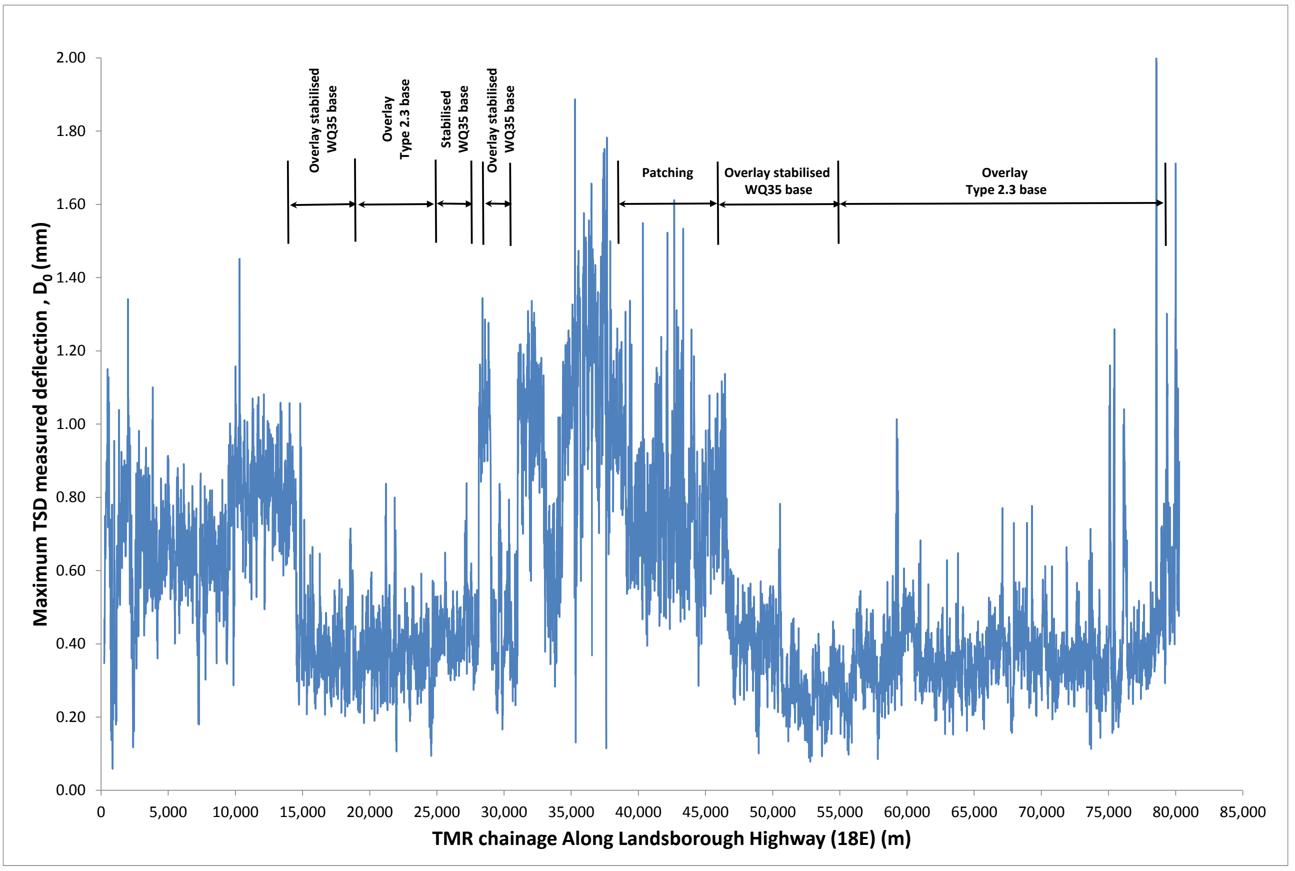
C.2 Landsborough Highway (13E)

As part of the extensive flood restoration program significant portions of the Landsborough Highway in Central West Queensland were rehabilitated. In total, there were 110 km of reconstruction and widening, as well as 114 km of full width stabilisation of existing pavement along this highway. In the 2014 annual TSD deflection survey, deflections were collected in the gazettal chainage along 13E (Landsborough Highway, Barcaldine to Longreach) on 26–27 June 2014.

C.2.1 Identify Changes of Pavement Treatments

The TSD maximum deflection (D0) along approximately 80 km of the Landsborough Highway (18E) is shown in Figure C 3 together with the associated pavement treatments. As expected, lower deflections were measured in sections where the pavements have been overlaid or in situ stabilised. Sections which did not receive any pavement treatment generally have high deflections. It is also noted that where maintenance works, such as patching, have been carried out, the deflections are usually higher than sections where full-width rehabilitation works were carried out.

Figure C 3: Maximum TSD deflection along Landsborough Highway 13E (Barcaldine to Longreach)



C.2.2 GMP – Forward Modelling

While it can be useful to identify different pavement treatments by inspecting the TSD measured deflections, this approach does not help to fully utilise the deflection basins measured by the TSD. One way to evaluate the TSD deflection is to undertake forward modelling to match the measured deflection basins. By knowing the pavement thickness profiles and associated material types, the deflection basins can be computed (i.e. forward modelled) using CIRCLY by assuming different elastic layer moduli. In this case study, five profiles from different sections along the Landsborough Highway were analysed. Details of the five selected profiles are summarised in Table C 1.

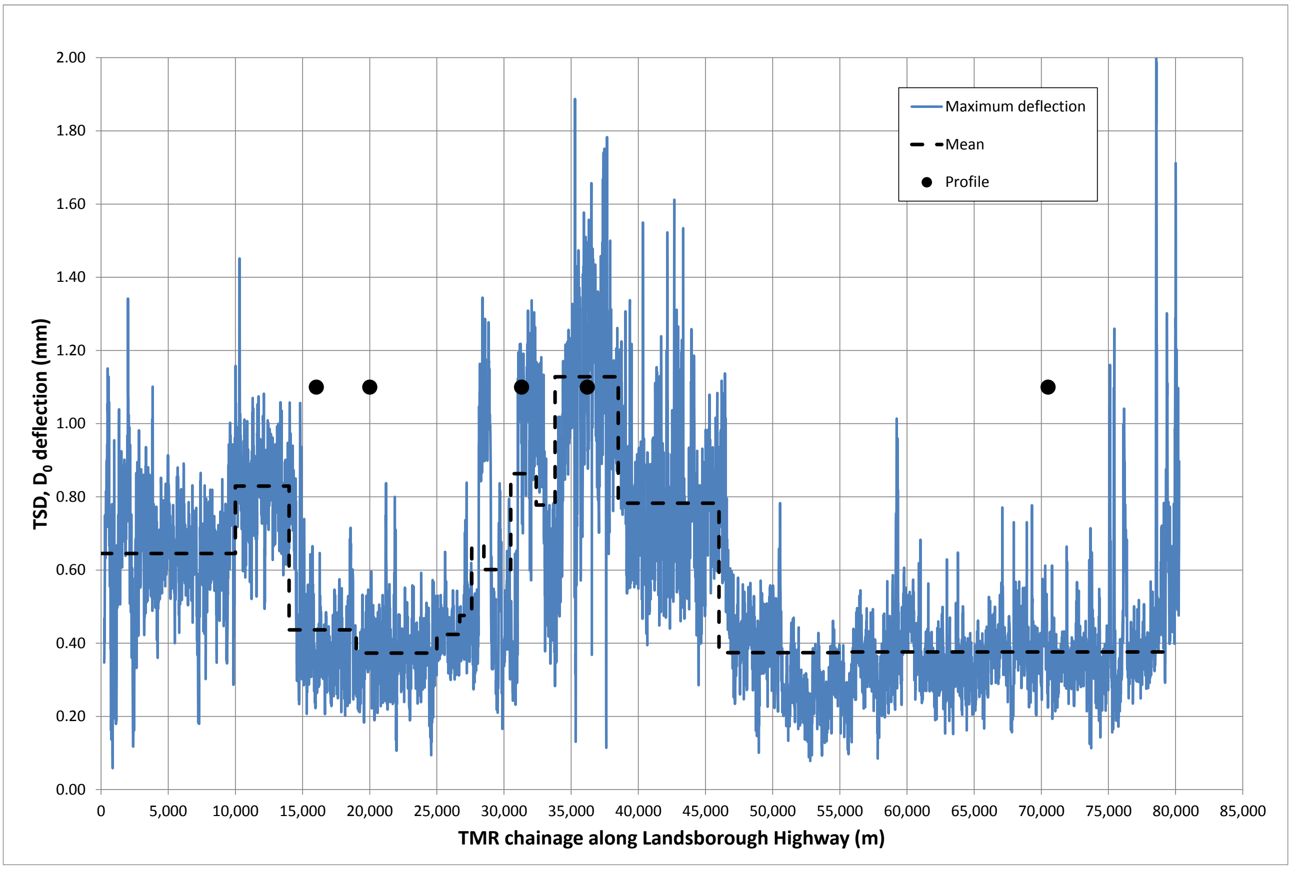
Table C 1: Selected TSD profiles for input to GMP

Profile	Chainage (m)	Treatment summary	CIRCLY layer model
1	16 020	Overlay stabilised WQ35 modified base 200 mm cement modified subbase	150 mm cement modified base 200 mm cement modified subbase 100 mm remaining granular Subgrade
2	20 000	Overlay Type 2.3 base 200 mm cement modified subbase	150 mm cement modified base 200 mm cement modified subbase 150 mm remaining granular Subgrade
3	31 310	No treatment	250 mm existing granular base 100 mm existing granular subbase Subgrade

Profile	Chainage (m)	Treatment summary	CIRCLY layer model
4	36 200	No treatment	150 mm existing granular base 250 mm existing granular subbase Subgrade
5	70 500	Overlay Type 2.3 base 200 mm cement modified subbase	150 mm cement modified base 200 mm cement modified subbase Subgrade

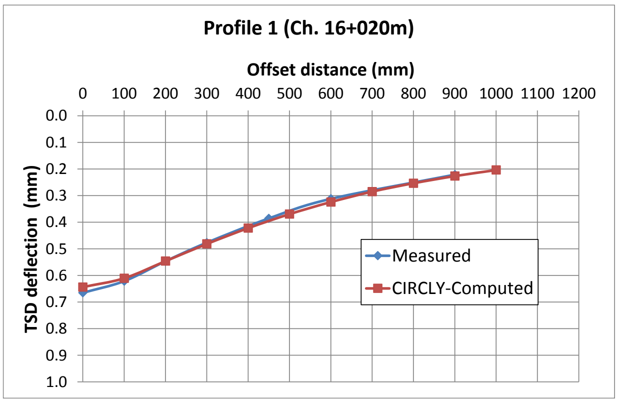
The locations of these five profiles are shown in Figure C 4 and each represent different types of pavement treatments adopted. As no pavement treatment was reported for Profiles 3 and 4, the deflection basin is expected to exhibit typical granular pavement behaviour. The other profiles contain a cement modified layer in the base and/or subbase, which are anticipated to provide a stiffer pavement structure and lower deflection values.

Figure C 4: Locations of selected profiles for GMP

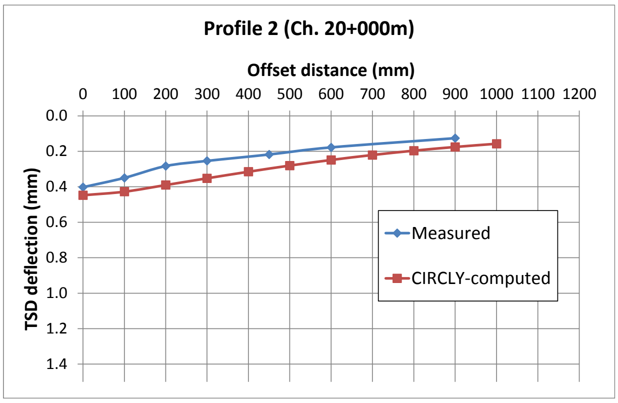


The material properties of each layer were computed in CIRCLY (using a trial-and-error method) to match or approximate the measured deflection basin from the TSD. Selected measured and computed profiles are presented in Figure C 5.

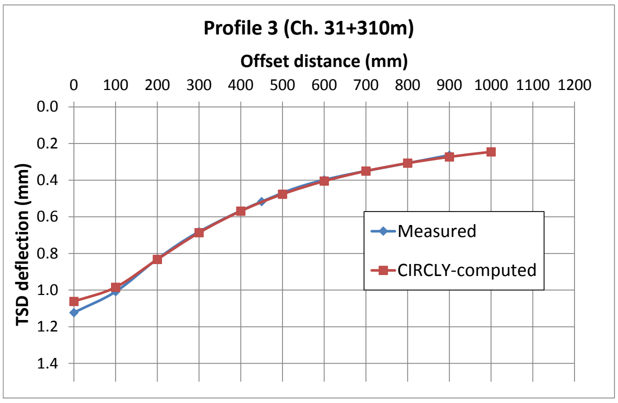
Figure C 5: Comparison of TSD measured deflection profile and CIRCLY computed profile at selected chainage stations on Landsborough Highway (13E)



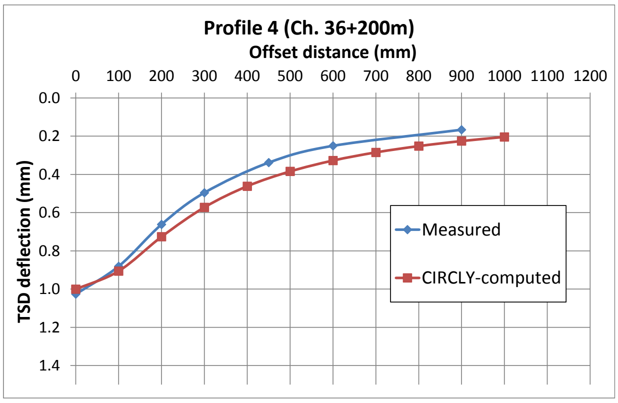
(a) Station 16+020 m



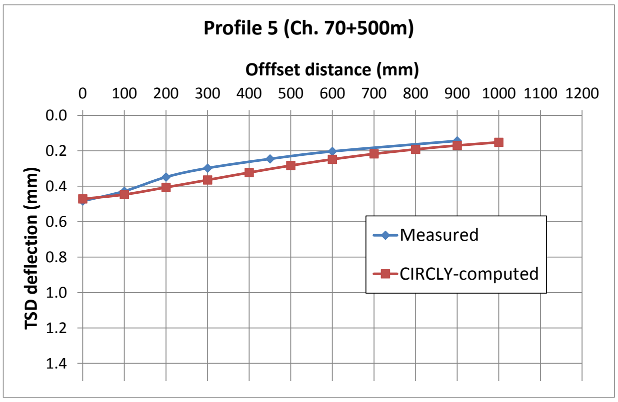
(b) Station 20+000 m



(c) Station 31+310 m



(d) Station 36+200 m



(e) Station 70+500 m

The material properties used in CIRCLY to obtain the deflection basin fits are summarised in Table C 2. The results demonstrated that the TSD deflection profiles can be reasonably modelled based on the material identified in the pavement design report.

Table C 2: Forward model of CIRCLY to match selected TSD profiles

Profile	Chainage (m)	Pavement layers	CIRCLY model
1	16+020	150 mm cement modified base 200 mm cement modified subbase 100 mm remaining granular Subgrade	Cement bound E = 500 MPa Cement bound E = 700 MPa Granular (sub-layered) E = 250 MPa Austroads subgrade E = 150 MPa
2	20+000	150 mm cement modified base 200 mm cement modified subbase 150 mm remaining granular Subgrade	Cement bound E = 700 MPa Cement bound E = 2000 MPa Granular (sub-layered) E = 150 MPa Austroads subgrade E = 200 MPa
3	31+310	250 mm existing granular base 100 mm existing granular subbase Subgrade	Granular (sub-layered) E = 350 MPa Granular (sub-layered) E = 250 MPa Austroads subgrade E = 120 MPa
4	36+200	150 mm existing granular base 250 mm existing granular subbase Subgrade	Granular (sub-layered) E = 350 MPa Granular (sub-layered) E = 150 MPa Austroads subgrade E = 150 MPa
5	70+500	150 mm cement modified base 200 mm cement modified subbase Subgrade	Cement bound E = 700 MPa Cement bound E = 2000 MPa Austroads subgrade E = 150 MPa

C.3 Bruce Highway Stabilised Sections

The third case study examines the potential use of TSD data in back-calculation of pavement layer moduli. The case study includes selected sections of stabilisation along the Bruce Highway. This information was collected as part of the NACOE P2 Stabilisation Practice in Queensland Project. Table C 3 provides a summary of the location, traffic volume and indicative pavement profiles information which was used in the analysis.

Table C 3: Traffic and indicative pavement profiles for selected stabilised sections of the Bruce Highway

Highway	Location	Start chainage (m)	End chainage (m)	Traffic volume	Indicative pavement profile
10L	51 km south of Townsville	36+150	37+700	AADT = 5211 vpd %HV = 16%	Sprayed seal 200 mm cement modified base 185 mm cement-bound subbase 300 mm stabilised subgrade
10M	Near Ingham	118+700	119+700	AADT = 6991 vpd %HV = 15%	Sprayed seal 300 mm cement modified base 150 mm granular subbase 150 mm select fill
10N	112 km south of Cairns	123+987	123+037	AADT = 5588 vpd %HV = 16%	Sprayed seal 250 mm foamed bitumen stabilised base 300 mm granular subbase 300 mm select fill
10P	Near Gordonvale	64+175	65+225	AADT = 15 077 vpd %HV = 8%	Sprayed seal 250 mm foamed bitumen stabilised base 100 mm granular subbase Natural subgrade

C.3.1 Back-calculation of TSD Deflection Data

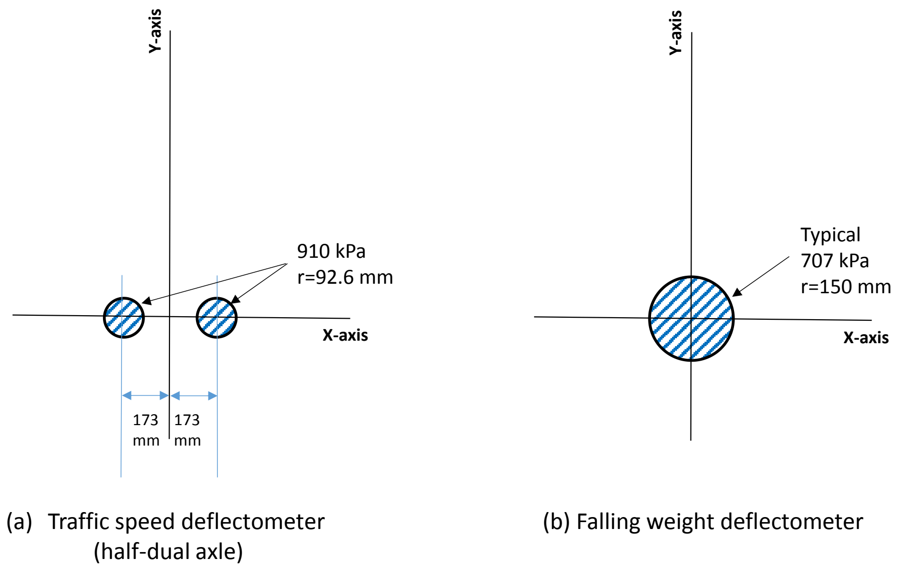
One potential project-level application is to back-calculate layer moduli for use in a GMP analysis. GMP analysis is generally required if a pavement contains a bound layer (e.g. stabilised material and asphalt) or design traffic exceeding 1 x 107 ESA.

There are many back-calculation algorithms available to estimate the in situ layer moduli of pavement layers. One software tool, EFROMD, was developed by ARRB Group using CIRCLY as the mechanistic computation engine. This allows the incorporation of features such as layer anisotropy, which accounts for the different directional behaviour of granular materials. More importantly, the same mechanistic engine used in the back-calculation process is used in the forward calculation process to mechanistically determine the thickness requirement for rehabilitation design.

The software allows for calculation of the layer moduli based on deflections measured under a set of dual tyres in a half axle configuration. This feature is normally not an option in other back calculation software, which are limited to a circular-plate type FWD loading. The dual tyre/half axle configuration allows the back-calculation process to be undertaken using the precise loading configuration of the TSD. Figure C 6 is a diagram illustrating the loading configuration used for the TSD and FWD, respectively, during the back-calculation process.

Back-calculation results using the above procedure are presented in Section C.3.2 and C.3.3 . The results show reasonable correlation for both the cement modified and foamed bitumen base pavements.

Figure C 6: Typical loading configuration used in back-calculation software for the TSD and FWD



C.3.2 Bruce Highway 10P

Back-calculation was carried out based on the indicative pavement profile shown in Table C 4 Back-calculation results from TSD and FWD deflection data using the EFROMD algorithm are presented in Table C 5. The results reported a reasonable level of calculation error (i.e. 1.0–5.4%). Figure C 7 shows the correlation of the back-calculated moduli of the foamed bitumen stabilised base layer from the FWD and TSD measurements, which shows a linear trend. The linear trend suggests early potential to determine the moduli of the stabilised layer and should be explored further in future study to confirm this application.

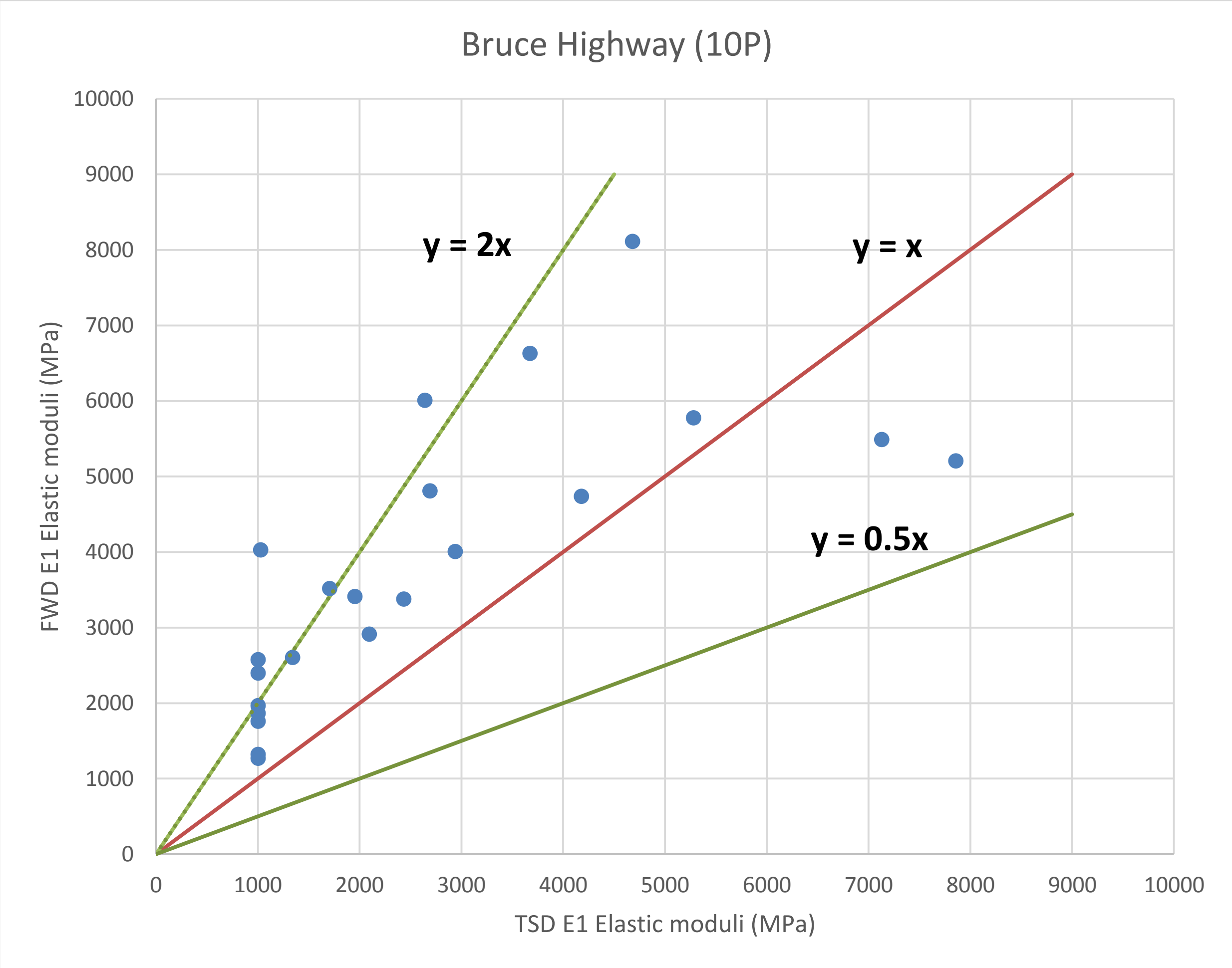
Table C 4: Indicative pavement profile for a section of Bruce Highway (10P)

Layer	Material	Layer thickness (mm)
1	Foamed bitumen stabilised base	250
2	Granular subbase	150
3	Selected fill	250
4	Subgrade	500
5	Bedrock	N/A

Table C 5: Back-calculation moduli results from the TSD and FWD for a stabilised section along the Bruce Highway (10P)

Chainage (m)	TSD back-calculation moduli (MPa)						FWD back-calculation moduli (MPa)					
	Layer 1 (E1)	Layer 2 (E2)	Layer 3 (E3)	Layer 4 (E4)	Layer 5 (E5)	Error (%)	Layer 1 (E1)	Layer 2 (E2)	Layer 3 (E3)	Layer 4 (E4)	Layer 5 (E5)	Error (%)
64+175	3671	440	134	81	407	3.6	6632	150	23	1000	326	2.3
64+225	2939	150	919	99	526	4.8	4010	502	106	79	240	1.8
64+275	2640	150	923	62	366	2.7	6012	392	58	104	283	1.5
64+325	2432	325	75	52	259	1.2	3381	548	34	286	227	1.0
64+375	7127	150	232	93	467	1.8	5493	2000	1000	37	548	2.0
64+425	4179	150	989	82	470	2.1	4738	2000	74	265	410	1.9
64+475	2691	405	1000	88	488	2.9	4813	510	88	127	438	1.8
64+525	1340	150	670	41	240	0.7	2607	333	84	116	303	2.5
64+575	1703	150	220	36	205	1.2	3519	419	87	97	389	2.6
64+625	1953	224	336	40	223	1.0	3414	585	121	112	404	2.1
64+675	2093	150	1000	209	1116	6.8	2913	730	156	146	532	2.2
64+725	4681	150	1000	90	491	1.9	8113	150	48	114	1004	3.7
64+775	1000	150	260	68	361	3.7	1322	299	88	195	465	5.4
64+825	1000	150	313	44	234	3.3	1968	150	79	499	344	2.5
64+875	1000	150	167	36	200	1.1	2578	204	52	199	383	3.9
64+925	1000	152	202	72	376	5.2	1272	667	109	105	452	3.5
64+975	1000	151	647	37	207	2.8	1761	545	97	115	379	2.2
65+025	1000	335	92	95	473	5.2	1868	150	49	987	382	3.3
65+075	5279	407	843	108	602	1.4	5780	2000	656	76	360	1.4
65+125	1000	150	192	36	194	1.7	2400	284	64	79	349	3.8
65+175	7855	150	30	72	359	4.6	5208	1045	155	84	253	2.1
65+225	1026	150	214	35	199	0.9	4030	150	20	1000	546	4.7

Figure C 7: Moduli of the foamed bitumen stabilised base layer using the FWD and TSD deflection data



C.3.3 *Bruce Highway 10M*

Back-calculation was carried out based on the indicative pavement profile shown in Table C 6. Back-calculation results from TSD and FWD deflection data are presented in Table C 7. Figure C 8 shows the correlation of the back-calculated moduli obtained from the FWD and TSD measurements. It is noted that there is more scattering in the linear relationship than the study carried out on the 10P section of Bruce Highway. This can partially be explained by the inherent variability in moduli of cement modified base material. Nevertheless, further study is recommended to explore the use of TSD to determine the in situ moduli of cement modified base material.

Table C 6: Indicative pavement profile for a section of Bruce Highway (10M)

Layer	Material	Thickness (mm)
1	Cement modified base	250
2	Granular subbase	150
3	Selected fill	250
4	Subgrade	500
5	Bedrock	N/A

Table C 7: Back-calculation moduli results from the TSD and FWD for a stabilised section along the Bruce Highway (10M)

Chainage (m)	TSD back-calculation moduli (MPa)					FWD back-calculation moduli (MPa)				
	Layer 1 (E1)	Layer 2 (E2)	Layer 3 (E3)	Layer 4 (E4)	Error (%)	Layer 1 (E1)	Layer 2 (E2)	Layer 3 (E3)	Layer 4 (E4)	Error (%)
118+700	750	51	187	125	6.3	1 336	182	62	143	6.0
118+750	10 000	175	94	449	3.2	8 429	1 215	500	196	3.6
118+800	6 369	570	308	500	5.6	5 871	641	311	258	7.5
118+850	3 094	383	154	432	2.0	6 862	2 000	311	333	9.6
118+900	3 298	178	119	260	1.1	4 467	2 000	500	246	5.8
118+950	750	63	500	228	20.3	750	162	84	240	14.1
119+000	750	78	500	249	19.1	750	67	114	264	16.8
119+050	750	88	500	289	14.2	1 079	257	63	262	8.4
119+100	750	70	500	172	20.2	750	211	85	243	20.9
119+150	1 217	207	133	389	1.5	1 019	147	85	354	4.7
119+200	750	811	158	213	6.0	3 220	258	94	235	12.5
119+250	750	97	500	160	16.3	750	179	64	199	15.2
119+300	750	50	300	349	22.1	750	202	77	168	16.9
119+350	750	50	500	203	8.5	750	150	57	239	10.9
119+400	750	106	500	187	3.0	1 553	199	88	274	10.0
119+450	750	57	500	125	3.8	1 188	74	145	176	6.0
119+500	4 572	767	500	500	193.0	3 000	500	100	100	614.9
119+550	750	58	500	153	7.6	1 405	384	500	220	7.1
119+600	750	51	207	119	12.5	887	130	69	191	9.2
119+650	750	68	500	167	6.7	865	277	228	171	5.7
119+700	750	60	299	212	5.0	750	57	147	176	10.0

Figure C 8: Moduli of the cement modified base layer using the FWD and TSD deflection data