REVIEW PAPER

S. Manoharan,¹ G. Chai,² S. Chowdhury,² and A. Golding³

A Study of the Structural Performance of Flexible Pavements Using Traffic Speed Deflectometer

Reference

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ABSTRACT

The falling weight deflectometer (FWD) is a non-destructive testing device that has been used by many road agencies worldwide since 1980 for structural evaluation of flexible pavements. In early 2000, the world first Doppler laser-based traffic speed deflectometer (TSD) was developed by Greenwood Engineering, and now eight TSD vehicles are in use worldwide. The two main advantages of the TSD technology are: (a) the ability to carry out continuous bearing capacity measurements instead of discrete points, (b) that testing can be carried out at traffic speeds without the need for lane closures with a stationary device such as FWD. The objective of this paper was to study the structural performance of flexible pavements using TSD deflection data. The study successfully established a correlation between maximum deflections TSD- D_0 and FWD- D_0 that are derived from the two devices. This study also drew some interesting conclusions in that deflection data collected by TSD could be transformed to FWD equivalent structural numbers with simple models as derived in the study. The outcome of this study was an established methodology for reporting structural performance at network level utilizing TSD deflection data.

Keywords

falling weight deflectometer (FWD), traffic speed deflectometer (TSD), adjusted structural number (SNP), maximum deflection (D_0), California bearing ratio (CBR)

Introduction

Queensland (QLD) is Australia's second largest state, covering approximately 1.8×10^6 square kilometers. QLD has approximately 174,000 km of road network managed by state and local governments [1]. The Department of Transport and Main Roads (TMR) is responsible for the maintenance of approximately 34,500 km of these roads, which includes approximately 29,500 km of sealed pavement [2]. This is the largest state controlled road network in Australia and has an estimated replacement value of AUD $\$51.04 \times 10^9$ as at 30 of June 2015 [3]. This infrastructure provides critical transportation links throughout the state, which results in it carrying approximately 80 % of the total road traffic in Queensland [4].

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¹ Portfolio Investment and Programming Branch, Queensland Dept. of Transport and Main Rd., Brisbane, QLD 4001, Australia, (Corresponding author), e-mail: sittampalam.p.manoharan@tmr.qld.gov.au

² School of Engineering, Griffith Univ., QLD 4222, Australia

³ Portfolio Investment and Programming Branch, Queensland Dept. of Transport and Main Rd., Brisbane, QLD 4001, Australia

A failure by road authorities to address pavement defects in a prompt manner can result in the need for large scale rehabilitation, increasing the whole of life cost of the road network. The ability to predict future pavement performance is highly advantageous for road asset managers as a means of efficiently directing the limited resources they command.

Pavement performance is based on the combination of functional and structural performance. Functional performance has been the subject of widespread local and international research that has resulted in a number of sophisticated deteriorations models for use in pavement management systems.

Structural deterioration modelling is the second major component in the prediction of structural performance road pavement. It is essential that the pavement performance be evaluated correctly by an appropriate methodology, utilizing functional and structural deterioration models.

Falling weight deflectometer (FWD) has been used by many road agencies globally since 1980 for evaluating pavement structural bearing capacity and is widely recognized as one of the most suitable non-destructive testing devices that accurately predicts bearing capacity. The FWD equipment used in QLD is depicted in **Fig. 1**. Over the last 30 years, extensive research has been undertaken into FWD usage in overlay design and determining remaining structural life.

The traffic speed deflectometer (TSD) is a new state of the art technology vehicle developed by Greenwood Engineering in the early 2000s using Doppler laser-based laser technology. The cross-sectional view of the TSD vehicle is shown in **Fig. 2** [5]. This technology is capable of continuously measuring bearing capacity of a pavement whilst moving at traffic speeds. The device's high accuracy and continuous deflection profiles are useful for network level applications, such as predicting road rehabilitation needs and remaining pavement life [6]. There are presently eight TSD vehicles in use around the world including USA, China, UK, South Africa, Poland, Italy, Denmark and a shared vehicle New Zealand & Australia. The TSD measures vertical deflection velocity using a Doppler laser, and the slope is calculated by dividing vertical velocity by vehicle driving velocity. Therefore, the accuracy of the deflection bowl is dependent on the manner in which the Doppler laser is mounted on the vehicle. The TSD vehicle sourced from Denmark was customized for Australian roads to collect deflection data in the Outer Wheel Path (OWP). The device consists of seven Doppler lasers, which measure locations in 100, 200, 300, 450, 600, and 900 mm from the center of the wheel load. A seventh Doppler laser is positioned 3,500 mm from the center of the wheel load known as a reference laser [7].

TSD DATA INTERPRETATION

This paper considered four alternative methods of interpreting TSD data, which are examined in depth below.

FIG. 1 Falling weight deflectometer (FWD) [19].

Method 1: Rasmussen

This TSD is an innovative Doppler laser based measuring system that can record 10 ton axle load deflection at 80 km/h. During operations, Doppler sensors measure vertical deflection velocities of the pavement surface at discrete points. When divided by the instantaneous vehicle speed, they produce deflection slopes at those points [8]. **Fig. 3** shows the pavement deflection velocity vectors under a rolling wheel. The corresponding deflection basin is shown in **Fig. 4** where deflection slopes (tangents) are displayed.

In order to determine the actual pavement deflections, deflection slope curve must be integrated using a closed-form solution of a mechanical model such as an elastic beam on Winkler foundation [8] as shown in **Fig. 5**. This is expressed in the 2-parameter Euler-Bernoulli beam as shown in equation (Eq 1):

$$EI \left(\frac{d^4}{dx^4} \right) w(x) + kw(x) = -F\delta(x) \quad (1)$$

where:

- F = point force,
- E = elasticity,
- I = moment of inertia,
- h = pavement thickness, and
- k = spring constant.

Method 2: Area Under the Curve (AUTC)

Another approach for analyzing TSD data to produce TSD deflection bowl is known as the area under the curve (AUTC) method [9]. This method was developed following the initial TSD trials in Australia in 2010. The AUTC method uses a numerical integration approach in accordance with the following procedures:

The base TSD data consists of a set of vertical pavement velocities, referenced against horizontal offset spaced along the axis of the wheel path and away from the loading of the dual tyred truck wheels. This data is termed the velocity profile.

FIG. 2

Traffic speed deflectometer (TSD) [5]. How the High Speed Deflectograph works:

- The value of the velocity at each point is a function of the pavement strength, the offset of the Doppler laser velocity sensor from the center point of loading, and the horizontal speed of the TSD vehicle (which affects the speed of the vertical loading).
- The slope is the ratio between the vertical and horizontal velocities at each measurement point and actual physical slope of the pavement surface within the deflection bowl centered under the moving TSD vehicle rear wheel.
- By plotting slope values against offsets from the load point as a slope profile curve show in Fig. 6 (analogous to the previously mentioned velocity profile), it is possible to

FIG. 3 Pavement deflection velocity under a rolling load [8].

FIG. 4 Pavement deflection velocity and deflection basin with deflection slopes (tangents) [8].

FIG. 5 Illustration of the road behaving as though it were on an elastic beam on a foundation of linear springs.

show that the cumulative area under the slope profile working from the tail is exactly equal to the vertical deflection at that point.

- The vertical difference between any two deflection points, such as for the bowl curvature, $(D_0 - D_{200})$, is equal to the area under the slope profile curve between these two points.

Full text of the AUTC procedure can be found in Austroads Publication No. AP-T279-14 entitled "Traffic Speed Deflectometer: Data Review and Lesson Learnt" [10].

Method 3: Graczyk

Graczyk et al. [11] proposed a unique analytical solution for pavement deflections in one-layer pavement system. The pavement is modeled as the Euler-Bernoulli beam, which is supported by the viscoelastic foundation, whereas the loading is assumed as a set of concentrated forces moving with a constant speed [11].

Method 4: Zofka

Zofka et al. [12] developed an algorithm for interpreting TSD results using an Eulerian-type approach as opposed to the Lagrangian-type approach. The algorithm has two distinct features: firstly, a focus on discrete points along the TSD route, which determines the deflection history at each point I as a function of time. Lastly, employing a specific function for the slope versus sensor locations vector at each TSD measurement point [12]. This algorithm proposed enables users to extensively customize TSD data based on their requirements. In addition, the deflection histories of the discrete points (Eulerian) can be used for the design of pavement rehabilitation, using clustering procedures to determine pavement sections that have a similar

structural capacity. The proposed method has a number of benefits as it is anticipated in the near future when the more sophisticated data is available its accuracy will increase.

TRIAL TSD TESTING PROGRAM

The Queensland Department of Transport and Main Roads (TMR) currently uses FWD deflection data predominantly for road rehabilitation projects using the TMR pavement rehabilitation methodology. The D_0 values of the deflection bowls are used for identification of structural weakness along road sections. Due to the time and cost associated with the collection of the deflection using FWD, the utilization of the deflection data for structural evaluation in pavement management has been limited. To overcome this, TMR undertook trials utilizing the TSD device to perform wide ranging continuous deflection measurements at traffic speed.

In 2010, a TSD trial was undertaken by TMR and Roads and Traffic Authority of New South Wales (RTA) for the first time in Australia. The trial consisted of 6,000 km of state-controlled road network in QLD (Fig. 7) [13] and significant lengths of road in New South Wales. The TSD trial was conducted to achieve the following objectives:

- Discovery of any correlation between TSD data and that obtained from other deflection measuring devices such as FWD.
- Identification of any factors that affect repeatability and reliability of correlations.
- Identification of factors that may impact TSD performance under local conditions.
- Assessment of the suitability of TSD as a network screening tool.

Methodology

A total of six flexible pavement trial sites were selected for this analysis and the trial sections varied from 500 to 1,000 m in length. The FWD and TSD tests were conducted concurrently to investigate if any correlation between the two devices and FWD tests were carried out mostly at 5 and 10 m intervals as stipulated in Table 1. The FWD and TSD measurements were taken from the inner wheel path of the road due to the TSD device as it originated from Denmark (Left-Hand drive). The deflection data collected by both devices was verified and eliminated all anomalies deflection data points. Temperature corrections were then adopted in accordance with methodology provided in *Pavement Rehabilitation Manual* [14]. The manual stipulates that for flexible pavements with less than 50 mm thick asphalt surfaced, no temperature correction is necessary. However, if the thickness is 50 mm or more temperature correction is required. The manual states the following three steps be carried out for temperature correction.

1. Determine the ratio of weighted mean annual pavement temperature for the site to the measured temperature at the time of testing.

FIG. 6 Relationship between pavement deflection (dx) at any wheel offset (x) and the cumulative area of the plot of slope (V_v/V_h), versus wheel load offset (x) [9].

FIG. 7
TSD trial network and six TSD & FWD test sites [13].

- Determine the appropriate correction factors for deflection and curvature function.
- Multiply the deflections and curvatures by the corresponding correction factors.

The deflection data was derived for TSD testing by using Rasmussen models as per method 1 provided in the data interpretation section. The FWD deflection data was collected using 40 kN standard load, and approximately 400 test locations

consisted of both TSD and FWD deflection data, which were selected for this analysis.

Table 1 displays trial sites, which were selected to appropriately capture various traffic volumes and different road classifications. TMR controlled roads have been classified according to subgrade material type and typically experienced rainfall levels. These classifications include wet non-reactive (WNR), wet reactive (WR), dry non-reactive (DNR), and dry reactive (DR). This analysis only considered flexible granular pavement with spray

TABLE 1 FWD testing sites with location details.

Sites	Highway Name	Chainage (km)	Traffic Volume per Day	Type of Pavement	Zone	Testing Interval (m)
10L	Bruce	68.00–69.0	5,800	Granular	WNR	10,50
10N	Bruce	122–122.5	4,300	Granular	WNR	5
14B	Flinders	200–200.5	500	Granular	DNR	10
13E	Landsborough	49–50	560	Granular	DR	10
18D	Warrego	93.2–94	1,250	Granular	DNR	10
28A	Gore	58.5–59.5	2,250	Granular	DR	10

FIG. 8 Equality plot of TSD max deflection vs FWD max deflection.

seal surfacing as this type of pavement makes up more than 85 % of the total QLD road network [15]. The typical structure of a granular pavement consist of approximately 250–300 mm thickness Type 1 or 2 base material specified in TMR Technical Specifications [16]. This granular material's unsoaked California bearing ratio (CBR) has a range from 45 to 80 and a fines ratio between 0.35 and 0.65 [16].

The FWD and TSD data for the 400 test locations were analyzed using the MATLAB program to investigate the relationship between the max deflection of TSD and FWD. The deflections were plotted in **Fig. 8**, which illustrates a linear relationship between the D_0 deflection measurement from FWD and TSD devices. This outcome demonstrates a highly beneficial method of converting TSD data to the FWD equivalent and using the existing FWD base technology for practical applications until development of TSD base technology.

To develop simple models for transforming TSD data to FWD equivalent adjusted structural number (SNP), Robert's [17] and Paterson's [18] FWD-based adjusted structural number equations were used in this study. Firstly, the FWD data was then converted to SNP using Robert's [17] equation (Eq 2) as shown below:

$$SNP = 167 * D_0^{-0.57} \quad (2)$$

where:

SNP = adjusted structural number, and

D_0 = maximum deflection in microns measured by FWD.

Conversely, the adjusted structural number (SNP) proposed by Paterson [18] was used to convert the FWD data to SNP. The equation (pavement base is not cemented) is expressed (Eq 3) as:

$$SNP = 3.2 * D_0^{-0.63} \quad (3)$$

FIG. 9 SNP calculated based on Robert equation vs TSD max deflection.

FIG. 10 SNP calculated based on Paterson equation vs TSD max deflection.

where:

SNP = adjusted structural number, and

D_0 = maximum deflection in millimeter measured by FWD.

The TSD maximum deflection (TSD- D_0) and SNP (Robert) correlation was established using the MATLAB's curve fitting tool. Subsequently, the SNP (Paterson) versus TSD- D_0 model was developed with the results presented in **Figs. 9** and **10**, respectively.

The newly developed models for predicting SNP values from TSD max deflections were compared against the SNP values calculated from FWD max deflection. These variations are displayed in **Fig. 11** and **12**, respectively.

FIG. 11 SNP predicted using TSD vs SNP based on Roberts equation. **FIG. 12** SNP predicted using TSD vs SNP based on Paterson equation.

DISCUSSION OF RESULTS

The aim of this study was to investigate the relationship between TSD Doppler lasers and FWD deflection devices. The establishment of a relationship between both devices is paramount for road asset managers and design engineers. Additionally, in the last 30 years, FWD has been extensively used by many road agencies as all technical information is referenced to FWD. Subsequently, it will require several years to accurately convert TSD deflection to the equivalent FWD, this is critical to business needs until the development of a methodology to use TSD data directly occurs. Direct comparison of TSD versus FWD is depicted in **Fig. 8**, which illustrates that FWD max deflections less than 1 mm have a higher correlation in comparison to those with a deflection greater than 1 mm.

The regression analysis identifies that TSD- D_0 and FWD- D_0 have a linear relationship as presented (Eq 4) below:

$$D_{0(TSD)} = 0.9845 * D_{0(FWD)} - 40.13 \quad (4)$$

where:

$D_{0(TSD)}$ = maximum deflection measured by TSD in μm , and

$D_{0(FWD)}$ = maximum deflection measured by FWD in μm .

The correlation is strong with an R^2 value equal to 0.8826 and RMSE is equal to 126.2.

This relationship was developed using the data from Queensland specifically, consequently calibration factors k_1 and k_2 were introduced to Eq 4 to enable global usage (Eq 5).

$$D_{0(TSD)} = k_1 * 0.9845 * D_{0(FWD)} - k_2 * 40.13 \quad (5)$$

where:

$D_{0(TSD)}$ = maximum deflection measured by TSD in μm ,

$D_{0(FWD)}$ = maximum deflection measured by FWD in μm ,

k_1 = calibration factor, and

k_2 = calibration factor.

This relationship will be referred to in the rest of the paper as “TSD-FWD Converter.”

The SNP calculated using Robert's equation versus TSD maximum deflection shown in **Fig. 9** has established that SNP has a power relationship to TSD max deflection similar to that of Robert's equation.

This analysis revealed that estimation of SNP from TSD maximum deflection can be defined as below (Eq 6):

$$SNP = 82.3 * D_{0(TSD)}^{-0.47} \quad (R^2 = 0.8797 \text{ and } RMSE = 0.4486) \quad (6)$$

where:

SNP = adjusted structural number, and

D_0 = maximum deflection measured by TSD in μm .

Similarly, the Paterson equation was also used to develop a relationship with TSD deflection as this model is used commonly worldwide to determine SNP from deflection. The SNP and TSD relationship can be defined as follows (Eq 7):

$$SNP = 3.2 * D_{0(TSD)}^{-0.52} \quad (R^2 = 0.8797 \text{ and } RSME = 0.5015) \quad (7)$$

where:

SNP = adjusted structural number, and

D_0 = maximum deflection measured by TSD in mm.

Fig. 10 shows Paterson SNP versus TSD maximum deflection.

Using Eqs 6 and 7, the calculated adjusted structural number was compared with that computed using Robert and Paterson's equations, respectively. The comparisons are shown in **Figs. 11** and **12**. The predicted SNP from FWD by Robert and Paterson relationships versus predicted SNP using the newly developed relationships exhibiting a strong correlation and the R^2 values are

TABLE 2 Proposed adjusted structural number bands with FWD and TSD deflections.

Band	Adjusted Structural Number (SNP)		FWD - D_0 (microns)		TSD- D_0 (μm)	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
Very good	≥ 8		≤ 200		≤ 160	
Good	≥ 6	< 8	≤ 340	> 200	≤ 300	> 160
Fair	≥ 4	< 6	≤ 700	> 340	≤ 650	> 300
Poor	≥ 2.5	< 4	$\leq 1,600$	> 700	$\leq 1,535$	> 650
Very poor	< 2.5		$> 1,600$		$> 1,535$	

greater than 0.80 and RMSE values are less than 0.625 for both predictions.

PAVEMENT STRUCTURAL CAPACITY CLARIFICATION AT NETWORK LEVEL

For Asset managers and maintenance engineers, viewing of structural raw data presents an initial indicator of structural capacity of pavements. The proposed adjusted structural number bands shown in **Table 2** provide guidance for flexible pavements with spray sealed or thin asphalt surface, comprising 85 % of sealed road network in QLD [15] and is the predominant pavement type in other countries. These bands were derived from the authors' experience and using tolerable deflection criteria for unbound pavement [19]. Furthermore, this table also includes FWD- D_0 and TSD- D_0 values in each band. These values are derived using Eqs 3 and 4. In addition, providing different attributes to each band will enable asset managers to use attribute values they are familiar with.

Subsequently, similar proposed bands are to be developed for other pavement types. This is vital as road network are comprised of different pavement types as it is not homogeneous. Two case studies were undertaken to classify the structural capacity based on TSD data collected in 2014 to ensure the accurateness of the models developed in this study. The TSD data used in this analysis is at 1 km intervals and tested approximately 6,500 km of the network.

FIG. 13 SNP predicted by four models (AUTC method derived FWD deflection data).

CASE STUDY 1: SENSITIVITY ANALYSIS OF NEWLY DEVELOPED RELATIONSHIPS WITH AUTC METHOD DERIVED FWD DEFLECTION DATA

This case study intends to explore the effectiveness of the models developed in this study to use at the network level using Hawkeye processing method [7] derived FWD deflection, as this method of conversion is used widely in Australia. Two separate analyses were carried out for this purpose. The first analysis was to investigate the correlation of Robert and the newly developed equivalent TSD model to Robert. For this comparison, the predicted adjusted structural number (SNP) from both methods are calculated and then Robert's predicted SNPs were sorted in ascending order. Similarly, Paterson's and the newly developed equivalent TSD model to Paterson analysis was carried out, and the correlation of four models are shown in **Fig. 13**. The results highlight that, overall, the four models are accurately predicting SNP; however, a noticeably minor deviation is evident for higher SNP.

The second analysis proposed adjusted number bands, given in **Table 2**, and is used to categorize the structural capacity of the network. This utilized the predicted SNP by all four models and categorized into the bands. The network level structural capacity classification is shown in **Fig. 14**. A 2014 TSD test on approximately 6,500 km road network revealed an accuracy of 4 % could be achieved across the four models. The accuracy was observed in

FIG. 14 Pavement structural capacity classification at network level (AUTC method).

TABLE 3 Structural capacity classifications based on AUTC method derived FWD deflection.

Model Type	Very Good (%)	Good (%)	Fair (%)	Poor (%)	Very Poor (%)
Robert's	0.65	4.73	53.76	40.82	0.05
Equivalent TSD model to Robert	0.29	2.9	42.93	42.93	0.00
Paterson's	1.13	6.22	39.75	39.75	0.24
Equivalent TSD model to Paterson	0.7	4.67	38.53	38.53	0.00

the results of the analysis. However, when examining each pair of models separately, Robert's and the equivalent TSD equation to Robert exhibits a strong correlation of 2 %, as deduced from the analysis. Case Study 1 results are tabulated in **Table 3**.

CASE STUDY 2: SENSITIVITY ANALYSIS OF NEWLY DEVELOPED STRUCTURAL NUMBER MODELS WITH NEWLY DEVELOPED LINEAR RELATIONSHIP TSD TO FWD CONVERSION MODEL ("TSD-FWD CONVERTER")

This study is similar to case study 1; however, instead of the AUTC method, the "TSD-FWD Converter" method, which was developed in this study, was used. Therefore, this analysis comprehensively tests all five models developed in this study and how these can be utilized at network level. The predicted SNP relationship displays a strong correlation; however at higher SNP values, there is a minor deviation. This can be attributed to the TSD to FWD conversion model development. The **Fig. 15** shows the correlation of predicted SNP.

Similar to case study 1, the second analysis was undertaken to classify network using the four models. Notably, the findings highlight that Paterson's and the newly developed model depict a strong correlation when using the "TSD-FWD Converter" model developed in this study as shown in the **Fig. 16**. Additionally, Robert's model identifies a correlation when using AUTC based deflection data as per case study 1. The Case Study 2 results are tabulated in **Table 4**.

FIG. 15 SNP predicted by four models (TSD-FWD converter method derived FWD deflection data).

FIG. 16 Pavement structural capacity classification at network level (TSD-FWD converter method).

TABLE 4 Structural capacity classifications based onTSD-FWD Converter method derived FWD deflection.

Model Type	Very Good (%)	Good (%)	Fair (%)	Poor (%)	Very Poor (%)
Robert's	0.61	4.62	55.44	39.25	0.08
Equivalent TSD model to Robert	0.29	2.9	53.88	42.93	0.00
Paterson's	1.00	6.10	54.29	38.35	0.20
Equivalent TSD model to Paterson	0.7	4.67	56.10	38.53	0.00

Conclusions

A tangible benefit can be achieved if asset managers use available deflection data appropriately in investment decisions. Structural data collection at the network level is generally considered cost prohibitive; however, when such data is used in a network needs analysis, the benefit can be much higher than the data collection cost. Hence, simple models are very useful for asset managers as it enables them to use available TSD data for their decision making process at network level for improving the timely identification of road sections requiring rehabilitation. This study draws some interesting findings in that deflection data collected by TSD can be

transformed to FWD equivalent structural number with a simple mathematical model as derived from this study. Therefore, these relationships can be used in the interim basis for use of TSD data until comprehensive studies have been conducted by various research organizations. This study focused exclusively on the relationship between the maximum deflections (D_0) of both devices. Therefore, further research is to be undertaken for the correlation between D_{200} , D_{300} , D_{450} , and D_{900} for TSD and FWD. The relationships were developed only for flexible pavement types (high deflections). Therefore, future research should be undertaken when TSD data for stiffer pavements is available to verify the developed relationship.

The newly developed mathematical models were developed using approximately 400 locations, which were tested in 2010. Two case studies were carried out to evaluate the accuracy of developed models in predicting adjusted structural number at network level utilizing approximately 6,500 km TSD data collected in 2014. These studies provide an insight into the simple models that can be used to predict structural number at network level similar to that of FWD based models without losing structural integrity. Hence, the finding of this study concludes that TSD deflection data can be used directly to categorize pavement structural capacities in the network.

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References

- [1] Talbot, S. and Pelevin, A., "The Queensland Asset Management Partnership," presented at the *21st ARRB & 11th REAAA Conference*, Cairns, Australia, May 18–23, 2003, ARRB Transport Research Ltd., Melbourne, Australia, pp. 1–28.
- [2] TMR, 2015, "Queensland State-Controlled Roads and Region Maps," <http://web.archive.org/web/20170825013216/https://www.tmr.qld.gov.au/Travel-and-transport/Maps-and-guides/Queensland-state-controlled-roads-and-region-maps.aspx> (accessed 25 Aug 2017).
- [3] TMR, 2015, "Transport and Main Roads Annual Report 2014–15," <http://web.archive.org/web/20170825014216/https://www.tmr.qld.gov.au/About-us/Corporate-information/Publications/Annual-report/Department-of-Transport-and-Main-Roads-archive> (accessed 25 Aug 2017).
- [4] TMR, *Queensland Transport and Roads Investment Program 2016–17 to 2019–20*, Department Transport and Main Roads, Brisbane, Australia, 2016.
- [5] Krarup, J. A., Rasmussen, S., Aagaard, L., and Hjorth, P., *Output From the Greenwood Traffic Speed Deflectometer*, ARRB Group Ltd, Canberra, Australia, 2006, pp. 1–10.
- [6] Greenwood Denmark, 2-15, "Traffic Speed Deflectometer," <http://web.archive.org/web/20170825014618/https://www.greenwood.dk/tsd.phptsd.php>. Greenwood Engineering (accessed 25 Aug 2017).
- [7] Chad, M. and Wix, R., *Trials and Tribulations of TSD Operations*, ARRB, Vermont South Australia, Australia, 2015.
- [8] Rasmussen, S., Aagaard, L., Baltzer, S., and Krarup, J., "A Comparison of Two Years of Network Level Measurements With the Traffic Speed Deflectometer," *Ljubljana Europe*, 2008, Transport Research Arena, pp. 1–8.
- [9] Muller, W. B. and Roberts, J., "Revised Approach to Assessing Traffic Speed Deflectometer Data and Field Validation of Deflection Bowl Predictions," *Int. J. Pav. Eng.*, Vol. 14, No. 4, 2013, pp. 388–402, <https://doi.org/10.1080/10298436.2012.715646>
- [10] Roberts, J., Ai, U., Toole, T., and Martin, T., *Traffic Speed Deflectometer Data Review and Lesson Learnt*, Austroads, Sydney, Australia, 2014.
- [11] Graczyk, M., Zofka, A., Sudyka, J., and Rafa, J., "Analytical Solution of Pavement Deflections and its Application to the TSD Measurements," presented at the *24th ARRB Conference*, Sydney, Australia, Oct. 22–24, 2014, ARRB Group Ltd, Sydney, Australia, 2014, pp. 1–13.
- [12] Zofka, A., Sudyka, J., Maliszewski, M., Harasim, P., and Sybilski, D., "Alternative Approach for Interpreting Traffic Speed Deflectometer Results," *Transp. Res. Rec.*, Vol. 2457, 2014, pp. 12–18, <https://doi.org/10.3141/2457-02>
- [13] Weligamage, J., Piyatrapoomi, N., and Gunapala, L., *Traffic Speed Deflectometer-Queensland Trial*, Transport and Main Roads, Brisbane, Australia, 2010.
- [14] TMR, *Pavement Rehabilitation Manual*, Queensland Department of Transport and Main Roads, Australia, 2012.
- [15] TMR, *SCENARIO V5.1 Technical Manual*, The Department of Transport and Main Roads, Brisbane, Australia, 2009.
- [16] TMR, 2015, "Category 5—Pavements, Subgrade and Surfacing (MRTS 05)," <http://web.archive.org/web/20170825020000/https://www.tmr.qld.gov.au/business-industry/Technical-standards-publications/Specifications/5-Pavements-Subgrade-and-Surfacing> (accessed 25 Aug 2017).
- [17] Roberts, J., "FWD Testing, STEP Calibration and Analysis of Selected Roads in Lake Macquarie City Council," *Report No. 008365-1*, ARRB Group Ltd, Melbourne, Australia, 2014.
- [18] Odoki, J., Henry, G., and Herali, R., *Analytical Framework and Model Descriptions*, Vol. 4, AIPCR, Birmingham, UK, 2000.
- [19] Baran, E., Conaghan, A., and Ramanujam, J., *Structural Assessment and Rehabilitation Design for Low Volume Roads*, Transport and Main Roads, Brisbane, Australia, 2013.