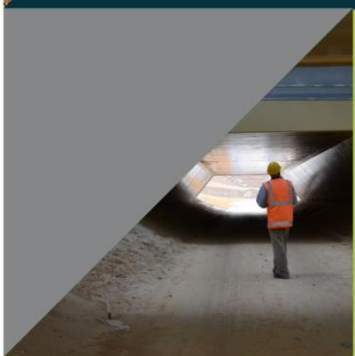

WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM

An Evaluation of the Traffic Speed Deflectometer for Main Roads Western Australia

AN INITIATIVE BY:

The Government of Western Australia

mainroads WESTERN AUSTRALIA

arrb AUSTRALIAN ROAD RESEARCH BOARD

An Evaluation of the Traffic Speed Deflectometer for Main Roads Western Australia

WARRIP

for Main Roads Western Australia

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AN EVALUATION OF THE TRAFFIC SPEED DEFLECTOMETER FOR MAIN ROADS WESTERN AUSTRALIA

AUSTRALIAN ROAD RESEARCH BOARD

May 2017

SUMMARY

In late 2015, Main Roads Western Australia (MRWA) and ARRB Group Ltd (ARRB) signed an agreement which strategically targeted a commitment to research and development, technology transfer and capability development. A key component of the agreement was the establishment of the Western Australia Road Research and Innovation Program (WARRIP), a program of research that specifically targets the areas of road pavements and surfacings, asset management and structures.

As part of WARRIP MRWA commissioned ARRB to conduct a trial of the Traffic Speed Deflectometer (TSD) in November 2016.

This report summarises the details of the survey completed as part of the trial, the method used, the technical operation of the TSD and recommendations in terms of how the data could be used to assist MRWA to make best use of the investment in their data collection program.

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1 INTRODUCTION

Over recent years, road agencies have come to recognise that there are significant benefits to be gained if road condition data can be collected at high speed. Whilst there have been great advanced in laser-based technology for the collection of roughness and rutting data, until recently it was not possible to collect deflection data at normal highway speed (80 km/h). This meant that data had to be collected using devices such as the Deflectograph, at a speed of 4 km/h, or the Falling Weight Deflectometer (FWD), when data is collected when the device is stationary. This is a time-consuming, and hence costly, process plus there are the associated workplace health and safety issues.

In late 2015, Main Roads Western Australia (MRWA) and ARRB Group Ltd (ARRB) signed an agreement which strategically targeted a commitment to research and development, technology transfer and capability development. Specifically, the agreement reflects a stronger commitment to building professional capability and implementing innovative practices that will achieve significant savings for MRWA in total road expenditure, and a higher rate of return through targeted research. A key component of the agreement is the establishment of the Western Australia Road Research and Innovation Program (WARRIP), a program of research that specifically targets the areas of road pavements and surfacings, asset management and structures.

In early 2016, MRWA expressed interest in trialling the TSD on the Western Australia (WA) road network, this work to be conducted under the WARRIP agreement. Due to the contractual arrangement with the existing Heads of Agreement, this was not possible until the end of the third year of collection for New South Wales and prior to shipping to New Zealand.

This report summarises the details of the survey completed as part of the trial, the method used, the technical operation of the TSD and recommendations in terms of how the data could be used to assist MRWA to make best use of the investment in their data collection program.

2 BACKGROUND

The background leading to the initial Australian TSD trials and how ARRB was able to procure a TSD for Australia and New Zealand is reported in Wix, Murnane and Moffatt (2016).

The development of the TSD by Greenwood Engineering in Denmark in the early to mid-2000s (Rasmussen, Krarup & Hildebrand 2002), offered the promise of assessing the structural performance of a road network across its entire length and reporting the results at much smaller reporting intervals. In 2009/10, and following initial investigations into the performance of the TSD in Denmark, the New South Wales and Queensland state road agencies contracted the Danish Road Directorate to undertake a trial survey of 18 000 km of road over a three-month period (Baltzer et al. 2010).

Some samples of these results were reviewed as part of an independent and national assessment of the applicability of the TSD to Australian and New Zealand conditions and practices (Austroads 2012a). The trials assessed the repeatability of the TSD across numerous test sites and compared its outputs with those from other deflection measuring devices such as Deflectographs and the Falling Weight Deflectometer (FWD). Based on the analysis of the TSD data, it was concluded that the TSD could be used as a network-level screening tool to identify suspect pavements and to target follow-up testing. Additional work was recommended to fully operationalise the TSD for Australian and New Zealand conditions, and to undertake further work to determine Australian state and New Zealand road agencies’ support for the value of acquiring network pavement strength data.

Using a questionnaire survey directed to eight Australasian road agencies regarding structural condition (deflection) data, Austroads (2012b) identified and clarified the then current perceptions and realities regarding the benefits and risks of network-level deflection data, including its then current uses, limitations and opportunities. Martin concluded that there was strong support among most agencies for network-level strength assessment if a device such as the TSD was available. Most agencies favoured the use of the TSD as a screening tool to identify the weak and vulnerable pavements in the road network. The next most favoured use of the TSD was for the estimation of major rehabilitation and reconstruction budgets.

The positive results of the trial and the perceived benefits of the technology ultimately led to a five-year agreement for data collection services between ARRB and three road agencies to operate a TSD in Australia and New Zealand – Roads and Maritime Services, New South Wales; Queensland Department of Transport and Main Roads; and the New Zealand Transport Agency. The agreement included a commitment from the agencies to survey a minimum length of road network each year at an agreed rate. In addition, ARRB committed to integrate a suite of additional automated data collection systems into the TSD to allow the simultaneous collection of functional pavement condition parameters, including automated cracking. Based on this commitment, ARRB procured a TSD with seven Doppler lasers situated at 100, 200, 300, 450, 600, 900 and 3500 mm from the centre of the rear axle in the outer wheelpath.

After satisfactorily passing Greenwood’s factory acceptance testing in Denmark, the TSD, along with a prime mover tractor unit with an additional generator for powering the TSD, was transported by ship to Australia. The TSD arrived in Australia in January 2014.

2.1 Summary of Data Collection Program

A rolling five-year program of data collection commenced in 2014 as described in Table 2.1. Since commencing operations, the TSD has travelled 290 000 km and collected data on over 120 000 km of the road network. This has involved the recording of about 12 million deflection bowls.

Table 2.1: Rolling five-year program of testing using TSD (2014 to 2019)

Year	Road length surveyed (km)				
	NZ	Qld	NSW	Total	Actual (%)
1	12 000	20 000	20 000	52 000	41 000 (79%)
2	6 000	20 000	10 000	36 000	42 500 (118%)
3	6 000[1]	20 000	20 000	46 000	45 700 (99%)
4	6 000	20 000	10 000	36 000	–
5	6 000	20 000	20 000	46 000	–

2.2 Use of Deflection Data by Road Agencies

Each road agency is using and applying deflection data in different ways. For example, Roads and Maritime Services (RMS) NSW (2016) have reported how they validate and use the data.

RMS identified the following uses for the data:

- identification of weak pavement areas
- estimation of the remaining life and pavement layer thickness using modelling programs
- input into models to develop forward maintenance programs
- pavement rehabilitation design (although further work is required to assess usefulness).

Details are also provided in RMS NSW (2016).

At a 'Data Collection Roundtable' meeting in November 2016, it was agreed that the benefits of the TSD were as follows:

- Road agencies can assess the level of risk that the road network is carrying in regard to failing pavements.
- The data is 'easy to work with'.
- Collecting functional and structural condition data at the same time saves time and money.
- There is now no need to conduct network-level FWD testing.
- Work, health and safety (WHS) issues associated with the FWD no longer apply.
- TSD data can be viewed alongside all the other surface condition outputs; the process of making decisions regarding how to prioritise funding is therefore much simpler.

[1] Year 3 for NZTA commenced on 4/1/2016 and hence is incomplete.

- The TSD data can be used to in the development of more compelling and evidence-based submissions for funding, e.g.
  - justification of the need for remedial action (and the associated savings) if action is taken before the pavement fails
  - the potential use of the data for project-level work, including the design of structural overlays.

2.3 Efficiencies of Data Collection

ARRB has recently integrated additional technologies into the TSD platform so that clients can gain efficiencies in data collection across their networks. The technologies that have been added are based on existing equipment used in other parts of ARRB's survey fleet, including imaging, automatic crack detection, roughness, rutting, texture, geometry and spatial data.

Data from all the systems is collected and recorded simultaneously. The data is backed up automatically and a copy transferred to the processing team for in-office processing. The processing of the imaging, deflection, roughness, texture, geometry and spatial data sets is relatively fast. The processing of the rutting and cracking data is more intense due to the volume of data that has to be processed and reported (i.e. 4 000 data points every 5 mm traversed.)

Usually the deflection data is reported in 10 metre long sections but it can also be reported in 20 metre, 100 metre and 1 km sections, with the latter negotiated on a case-by-case basis.

Data can then be loaded and viewed using a number of methods, including export of Excel data into a flat file for upload into the clients' own system, Access databases, Hawkeye Data Viewer or Hawkeye Insight (cloud- based online data viewing.)

3 TECHNOLOGY

The following is an edited excerpt from the current Heads of Agreement Quality Plan (Version 1.1, dated 5/1/2017) between ARRB, Roads and Maritime Services, New South Wales (RMS), Queensland Department of Transport and Main Roads (TMR); and the New Zealand Transport Agency (NZTA) (ARRB Group 2017). It describes the collection and processing of data that was used for the trial.

3.1 Data Collection

As already discussed, the fact that the TSD is capable of scanning the bearing capacity of a road network at traffic speeds minimises the use of traditional stationary or slow-moving equipment such as a Falling Weight Deflectometer (FWD) or Deflectograph. The measuring speed is typically up to 80 km/h.

As reported by Wix (2016), there is a good correlation between the maximum deflection measured by the TSD and the FWD. Whilst some differences were observed, this is to be expected because the FWD takes a reading at a specific location whilst the TSD reports an average value over a 10 metre interval. In addition, the FWD measures deflection whilst stationary, whilst the TSD measures deflection whilst it is moving.

TSD deflection is measured using Doppler lasers. These lasers measure the instantaneous deflection velocity of the pavement as a load is applied via the rolling trailer tyres on the rear axle. The Doppler lasers are mounted on a rigid beam that is aligned longitudinally along the side of the TSD trailer chassis as shown in Figure 3.1. In Australia, this beam is mounted on the left side.

Figure 3.1: Doppler laser assembly

Source: ARRB.

3.1.1 Doppler Lasers

The Doppler lasers measure the pavement velocity[2] by sensing the frequency shift of back-scattered light from a moving surface. The pavement velocity is the rate of recovery of the pavement after a vertical load has been applied.

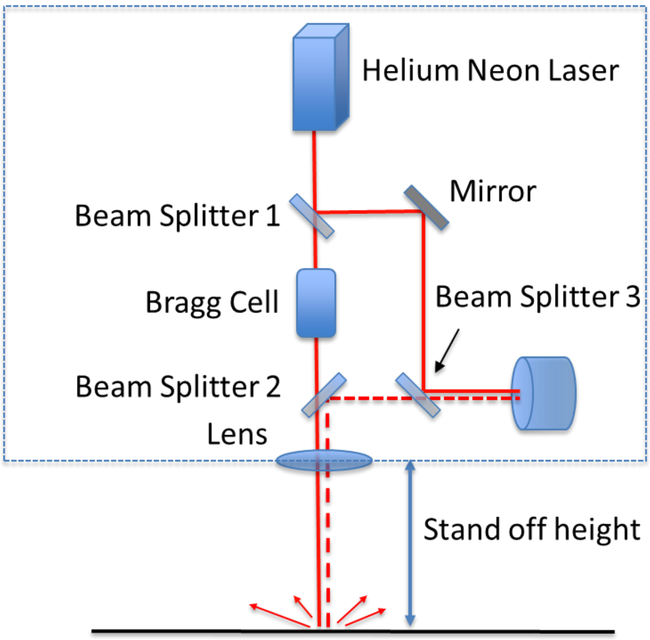
The basic principle of their operation involves splitting a beam from a helium neon laser into a reference beam and a measurement beam as illustrated in Figure 3.2. As the length of the light path of the reference beam is constant over time, the movement of the pavement generates a dark and bright (fringe) pattern on the detector, the frequency of which is equivalent to the Doppler shift between the emitted and reflected light.

The modulation frequency of the resultant fringe pattern is directly proportional to the velocity of the pavement surface at the point of measurement. This reflected light is detected by a photodiode; the electrical signal is then digitally processed to determine the frequency and hence the speed of the deflection recovery.

A gyroscope, accelerometer and inclinometer are mounted in the centre of the Doppler beam assembly to provide data to compensate for any movement of the beam.

The temperature of the beam and internal trailer are controlled using an air-conditioning system and circulation fans. This is to ensure that there is no thermal expansion or contraction of the beam and mounting components that may introduce torsional movement or bending of the beam. This ensures that the relative Doppler alignment angles remain constant.

Figure 3.2: Doppler laser measurement principle



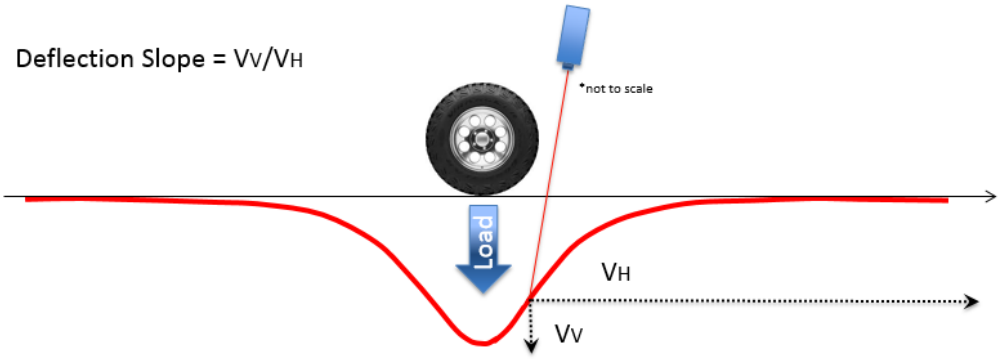
Source: ARRB.

2 The load applied to the pavement and the vertical motions at various radial distances from the centre of the load are measured using velocity transducers. The deflections at the radial distances are calculated from the outputs from the velocity transducers.

3.1.2 Slope Measurement

Measuring the slope of the pavement deflection is the core function of the TSD. As the Doppler lasers are mounted at an angle, the deflection velocity of the loaded pavement recorded by the TSD contains a vertical and horizontal component. Knowing the mounting angle of the laser allows the vertical velocity component (V_V) to be calculated whereas the horizontal component (V_H) is equal to the speed of the TSD. Once these two values are determined the slope of the deflection can be easily calculated. The measurement principle of the TSD is explained in Figure 3.3.

Figure 3.3: Schematic of TSD measurement technique



Source: ARRB.

The deflection velocities and resultant slope measurements can be used to mathematically model other traditional deflection measurements using beam curve fits and numerical modelling, etc.

3.1.3 Doppler Laser Location

The TSD was built to collect deflection data in the outer wheel path (OWP). As already discussed, six Doppler lasers measure deflections at distances of 100 mm, 200 mm, 300 mm, 450 mm, 600 mm and 900 mm from the centre of the wheel load. The seventh laser, known as the reference, is positioned 3 500 mm from the load. It is presumed that this laser is relatively unaffected by the load applied by the axle; hence the magnitude of the vertical pavement deflection velocity will be very small. As a result, its response is used to remove unwanted vertical velocity inputs (arising from driving velocity and vehicle movement) from the six measurement lasers.

3.1.4 Rate of Data Collection

The data rate is the rate of response in the samples of received light; it is not a direct data record measurement. The maximum data rate is the frequency of the outputted light at 1 000 Hz. The Doppler lasers used on the TSD typically operate at 900 Hz. However, data recording rates can be as low as 500 Hz before the confidence level in the velocity reading diminishes. The cut-off level for the ARRB TSD is currently set at 600 Hz.

The following factors can affect the rate that data is recorded:

- *Speed:* the higher the speed the more the laser scatter and the less that light is reflected and detected by a photodiode.
- *Surface reflectivity:* dark surfaces absorb more light and slick surfaces scatter more light. The rate of data recording on dark, flushed surfaces will be lower than lighter-coloured surfaces. When the rate of data collection is low, the speed of operation can be reduced to provide more opportunity for light to be reflected back to the detector.

- Focus: the focusing of the convergence of laser beam is critical in maintaining good data collection rates.

The Doppler mounting beam (Figure 3.1) is suspended by a motion-controlled servo system which keeps the distance between the Doppler lasers and the road constant to ensure that the lasers are in focus.

At the optimum distance (i.e. 1 662 mm), the laser spot is small and the most light is reflected. When the distance deviates from optimum, the size of the spot increases and less light is reflected because the intensity is lower and there is more scatter in the data.

The static ride height at the axle and king pin is 1 260 mm ±15 mm. This height fluctuates throughout the survey in response to movement of the suspension caused by changes in the road geometry and body roll, etc. The purpose of the servo system is to keep the distance between the Doppler lasers and the road surface as close to optimum as possible.

The servo system consists of two electrical servo motors connected to each end of the mounting beam. The motors are constantly lowering or raising the beam whilst the TSD is in motion. The magnitude of this movement is based on input from the distance measuring laser which is measuring the height of the trailer chassis above the ground.

The servo system can compensate for slow changes in stand-off distance, for example, caused by driving along a curve. However, it will not react to fast changes caused by potholes or steps in the road surface. Sudden changes in surface profile are, in most cases, still within range of the servo system (± 100 mm).

3.1.5 Pavement Loading

The load on the axles is 10 tonnes (nominally 5 tonnes per wheel set), which corresponds to a vertical loading of 50 kN.

The static load of the TSD comprises the trailer itself, a main ballast weight of 3 275 kg situated under the belly of the trailer, and a smaller ballast weight of 1 050 kg situated underneath the rear of the trailer. These loads are balanced to provide a suitable centre of gravity for the purpose of road handling as well as the nominal 5 tonne load over each wheel set.

Strain gauges are mounted on the rear axle to measure the bending moment on both the left and right side of the loaded axle. The load data is collected continuously and averaged over the selected report intervals. The measured load is derived from a load vs. signal equation derived from the strain gauge outputs; it is not a direct load cell weight or force measurement. The tolerance between the actual and measured strain (load) in a static setting is ± 200 kg. This is acceptable considering the weight of the trailer, air pressure and suspension balancing valving, and the engineering tolerance in the TSD chassis/suspension construction.

The actual trailer axle masses are slightly less than 10 tonnes. This is to keep within legal axle mass limits (the weight can be adjusted by adding or removing individual 32 kg ballast weights). The axle masses recorded (using Haenni scales) during the trial in November 2016 are presented in Table 3.1.

Table 3.1: TSD trailer axle masses recorded during trial in November 2016

Configuration	Left side (measuring side) [kg]	Right side (drivers side) [kg]
All loads on (survey configuration)	5 150	4 830
Big load only	4 670	4 360
Small load only	3 960	3 680
No loads	3 540	3 220

The loading being applied to the pavement can be calculated using Newton's equation:

Force (N) = mass (kg) x acceleration (m/s^2).

As a mass of 1 kg exerts a downwards force of approximately 9.81 N, the estimated force applied to the pavement can be derived by the following formula:

N = mass (kg) x 9.81.

This calculation applies for a nominal static load only; it will typically fluctuate by ±4% due to the changes in the vector component of gravity, as the TSD measures up/down slopes, and dynamically due to movement in the truck suspension, tyre and unsprung weight mass. However, as the mass does not change, these dynamic factors can be averaged or cancelled out over time and distance as the TSD travels along the pavement.

Depending on the loading, permits are sometimes required before the TSD can travel over a road network.

3.1.6 Pavement Temperature

The pavement surface and air temperature is recorded to an accuracy of ±1 °C and reported with the TSD data. The measurements are made using a calibrated air temperature probe situated beneath the trailer chassis, and a calibrated infrared temperature sensor that measures pavement surface temperature in the OWP.

3.1.7 TSD Data Outputs

Compared to other strength measuring devices the TSD collects a very large amount of raw data, including:

- continuous data streams of vertical velocity (v), horizontal velocity (h) at each laser location
- deflection velocity to an equivalent resolution of 5 µm for every 0.02 m travelled
- data volume of approximately 6 Megabytes per kilometre (depending on driving speed)
- approximately 1 000 data samples per second per laser.

3.2 Processed Outputs

The deflection data is processed to determine and report:

- average deflection using the Area Under The Curve (AUTC) (Roberts-Muller) model at the following longitudinal locations from the load axle in the OWP: 0 mm, 200 mm, 300 mm, 450 mm, 600 mm, 750 mm, 900 mm, 1200 mm and 1500 mm
- deflection utilising the Greenwood model at the following longitudinal locations from the load axle in the OWP: 0 mm, 200 mm, 300 mm, 450 mm, 600 mm and 900 mm
  (Note that measurements at offsets of 750 mm, 100 mm and 1 500 mm are currently not available).

- average structural curvature index (SCI) for SCI 200, SCI 300 and SCI 900 (subgrade)
- surface and air temperature to nearest 1 C
- applied axle load, left and right (kg)
- estimated load in the IWP and OWP (kN – kg x 9.8/1 000).

3.3 Data Validity

There are circumstances when the pavement response, geometry, speed, or internal system factors, do not allow the TSD to generate a valid deflection velocity for analysis. An invalid laser result is a negative, null or 0 value. This will most commonly occur when rigid pavements are being surveyed. As rigid pavements do not deflect in the same way as flexible pavements, and the magnitude of the deflection is often very small, it is likely that zero, negligible or negative deflection velocity readings will be recorded at multiple laser positions.

Intermittently there are isolated areas where the pavement does not respond uniformly and this will result in invalid readings. This is also common in other forms of deflection testing systems such as the FWD, where the bowl shape is irregular and non-decreasing deflection and other phenomena occur. This is generally a reflection of the pavement structure, e.g. stabilised subgrades, voids, rocky infill, cut and fill, subgrade irregularities, culverts, rock outcrops, service pipes, etc.

Post-processing software analyses this data and a result will only be reported when there are at least three valid velocity readings and a valid AUTC model calculation can be made.

3.3.1 No Model Fit

Two models are used to transform TSD slope measurements into a deflection bowl: the AUTC model calculation (ARRB), and the Asymmetric model (Greenwood).

The Greenwood model only supplies a bowl deflection at six locations from 0 to 900 mm from the load, with the algorithm using an optimised Euler-Bernoulli Beam model (curve-of-best-fit of slope measurements). This often results in a poor fit to the actual TSD slope data as there are only two 'levers' to adjust and fit the curve to the actual pavement response.

The Roberts-Muller method, otherwise known as AUTC model, supplies a full nine-point bowl from 0 to 1 500 mm from the load. This method is not as explicit as the asymmetric model. It involves fitting the TSD slope measurements and numerically integrating them over the length of the deflection bowl, working towards the wheel load. Using this method, the entire deflection bowl profile can be determined; it is not constrained by a curve fit.

While the Greenwood deflection bowl algorithm cannot fit a curve to the raw Doppler readings, the ARRB algorithm can still obtain a result as shown in Figure 3.4 (the data is flagged).

Figure 3.4: TSD data with no Greenwood model fit

COMMENT	SURVEY_SP	EVENT_COD	SLP100	SLP200	SLP300	SLP450	SLP600	SLP900	TD0	TD200	TD300	TD450	TD600	TD900	D0	D200	D300	D450	D600	D750	D900
	78		171.8	163.5	201.6	198	52.6	100.6	-204	-166	-144	-119	-103	-83	-138.1	-110.6	-92.4	-62.1	-43.3	-36.4	-30.8
	78		167.7	157.3	185.4	127.3	24.7	76.3	-89	-58	-41	-23	-12	-4	-99.2	-72.5	-55.4	-31.1	-20.3	-17.1	-14.5
	78		165.7	170.4	168.5	119.7	29.3	118.6	-89	-58	-41	-23	-12	-4	-101	-73.8	-56.8	-34.6	-24.1	-20.3	-17.2
No model fit	78	E	90.2	138.2	120.8	130.4	4.3	62.3							-102.7	-85.9	-72.9	-53.9	-37.5	-27.5	-22.2
No model fit	78	E	92.1	108.8	142.8	146.9	-2.3	62.1							-76.3	-60.6	-48	-26.2	-12.7	-8.9	-7.1
No model fit	78	E	88.5	70.8	138.[illegible]	92.3	34.2	66.9							-79.3	-65.7	-55.2	-37.6	-28.3	-23.7	-20
No model fit	78	E	65.5	78.5	109.1	59.1	-30	31.8							-68.7	-57.6	-48.1	-35.2	-27.8	-22.7	-18.9
	78		291	330.3	267.1	222.8	16.7	69.6	-223	-151	-111	-67	-40	-15	-172	-123	-92.8	-55.9	-36.2	-30.2	-25.4
	78		327.2	356.6	322.3	251.8	99.9	90.7	-248.9	-187.4	-153	-111.8	-84.8	-54.9	-240.3	-185.8	-151.6	-107.9	-82.3	-69.2	-58.5
	78		335.5	303	258.9	226	107.6	107.4	-257.9	-199.5	-169.6	-133.8	-109.6	-78.3	-231.4	-178.1	-150.2	-113.6	-88.6	-74.5	-63
	78		206.7	197.5	181.3	140.7	25.2	46.3	-130.3	-94.4	-75.2	-53.1	-39.9	-25.7	-134.6	-101.3	-82.5	-58	-41.7	-32.7	-27
	78		278.6	230.6	184.8	140	71.6	50.1	-148.1	-98.3	-77.7	-55.1	-38.4	-18.8	-168.1	-124.7	-104	-79.7	-62.3	-50.5	-42.1

Source: ARRB.

In these situations an 'E' is put in as an event code and the comment for the blank/missing Greenwood model deflection data is: '*No model fit TD0 – TD900'.*

3.3.2 Low Reading

Low readings occur when one or more of the laser measurements is reaching its limits, and/or when the pavement does not respond uniformly over the sampling interval. On most occasions, a valid deflection bowl can still be calculated with both the Greenwood and AUTC model as is shown in Figure 3.5. The event code in the database is 'E'.

Figure 3.5: TSD data with low reading and valid deflection result

COMMENT	SURVEY_SP	EVENT_COD	SLP100	SLP200	SLP300	SLP450	SLP600	SLP900	TD0	TD200	TD300	TD450	TD600	TD900	D0	D200	D300	D450	D600	D750	D900
	65		184.5	226.2	240.9	167.2	133.3	55.7	-178.6	-144.4	-120.6	-90	-67.6	-41.2	-180.3	-148.6	-125	-93.9	-71.4	-54.7	-44.5
	65		231.2	229.3	248.6	170.1	147.1	55.1	-193.8	-150.6	-126.2	-94.6	-71.8	-43.4	-189.4	-152	-128.1	-96.3	-72.5	-54	-43.4
	64		134	138.4	150.1	90.4	88	26.1	-125.2	-100	-85.8	-68	-55.2	-38	-128.5	-106.5	-92.1	-74	-60.6	-48.5	-39.8
Low sensor reading	64	E	77.3	99.8	88.4	79.4	44.5		-54	-39.4	-29.6	-18.2	-10.4	-3.6	-82.1	-68.5	-59.1	-46.3	-37.1	-30.9	-25.4
Low sensor reading	64	E	158.8	113	134.1	98.2	53.2		-89.6	-53	-40.6	-24.6	-14.2	-4.8	-109.1	-85.4	-73.1	-55.2	-44.2	-36.8	-30.3
Low sensor reading	64	E	173	84.7	126.2	77.6	30.9		-83.2	-40.6	-30.2	-17.2	-9.6	-2.6	-82.9	-58.9	-48.3	-32.5	-24.9	-20.5	-16.8
Low sensor reading	63	E	125.2	92	154.6	88.9	45.3	-30.8	-72.2	-51.2	-38.6	-23.2	-13.4	-4	-79.7	-60.9	-48.5	-29.7	-20	-14.5	-11.3
	63		240.3	228.4	271.9	170.3	102.4	13.1	-151.8	-108	-82.2	-51.6	-30.8	-11.4	-142.1	-103.7	-78.7	-44.6	-24.4	-13.3	-9.5
	62		515.5	482.1	456.1	316.9	166	3.9	-276.4	-182	-132.8	-78.8	-45.4	-16	-308.5	-226.1	-179.1	-120	-84.7	-64.6	-52.1
	62		673.2	639	578.7	361.9	201.5	4.4	-336.8	-213.4	-150.6	-84.4	-45.8	-13.8	-401.9	-293.8	-232.6	-161.3	-120.5	-94.9	-77.1
	62		590.9	566.3	536	304.4	182.1	9.9	-302.2	-193.4	-137.2	-77	-42	-12.2	-332.7	-237.7	-182.4	-118.2	-82.8	-61.2	-49.1

Source: ARRB.

3.3.3 Drop-off

Drop-off occurs where resolution of the measurement exceeds its limits, i.e. a very low deflection becomes a zero deflection. As a very strong (e.g. rigid) pavement does not deflect in the same or uniform manner as a flexible pavement, e.g. slab tilt and/or irregular load transfer, the magnitude of the deflection it also greatly reduced (sub 100 microns). In these cases, is a zero, negligible or negative deflection velocity reading at multiple laser positons may occur, making the result invalid.

It is not uncommon to have 'No model fit TD0 – TD900' and 'Low reading' in the comment column prior to and after 'drop-off' locations, where the resolution of the measurement is approaching the limits of measurability (see Figure 3.6). The Event code in the database is 'D'.

Figure 3.6: TSD data with laser drop off over bridge

COMMENT	SURVEY_SP	EVENT_COD	SLP100	SLP200	SLP300	SLP450	SLP600	SLP900	TD0	TD200	TD300	TD450	TD600	TD900	D0	D200	D300	D450	D600	D750	D900
	71		476.1	394.9	298.3	264.7	146	127.9	-322.1	-237.9	-201.9	-161.9	-131.2	-89.1	-301.8	-227.5	-193.2	-151.1	-120.4	-101.2	-85.5
	71		746.5	616.2	487.1	355.8	168.1	133.2	-365.3	-233.2	-178.1	-117.6	-76.6	-33.4	-410.9	-294.6	-239.7	-176.5	-138.4	-116.4	-98.4
	71		663.5	532.9	365	256.7	79	70	-262.8	-148.4	-103.2	-60.4	-35.3	-12.2	-282.8	-179.8	-135.3	-88.9	-65	-54.7	-46.3
Bridge Abutment	71	B	108.8	66.6	15.3	16	-87.3	-43.7	-210	-110	-72	-40	-23	-8	-213	-121.9	-84.9	-48.8	-32	-27	-22.8
Sensor drop off	71	D																			
Sensor drop off	71	D																			
Sensor drop off	71	D																			
Sensor drop off	70	D																			
Bridge Abutment	70	B	247	197.7	153.2	84.3	-47.9		-149	-76	-46	-21	-9	-2	-130.8	-67.8	-39.3	-9.6	-0.7	-0.6	-0.5
	70		798.3	653.4	519.5	320.4	58.8	17.1	-324.7	-180.3	-120.9	-64.4	-34.2	-9.7	-302.6	-178.5	-119.9	-56.6	-30.5	-23.8	-19.5
	70		794.7	638.1	518.2	346.1	92.4	49.2	-341.2	-190.7	-132.7	-72.5	-38.7	-10.9	-336.6	-213.6	-156	-90.8	-59.9	-48.7	-40.5
	70		1003.9	839.8	632.6	386.7	131.2	77.4	-410.5	-233.4	-159.7	-89	-50	-17	-437.4	-280.4	-206.8	-130.7	-94.3	-77.8	-65.2

Source: ARRB.

3.3.4 'No Velocity' Reading

A 'no velocity' reading occurs when the speed of data collection is too low, and the pavement response, data rate, or some other internal system factor stops the TSD from producing a valid deflection velocity. In situations when the speed falls below 40 km/h, the event code in the database is 'S' (see Figure 3.7).

Figure 3.7: TSD data with null values where speed is below 40 km/h

COMMENT	SURVEY_SP	EVENT_COD	SLP100	SLP200	SLP300	SLP450	SLP600	SLP900	TD0	TD200	TD300	TD450	TD600	TD900	D0	D200	D300	D450	D600	D750	D900
	46		67.2	85.1	51.2	77.3	61.2	36.2	-116	-94	-78	-56	-38	-17	-83.8	-72.1	-65.3	-55.6	-45.1	-37	-30.9
	44		21.6	85.4	69.4	48.4	47.7	13.8	-45	-37	-30	-20	-13	-5	-50.5	-44	-36.1	-27.5	-20.3	-14.1	-11.1
	42		14.7	89.2	78.6	44.2	47.6	9.2	-45	-37	-30	-20	-13	-5	-45.7	-39.8	-31.3	-22.3	-15.4	-9.3	-6.8
Speed or distance outside limits	38	S																			
Speed or distance outside limits	33	S																			
Speed or distance outside limits	28	S																			
Speed or distance outside limits	15	S																			
Speed or distance outside limits	2	S																			
Speed or distance outside limits	18	S																			
Speed or distance outside limits	22	S																			
Speed or distance outside limits	28	S																			
Speed or distance outside limits	33	S																			
Speed or distance outside limits	34	S																			
Speed or distance outside limits	37	S																			
Speed or distance outside limits	39	S																			
	42		51.4	79.1	138.3	141.5	113	68.7	-125	-114	-103	-83	-65	-36	-145.7	-136.4	-125.3	-104.2	-84.8	-69.8	-58.4
	44		89.4	133.8	205.8	116	164.7	87.1	-125	-114	-103	-83	-65	-36	-188.3	-172.2	-154.7	-130.6	-109.5	-86.9	-71.4

Source: ARRB.

3.3.5 High Deflection Readings

High deflection readings (in excess of 3 000 µm and above) occur when the pavement is very weak. In those cases, further more detailed pavement investigation may be warranted. If the data is reported as a legitimate deflection, but further investigation is required, then the event code in the database is 'E' and the comment is 'High deflection' (see Figure 3.8).

Figure 3.8: Raw TSD data with deflection values above 3 000 micron

COMMENT	SURVEY_SP	EVENT_COD	SLP100	SLP200	SLP300	SLP450	SLP600	SLP900	TD0	TD200	TD300	TD450	TD600	TD900	D0	D200	D300	D450	D600	D750	D900
	60		3046.6	2252.6	1565.8	698.7	329.1	134.5	-1029.8	-507.5	-319.6	-158.3	-78.9	-20.1	-1059.1	-594.8	-404.7	-240.2	-167.5	-129	-105.3
	60		5491.2	3630.7	2117.2	866.7	368.5	115.8	-1578.4	-662	-382.3	-173.9	-82.9	-19.2	-1552.3	-732.2	-449.5	-237.3	-150.8	-109.8	-88.1
	60		6393.3	4436.7	2706.4	1221.7	555.9	138.9	-1979.7	-897.5	-548.2	-274	-143.3	-41.5	-1916.5	-953	-600.4	-318.3	-192.2	-131.8	-103.8
High deflection	60	E	5422.9	4442.2	3239.5	1783.6	878.6	174.4	-2098.1	-1137.1	-752.3	-384.9	-193.2	-48.5	-2052.9	-1208.5	-824.3	-453.9	-261.4	-167.4	-128.8
	60		3555.2	2604.1	1679.2	730	336.6	125.3	-1148.5	-539.1	-329.3	-159.3	-79.2	-20.2	-1162.2	-620.8	-408.1	-234.8	-159.4	-120.7	-98.1

Source: ARRB.

3.3.6 Tail Taming

The 'tail of the bowl' is defined as being from the 900 mm offset to where the pavement response velocity is assumed to be 0, which is the 3 500 mm location. There are no lasers within the tail other than those at each end, i.e. 900 and 3 500 mm and very small fluctuations in readings naturally occur in this area for various reasons.

However, as the AUTC calculation algorithm fits a curve between all the slope results, and if the 900 mm result is similar, or close to, the 600 mm result, it will result in a flatter, less-tapered curve all the way out to the 3 500 mm location. As the distance between the 900 and 3 500 mm laser is 2.6 m, a small fluctuation can add up to a significant variation in the resultant calculated deflection bowl.

Limiting the slope fluctuations at the 900 mm laser location to no more than 2/3rd of the slope at the 600 mm laser location, eliminates the possibility of a flat or bulged curve (from 900 to 3 500 mm) but a more tapered 'natural' deflection curve.

3.4 Automated Crack Detection

The ARRB Automated Crack Detection system (ACD) consists of two high-performance 3D sensors that are fitted to the rear of the TSD trailer, 2.2 m above the pavement as shown in Figure 3.9.

Figure 3.9: View of automated crack detection (ACD) system fitted to TSD

Source: ARRB.

Each sensor consists of two main components: a high-power spread line laser and a high-speed 3D camera mounted off-axis to the laser light source. When combined, the two 3D laser units project a 4 m wide laser line consisting of over 4 000 measurement points onto the pavement. Half of the image is captured by each camera which interpret the distortions to the straight laser line as variations in the vertical surface profile. Because of the high pixel resolution, measurement accuracies of 0.5 mm are possible. The operational specification of the equipment is shown in Table 3.2.

A picture of the road surface can be built up by combining sequential transverse profiles which, at a speed of 90 km/h, are only 5 mm apart (closer together at lower speeds). The sensors produce both range and intensity profiles which are merged to produce a 3D image. The information contained in this image allows the ACD to automatically identify cracks and a variety of other defects.

Table 3.2: Operational specification for ACD

Item	Specification
Number of laser profiles	2
Sampling rate	5 600 profiles/second
Vehicle speed	0 to 100 km/h
Profile spacing	5 mm
Transversal field of view	4 m
Transversal accuracy	1 mm
Transversal resolution	4 096 points/profile
Depth range of operation	250 mm
Depth accuracy	0.5 mm

The data processing software divides the road surface into small sections 5 m long by 4 m wide which are automatically analysed for cracks and other surface defects. An example of a cracked surface is shown in Figure 3.10.

The variation in the colour gives an indication of the average width of each crack. The line at the left edge of the picture indicate the boundary of the area where the cracking is analysed. It is automatically determined based on the presence of reflective line markings.

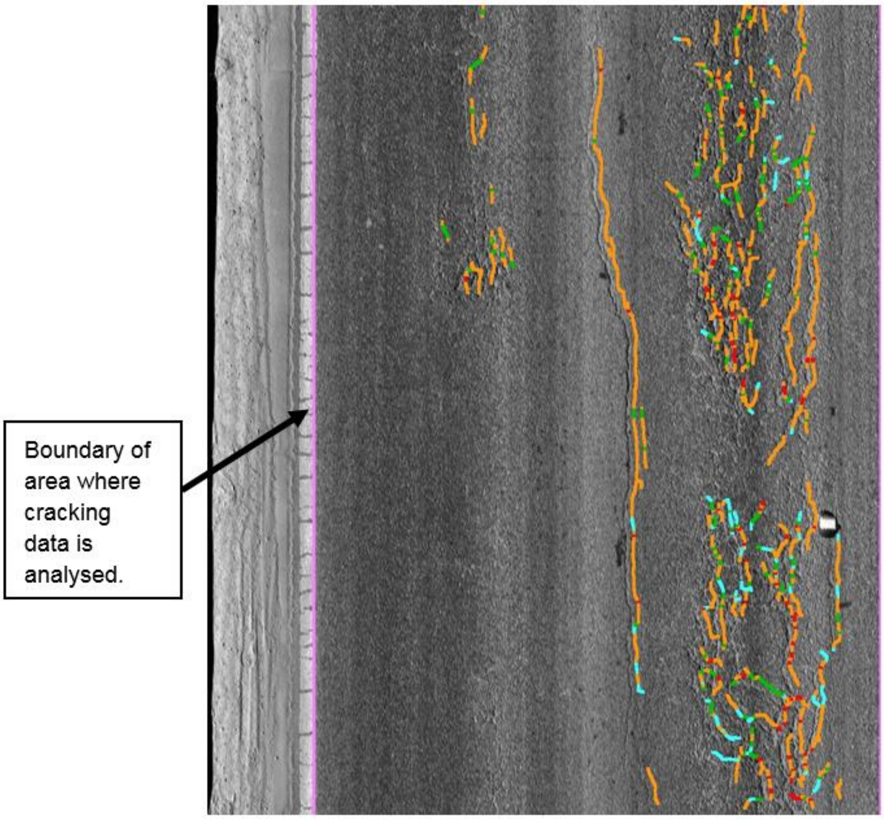
Each crack map can be used to identify and report the crack type and, because the image is calibrated, the extent of cracking can be accurately measured in both the longitudinal and transverse directions. The ACD system can also measure crack width; this allows the severity of the cracking to be determined.

The results from each image are combined and expressed for a given interval, e.g. 100 m.

3.4.1 Automated Crack Detection Processing

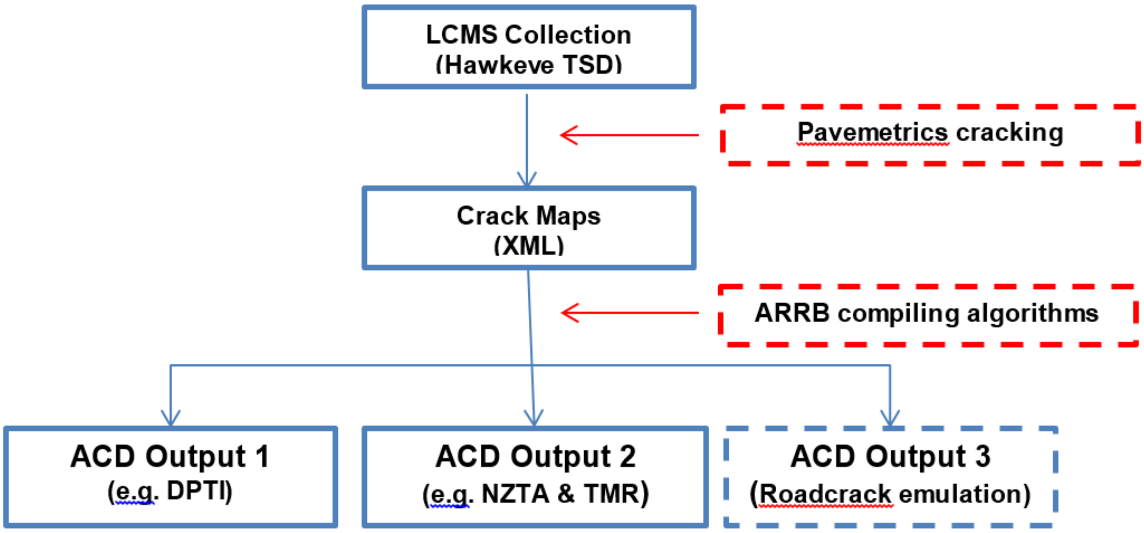
ACD processing is separated into two distinct phases. First, the raw data is processed into crack maps using proprietary Pavemetrics software algorithms. ARRB has minimum control over the parameters in this process. The data for the 'crack maps' are stored in XML format. These files can then be analysed using ARRB's proprietary algorithms which classify, weight and aggregate the cracking information into the format required. A graphical representation of this process is shown in Figure 3.11.

Figure 3.10: 3D image of a cracked surface with cracks highlighted



Source: ARRB.

Figure 3.11: Laser Crack Measurement System (LCMS)/Automated Crack Detection (ACD) processing flow chart



Source: ARRB.

3.4.2 *Standard Crack Processing Specifications*

Definitions

- image = each 5 m x 4 m images from LCMS (adjustable)
- frame = 1 m x 1 m processing area
- reporting segment = each 10 m segment
- channel = each of the three 1 m x 1 m frame areas transversely (in the OWP, between the wheelpaths and in the IWP).

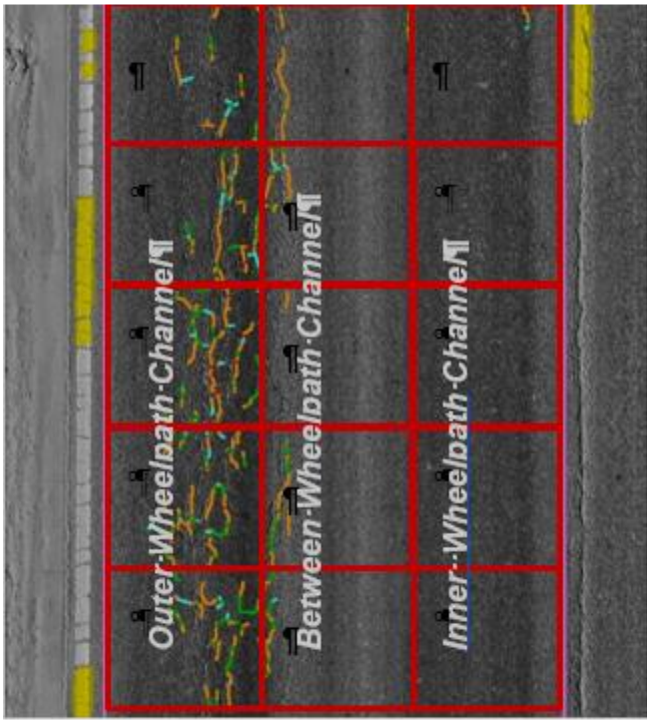
Processing intervals/areas

The pavement is divided into three 1 m x 1 m frames, centred on the tracking line of the vehicle. The areas designated as channels are defined as OWP, between the wheelpaths and IWP channels as shown in Figure 3.12.

Image analysis rules

Where the lane width is less < 3 m, areas outside the edge marking are eliminated from the analysis. Where tracking is too far left or too far right of the lane, the edge marking is used as the boundary at all times and no re-centring of the frame takes place (vehicle tracking line should be used at all times). Detail on defining the assessment area boundaries are provided in Section 3.5.5.

Figure 3.12: Frame and channel designation on processed image



Source: ARRB.

Categorisation

Each frame is analysed to determine the presence of the following cracking types as well as straight features (trenches, joints, patches – longitudinal & transverse):

- longitudinal crack
- transverse crack
- crocodile crack
- no cracking.

When four or more cracks occur in the one frame, the frame is classified as containing crocodile cracking. If there are less than less cracks, then the frame will contain either longitudinal, transverse or both longitudinal and transverse cracks. In the latter case, both the ’longitudinal’ and ‘transverse’ cracks are included in their respective cracked frames totals. However, they are only counted once for the ‘total cracked frames’ result.

The ‘*predominate’* cracking type for each segment and wheelpath is also determined. This is determined by calculating the affected area for each crack type; the type with the greatest affected area is then reported as the predominant crack type.

Severity and width

A value for the *average* crack width is reported for each frame. The section average is the average of the cracked frame values over the total number of cracked frames, not the total number of frames within the segment.

Intensity/length

A value of 'intensity' is calculated by dividing the total crack length within an area. Two types of intensity are reported:

- intensity across the entire segment
- intensity per frame, and then averaged over the number of cracked frames.

This is similar to the AASHTO standard PP67 for automated cracking analysis (Qui et al. 2016).

Wheelpath cracked length (WPCL)

If a crack is detected in either the OWP or IWP, or both wheelpaths, then the longitudinal position is counted as 'cracked'. The frame is analysed in the transverse direction and reported in the longitudinal direction. A value of WPCL was reported for each segment specified.

Output format

As stated previously, the output report is aggregated into 10 m segments for each channel. All values are reported as 'number of cracked frames' unless otherwise specified. The outputs and categorisations are defined as shown in Table 3.3.

3.5 Pavement Profile, Roughness and Texture

3.5.1 A five laser profiler is fitted to the TSD as per Figure 3.13. It is used to measure the roughness and texture of the pavement surface. The specification for this laser system is outlined in Roughness

Roughness data is collected in accordance with the ARRB Test Method and the specification set out in Austroads Test Method AG:AM/T001 (Austroads 2016a).

The ARRB laser profiler is classified as a non-contact inertial laser profiler. It uses a paired laser and accelerometer located in each wheelpath (defined as 750 mm either side of the centreline of the vehicle) to measure the longitudinal profile of the pavement. The profiles are sampled every 25 mm of longitudinal travel. The lasers have an accuracy of 0.01 mm, and the accelerometers are capable of measuring wavelengths up to 90 metres or more.

Once the longitudinal profile is calculated, it is passed through the quarter-car model to calculate the International Roughness Index (IRI) and NAASRA lane roughness as per the methodologies specified in the Austroads *Guide to Asset Management Part 5B: Roughness* (Austroads 2007) and other international standards.

ARRB has incorporated automated checks into the data processing software to exclude any contribution to roughness from data collected at locations such as cattle grids, railway crossings, bridge abutments, etc. and also if the survey speed is below the typically level of 20 km/h (user definable).

Table 3.4. The LCMS, shown in Figure 3.9, is used to measure the transverse profile and rut depth in addition to crack measurement.

Figure 3.13: Image of five laser assembly

Source: ARRB.

Table 3.3: Output report: crack detection

Outer wheelpath (10 m segment)	Inner wheelpath (10 m segment)	Between wheelpaths (10 m segment)
Longitudinal cracked frames (no. of frames)	Longitudinal cracked frames (no. of frames)	Longitudinal cracked frames (no. of frames)
Straight features (trenches, patches – long. & trans.) (no. of frames)	Straight features (trenches, patches – long. & trans.) (no. of frames)	Straight features (trenches, patches – long. & trans.) (no. of frames)
Crocodile cracked frames (no. of frames)	Crocodile cracked frames (no. of frames)	Crocodile cracked frames (no. of frames)
Transverse cracked frames (no. of frames)	Transverse cracked frames (no. of frames)	Transverse cracked frames (no. of frames)
Total cracked (long., croc. & trans.) frames (no. of frames)	Total Cracked (long., croc. & trans.) frames (no. of frames)	Total Cracked (long., croc. & trans.) frames (no. of frames)
Total no. of frames (all frames surveyed within segment)	Total no. of frames (all frames surveyed within segment)	Total no. of frames (all frames surveyed within segment)
Predominant crack type (type with the overall greatest calculated area of affect in particular segment)	Predominant crack type (type with the overall greatest calculated area of affect in particular segment)	Predominant crack type (type with the overall greatest calculated area of affect in particular segment)
Crack width averaged over no. of cracked frames (mm) (all three types together)	Crack width averaged over no. of cracked frames (mm) (all three types together)	Crack width averaged over no. of cracked frames (mm) (all three types together)
Crack Intensity averaged over segment (m/m^2) (all three types together)	Crack Intensity averaged over segment (m/m^2) (all three types together)	Crack intensity averaged over segment (m/m^2) (all three types together)
Crack Intensity averaged over no. of cracked frames (m/m^2) (all three types together)	Crack Intensity averaged over no. of cracked frames (m/m^2) (all three types together)	Crack Intensity averaged over no. of cracked frames (m/m^2) (all three types together)

3.5.2 Roughness

Roughness data is collected in accordance with the ARRB Test Method and the specification set out in Austroads Test Method AG:AM/T001 (Austroads 2016a).

The ARRB laser profiler is classified as a non-contact inertial laser profiler. It uses a paired laser and accelerometer located in each wheelpath (defined as 750 mm either side of the centreline of the vehicle) to measure the longitudinal profile of the pavement. The profiles are sampled every 25 mm of longitudinal travel. The lasers have an accuracy of 0.01 mm, and the accelerometers are capable of measuring wavelengths up to 90 metres or more.

Once the longitudinal profile is calculated, it is passed through the quarter-car model to calculate the International Roughness Index (IRI) and NAASRA lane roughness as per the methodologies specified in the Austroads *Guide to Asset Management Part 5B: Roughness* (Austroads 2007) and other international standards.

ARRB has incorporated automated checks into the data processing software to exclude any contribution to roughness from data collected at locations such as cattle grids, railway crossings, bridge abutments, etc. and also if the survey speed is below the typically level of 20 km/h (user definable).

Table 3.4: Specification for LIMAB laser

Performance	
Stand off	200 mm
Measurement range	200 mm
Resolution (internal)	0.01 mm
Sample speed	32 kHz
Detector type	Charged Coupled Device (CCD)
Power supply	10–36 Volts Direct Current (VDC)
Laser	
Wavelength	635–670 nm
Laser power	< 20 mW
Laser class	3B
Enclosure	
Dimension	175 x 112 x 44 mm
Weight	1.3 kg
Protections class	IP 65
Operating temperature	0 +40 °C
Storage temperature	–20 °C to +70 °C
Material	Lacquered aluminium
Interfaces	
Service interface	Ethernet
RS422 Clock/Data	Output rate 16 / 32 / 62 kHz (Compatible with Selcom)
Functions/Features	
Measuring algorithm Triangulation with modified 'centre of gravity'	
Suppression of background light and second reflections	

The operators receive in-vehicle feedback, including calculated values, historical graphs and automatic error check messages in real time. All automatic errors are logged with the data for future interrogation when checking for data irregularities.

In order to identify significant events that may affect the data, e.g. wet surface, driving deviation from nominated wheelpath, events are recorded during the data acquisition in line with general best practice.

Advanced calculations such as maximum and minimum values, standard deviations, binning and a further pavement condition index called Ride Number (calculated in accordance with American Society for Testing and Materials(*ASTM 2013)* can also be generated by the processing software as required.

The IRI is calculated in accordance with the computer code contained in ASTM (2015).

In summary, each of the lasers are factory calibrated and then block checked to ensure that the measurements made by the lasers are accurate. Additionally, the system undergoes a daily 'still and bounce test', which simulates data collection on a perfectly flat section of road. The IRI measurements should be close to zero if the lasers and accelerometers are working correctly. ARRB has set a limit of 0.1 and 0.2 m/km for the outputs of the 'still and bounce' phases of the test respectively.

ARRB's Hawkeye processing software uses the longitudinal profile it measures to calculate the roughness. Roughness is reported as:

- outer (left) and inner (right) wheelpath IRI (quarter car model)
- lane IRI (half car model i.e. profile average)
- NAASRA roughness (counts/km).

3.5.3 Surface Texture (Macrotexture)

Roughness data is collected in accordance with the ARRB Test Method and the specification set out in Austroads Test Method AG:AMT/013 (Austroads 2016b).

The ARRB Hawkeye system measures the macrotexture of the pavement surface using three non-contact 32 kHz lasers. The speed of the data collection from the laser is sufficient that height measurements are made every 1 mm or less at a collection speed of 100 km/h.

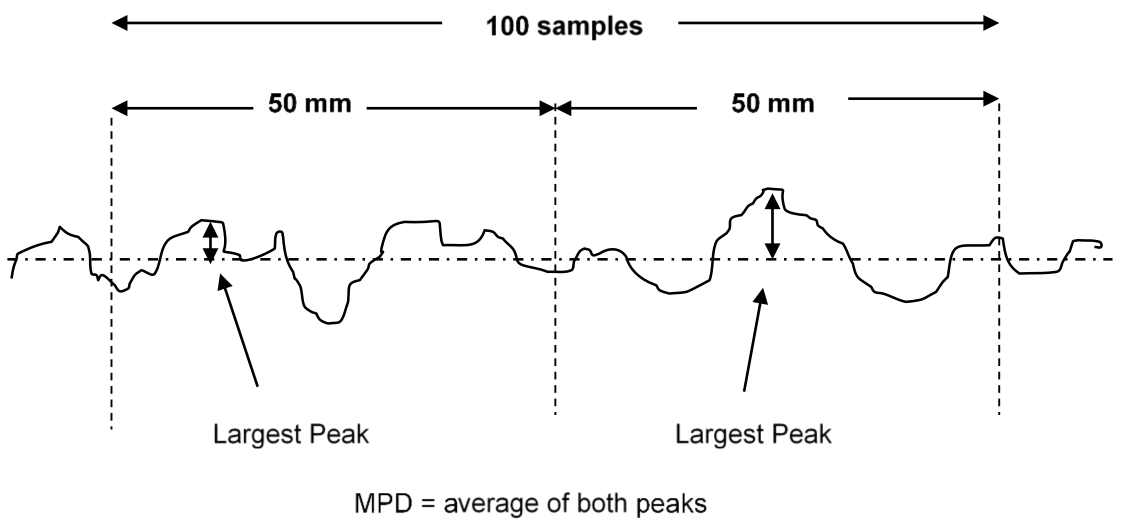
Mean profile depth (MPD)

The macrotexture is reported as MPD. It is measured once every 1 metre in each measurement path and averaged for the selected reporting interval, e.g. 100 m. The MPD is reported in accordance with Austroads (2016c).

The basic premise of the calculation is shown in Figure 3.14. The pavement profile is measured every 1 millimetre and divided into 100 mm segments consisting of 100 samples points. A linear regression line is calculated using all of the sample points and subtracted from the profile to suppress the slope of the profile curve.

The 100 mm segment is then divided in two and the height of the highest peak calculated for each 50 mm section. The mean profile depth for each segment is determined by averaging the two peak values and subtracting the average profile level, i.e. the linear regression line.

Figure 3.14: Calculation of mean profile depth



Source: ARRB.

Sand patch texture depth (SPTD)

An estimate of the sand patch texture depth is calculated using the following equation (International Organization for Standardization (ISO) 1997):

ETD = 0.8 x MPD + 0.2

However, this relationship does not take into account differences in laser performance, especially noise levels, nor variations in manual sand patch measurements.

3.5.4 For this reason SPTD values in the supplied database are calculated from laser measured texture depth (SMTD[3]) measurements using a correlation equation that was developed specifically for the LIMAB lasers fitted to the TSD. The LIMAB laser specification is presented in Roughness

Roughness data is collected in accordance with the ARRB Test Method and the specification set out in Austroads Test Method AG:AM/T001 (Austroads 2016a).

The ARRB laser profiler is classified as a non-contact inertial laser profiler. It uses a paired laser and accelerometer located in each wheelpath (defined as 750 mm either side of the centreline of the vehicle) to measure the longitudinal profile of the pavement. The profiles are sampled every 25 mm of longitudinal travel. The lasers have an accuracy of 0.01 mm, and the accelerometers are capable of measuring wavelengths up to 90 metres or more.

Once the longitudinal profile is calculated, it is passed through the quarter-car model to calculate the International Roughness Index (IRI) and NAASRA lane roughness as per the methodologies specified in the Austroads *Guide to Asset Management Part 5B: Roughness* (Austroads 2007) and other international standards.

ARRB has incorporated automated checks into the data processing software to exclude any contribution to roughness from data collected at locations such as cattle grids, railway crossings, bridge abutments, etc. and also if the survey speed is below the typically level of 20 km/h (user definable).

Table 3.4.

For the TSD, SPTD is calculated using the following equation:

SPTD = 1.2361*SMTD + 0.1246.

This is also reported continuously along the pavement surface in accordance with Austroads (2016c).

Texture results in MPD and SPTD format, and advanced calculations such as per cent length flushed (ETD < 0.64 mm), are also calculated for each reporting interval for the centre, inner and outer wheelpath locations.

3.5.5 Rut Depth

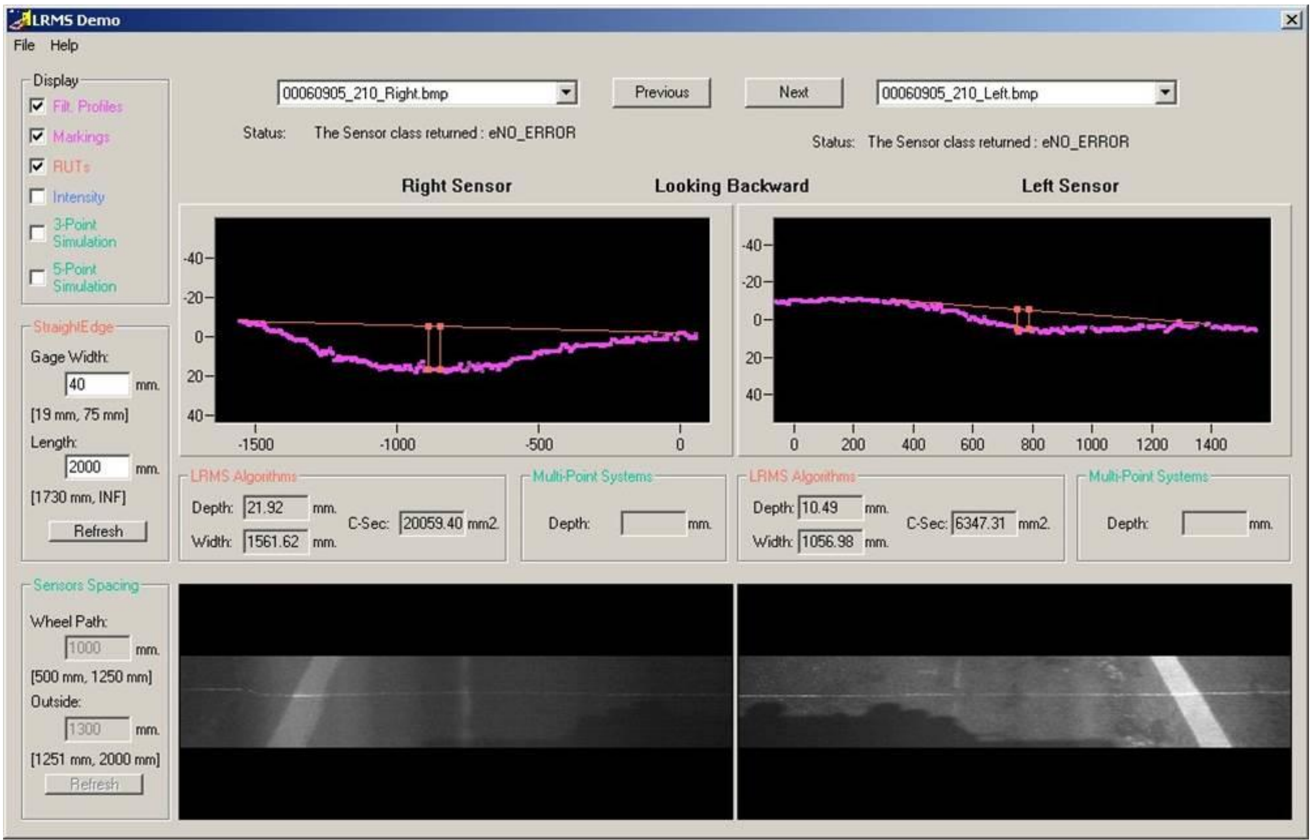
Roughness data is collected in accordance with the ARRB Test Method and the specification set out in Austroads Test Method AG:AM/T009 (Austroads 2016c).

3 SMTD is not reported in the database.

The ACD system can also measure rutting (see Figure 3.9). The ACD measures the transverse profile of the pavement at a sampling rate of 5.6 kHz, which equates to one transverse profile being recorded every 5 mm of longitudinal travel at a survey speed of 100 km/h. It does this over a nominal 4 m width at a 1 mm resolution.

The rutting results are produced every 1 m and aggregated to produce a value for the given report interval, e.g. 100 m. An example of the transverse profile measured by the ACD in each wheelpath is shown in Figure 3.15.

Figure 3.15: ACD rut depth measurement



Source: ARRB.

The high resolution of the transverse profile allows the ACD to identify other features such as edge drop-off by detecting the relative height measurements towards the edge of the rut profile whilst the intensity values can identify the presence of line marking. These features are used to limit the rut measurements to the lane itself.

Identifying these features enables the edge effects that may be experienced when travelling along narrow carriageways, such as kerb and edge drop-off, to be eliminated from the results. Rutting is calculated based only on data points that fall within the lane width, and measurement is restricted to the wearing surface of the pavement. The limiting extent for rutting measurement are:

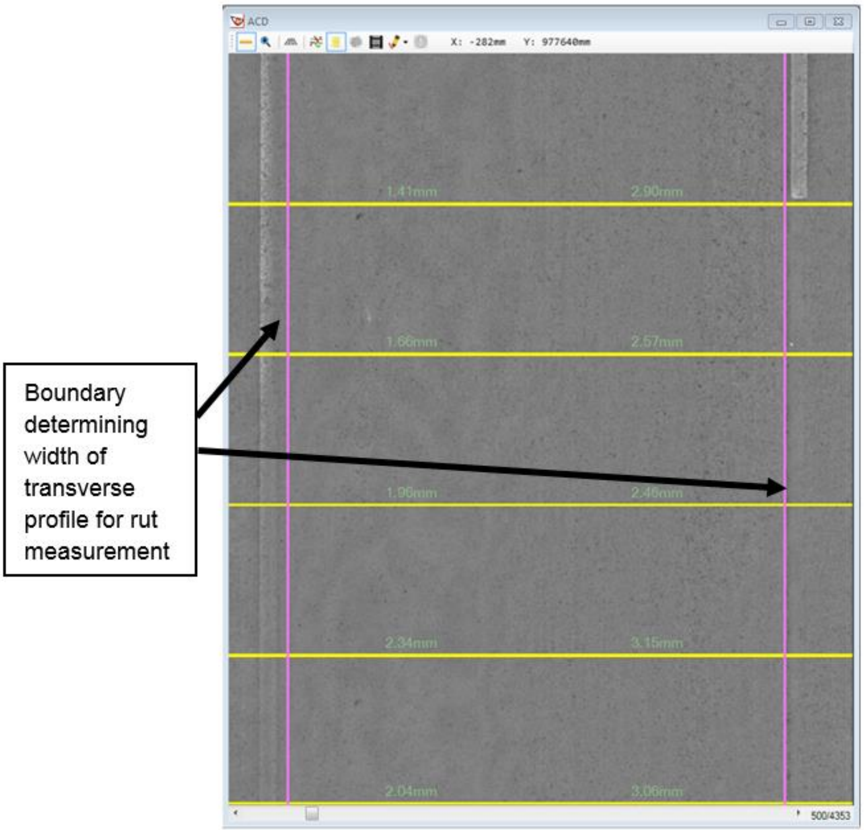
- where line-marking is detected on each side of the lane, the ends of the transverse profile are 75 mm in from each of the line-marks
- where edge drop-off of greater than 12.5 mm height is detected, the corresponding end of the transverse profile is 150 mm in from the edge of the drop-off

- where a kerb of greater than 22.5 mm height is detected, the corresponding end of the transverse profile is 300 mm in from the kerb edge
  Note that the kerb edge is the vertical face of the kerb.
- if line marking, edge drop off, or a kerb are only identified on one side of the road, the corresponding end of the transverse profile can be set to either 75 mm, 150 mm or 300 mm in from the detected feature and the width of the transverse profile set to 3 000 mm
- where there is no line marking, kerb or edge drop off detected, the width of the transverse profile is set to 3 000 mm and positioned 1 500 mm either side of the centre line of the survey vehicle.

The boundary definition is locked for two successive frames to keep the assessment area consistent along the lane, for example, where the edge line marking to the left momentarily stops when passing through intersections, or spacing between the centreline marking is sporadic or worn.

The assessment area is defined in Figure 3.16. The lines to the left and right of the picture indicate where line marking has been detected and the boundaries of the area in which the rutting data is analysed.

Figure 3.16: Definition of transverse profile width



Source: ARRB.

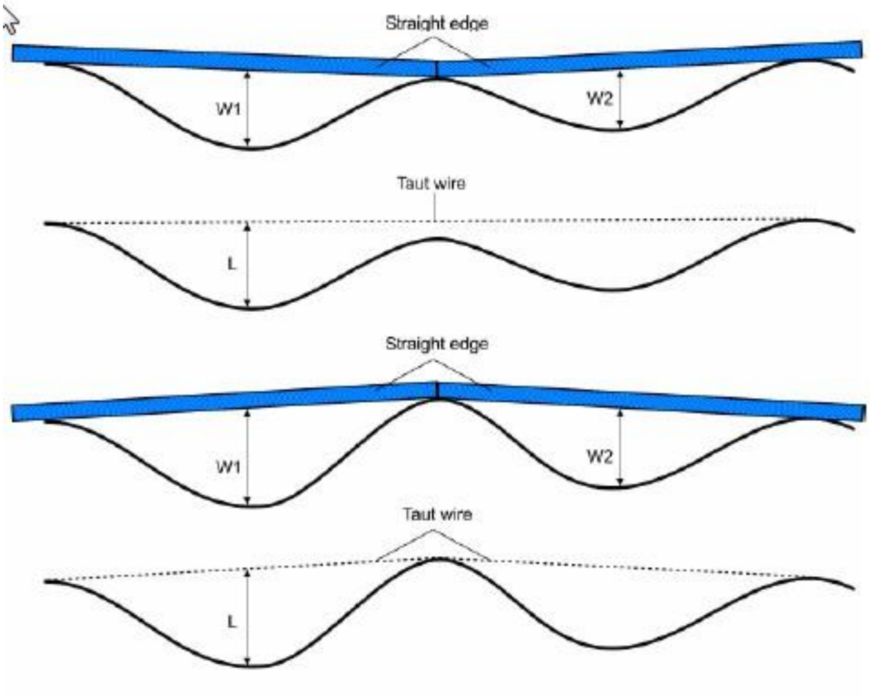
It should also be noted that a smoothing filter is applied to the transverse profile and not all of the points are necessarily used to calculate the rut depth. The smoothing filter for this project is usually set to 125 mm.

The ACD has the added advantage of being able to model the width of the gauge block, which is also as shown in Figure 3.15. The gauge block width specified most projects is 40 mm.

The system can either calculate the rut depth in each wheel path independently or the two profiles are stitched together to produce a full 4 m transverse profile across the lane[4]. The ACD can model a taut wire (or string line) across the entire transverse profile, which is useful when trying to determine the maximum rut depth across a lane, or emulate a straight edge of a specified length e.g. 2 m.

The different measuring methodologies are shown in Figure 3.17.

Figure 3.17: Different rut measurement methodologies



Source: ARRB.

The algorithm is flexible: a straight edge of any length up to 4 m can be emulated, as can a 4 m taut wire.

3.6 Distance and Location Measurement

3.6.1 Data Location Referencing and Direction

All data is referenced to the information made available through dialogue between ARRB and MRWA. For this trial, ARRB created a road list based on spatial data; it was then edited based on past surveys completed for MRWA. Once scheduled the road list was loaded into Hawkeye Manager, which is used to track completed surveys and monitor progress via a 4G connection in the vehicle.

4 The actual width of the transverse profile is less than 4 m as there is some overlap between the two wheelpath profiles.

All roads included in the road list must be suitable for the size and weight of the TSD. Where necessary, permits must be obtained to allow passage on bridges and local roads.

3.6.2 Distance Measurement

High-resolution horizontal velocity measurements, i.e. the travel speed of the TSD, are critical for making the deflection slope calculations. Distance and velocity are measured utilising an odometer wheel assembly as shown in Figure 3.18.

Figure 3.18: Odometer wheel assembly

Source: ARRB.

The odometer assembly consists of a mounting column positioned just behind the load wheel. It has an integrated air suspension system which pushes the wheel on to the road surface utilising the pressure from the prime mover air system at 5 bar (72.52 psi or about 520 kPa). The wheel can be raised or lowered remotely using control panels. The specification for the odometer is shown in Table 3.5.

The distance measuring device is calibrated prior to the commencement of each survey in accordance with Austroads (2011). A calibration routine contained within the acquisition software is used in conjunction with a distance calibration site of any length. The accuracy is within ± 0.1%.

The same odometer pulse count is used for all distance measurements within the TSD system such as crack detection and laser profiling.

Table 3.5: Specification for the odometer

Specification	
Tyre type	Bridgestone Battlax BT 56F
Dimension	120/60 R 17
Pressure	45 psi (310 kPa)
Encoder type	Heidenhain ROD 420
Pulse per revolution	20 000

The odometer must remain accurate at all times during the survey.

3.6.3 Global Positioning System

A Global Positioning System (GPS) is used to supplement the location reference system. A GPS coordinate is provided at the start and end of each processed data segment.

GPS is collected with a differentially-corrected Global Navigation Satellite System (GNSS) receiver at intervals of 1 second. The system utilises a 24-channel GNSS GPS receiver with external antenna. The system is capable of delivering real-time sub-metre accuracy[5].

The GNSS utilises up to 55 Medium Earth Orbit (MEO) satellites spread between several orbital planes from both the United States NAVSTAR Global Positioning System (GPS) and the Russian Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) satellite constellations. The specification for the DGPS equipment is presented in Table 3.6.

Table 3.6: DGPS specification

Description – GPS	Specification
Model type	SPS855 GNSS Modular Receiver
Satellites	Up to 24 satellites with clear view of sky
Operating temperature	–40 °C to +65 °C
Update rate	1 second
Position accuracy	OmniSTAR Positioning VBS service accuracy Horizontal <1 m
Data format	NMEA 0183 Version 2.0 ASCII

3.6.4 Gipsi-Trac

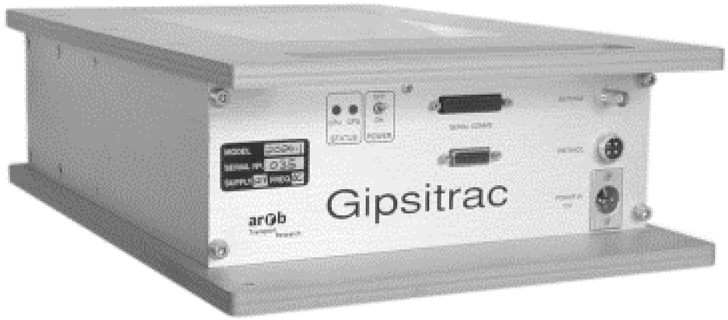
The Gipsi-Trac road geometry system uses dead-reckoning sensors and a GPS receiver to collect road geometry information for continuous 3D highway mapping (see Figure 3.19). The high-precision unit contains two accelerometers and a gyroscope which allow it to accurately measure the following parameters:

- horizontal curvature
- vertical curvature
- centreline alignment
- slope
- crossfall.

This information is sampled every 2 metres of longitudinal travel. It can be reported at any desired interval above 10 m. Gipsi-Trac provides road geometry and position for complex 3D highway mapping; it can locate potential sites for rainfall ponding and also estimate speed and travel times.

5 At the present time, electronic radiation interference from the Doppler laser units is affecting the OmniSTAR differential correctional signal, causing it to only to be received intermittently. Whilst a temporary solution is improving the results, a permanent solution is yet to be implemented.

Figure 3.19: Gips-Trac unit



In areas where the GPS is blocked by trees, buildings, etc. or if the GPS signal is weak, the unit can be utilised to 'correct' the spatial position of the processed GPS data.

3.6.5 Data Alignment

The TSD data is output every 10 metres. The data is aligned and integrated through GPS time-based primary keys (PK) with other data streams and road location reference points. All reference measurements are recorded from the same original source of odometer (distance) and GPS receiver (spatial coordinates).

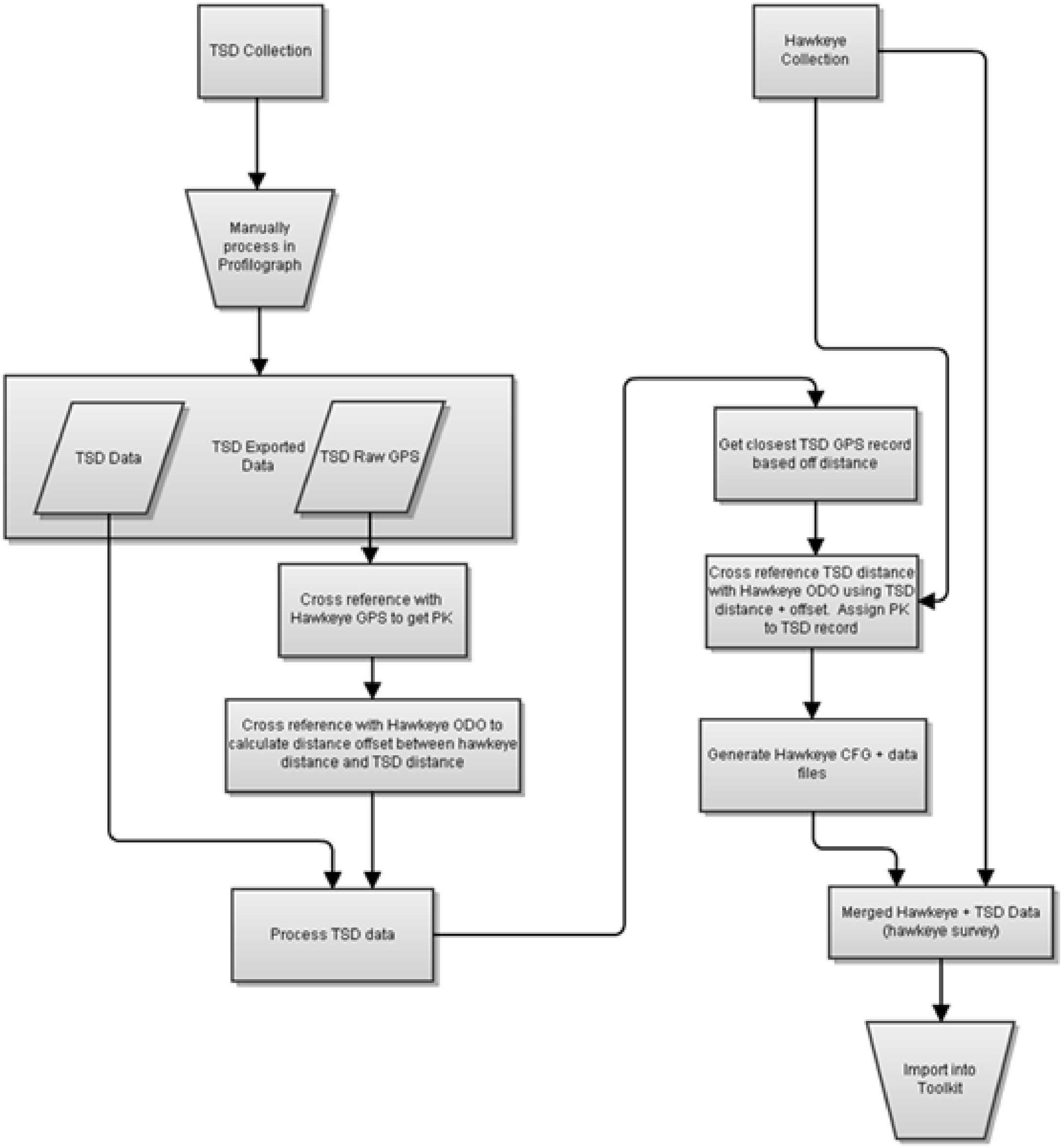
A merge utility program merges raw TSD data (Greenwood) to Hawkeye (ARRB) data for processing within the Hawkeye toolkit. The raw TSD data first needs to be processed by the Greenwood profilograph software, which produces a CSV output[6]. This is then imported into an existing Hawkeye survey database with the primary key (PK) allocated based on the GPS time data.

To improve accuracy and reduce prevent drift on longer survey runs, the TSD GPS raw file (gpsraw.txt) is exported from the TSD software as it contains the distances for each GPS time value. Utilising the Hawkeye GPS file, a lookup query identifies the PK at each of the TSD GPS times. Whilst the exported TSD data contains a distance for each result interval, the data does not contain any direct references back to the GPS file. The distance offset is calculated from the TSD distance vs Hawkeye distance using the difference between TSD distance and Hawkeye distance at the GPS time.

The utility then reads through the TSD data file to retrieve a PK for each interval distance using the TSD distance + offset to look up the binary Hawkeye odometer file. To tighten this up further the offset is taken from the closest TSD GPS time to avoid any potential drift in the results. The process flow chart for data merging and alignment is shown in Figure 3.20.

6 CSV is a simple file format used to store tabular data, such as a spreadsheet or database. Files in the CSV format can be imported to, and exported from, programs that store data in tables, such as Microsoft Excel or OpenOffice Calc. CSV stands for 'comma-separated values'.

Figure 3.20: Process flow chart for data merging and alignment

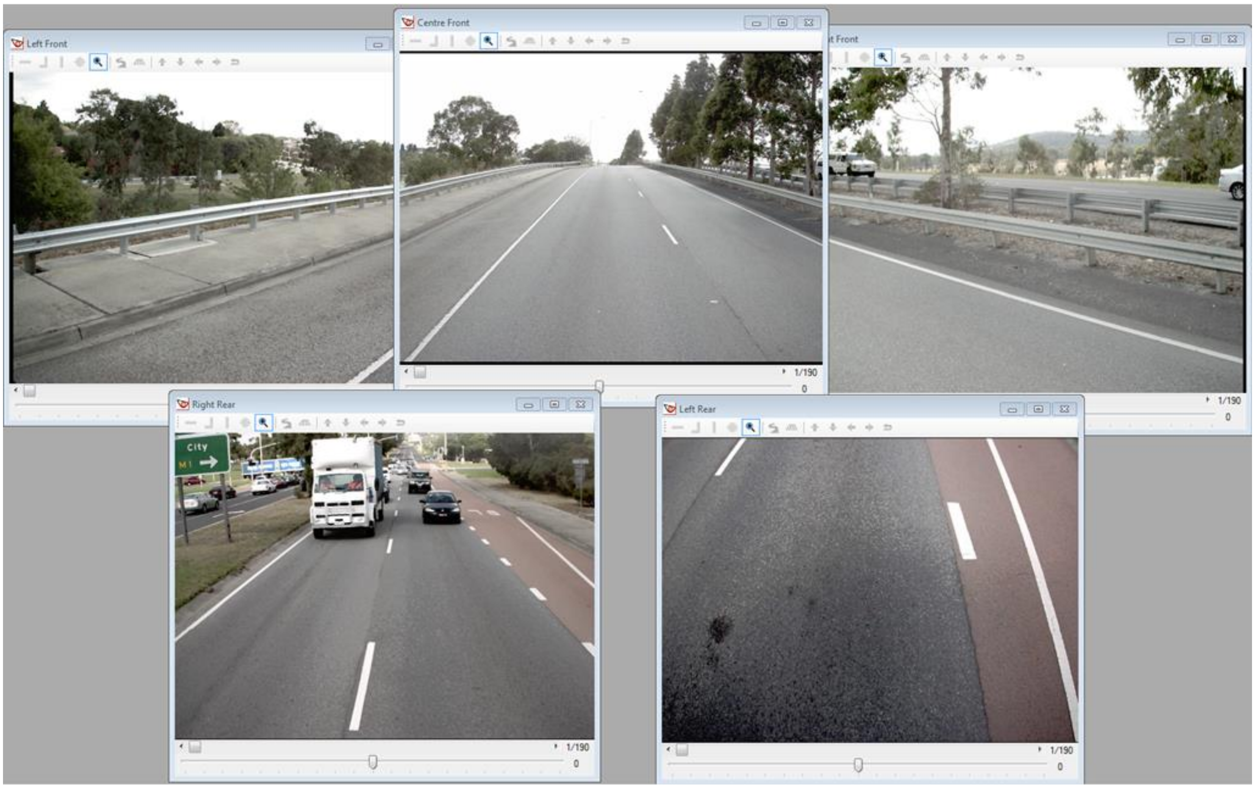


Imaging

The TSD is fitted with a number of digital imaging cameras mounted within the prime mover cabin, and on the rear facing ACD pods as shown in Figure 3.9. These cameras are used to record digital images of the pavement and road assets. They are orientated to ensure that points of interest are recorded in the camera's field of view. All cameras are calibrated, therefore enabling the position of all assets to be referenced geospatially.

An example of images captured by the cameras is provided in Figure 3.21.

Figure 3.21: Example of Images captured by cameras



Captured images are referenced by linear position (in relation to road location information) and geospatially (latitude and longitude). This makes it possible to locate defects or features on the network by chainage and spatial coordinates. This facility also makes it possible to capture inventory information, complete with a unique GPS position.

The width of the combined view enables roadside hazards and pavement assets up to 5 metres or more from the left-hand side of the pavement to be identified. The Hawkeye software will provide a clear picture of intersections and junctions alongside the road.

As the primary focus of the TSD is to collect deflection data, followed by cracking and other profiler data, imaging data is only collected where conditions allow (see Section 3.6.9).

3.6.6 Video Image Sample Interval

The digital images are collected every 10 metres to ensure that detailed information is not lost. The images themselves have a high resolution and the set-up of the cameras easily allows lettering less than 100 mm in height to be read. The viewing software also has a zoom function to allow smaller lettering to be read.

3.6.7 Lane Data Capture

All surveys were conducted in both directions, and in the most-heavily trafficked lane of multi-lane pavements. The road location information was incorporated into the data during capture.

3.6.8 Camera Configuration

A five (5) camera configuration was used to capture pavement defects. All the cameras were calibrated for scale measurement, thus enabling the position of all assets to be referenced geospatially. The specification for the cameras that are mounted on the TSD are shown in Table 3.7.

Table 3.7: Specification for cameras

Description	Specification
Image position error	Less than 1 m with DMI distance sensor
Typical sensor type	1/1.8" IT CCD progressive scan
Exposure control	Automatic or manual control
Camera interface	RJ45 connector with 10/100 Base-T Ethernet
Image resolution	1 600 x 1 200 (2 Megapixels)
Picture size	1 600 x 1 184 pixels
Colours	Full colour, non-compressed YUV 4:2:2
Survey speed	Zero to full highway speeds
Frame rate	Able to capture frames at 5 m intervals while travelling at maximum survey speed of 100 km/h (10 m for this project)
Frame rate configuration	Software configurable, based on time or distance, external trigger operation
Compression	Colour MJPEG
Lens type	Focal length 3.8 to 13 mm, 3.4× optical zoom; DC auto iris (controlled from camera) Manual focus and zoom
Field of view	80 ° to 28 ° (horizontal) – default setting is 44°
Storage format	AVI

3.6.9 Restrictions

Noting that imagery in a secondary data set, operators will take into account the following restrictions during data capture to ensure that quality data is not compromised (where possible):

- Imaging technology requires appropriate lighting: images are collected when lighting conditions are conducive to recording images of high quality.
- Wet pavements can mask defects: images should only be collected on dry pavements.
- Extreme contrast can cause bleeding on an image: images should be collected in such a manner to reduce the impact of bleeding, i.e. the vehicle should not be driven in 'low angle sun' at the start and end of the day.
- A dirty lens can affect images: prior to commencing data collection, the lens of each camera should be checked for cleanliness to ensure that images are free of degradation due to dirt, insects, etc.
- Images can be affected by vibration: the cameras are mounted inside the cabin of the truck which minimises vibration and allows the cameras to be orientated to suit the needs of individual clients. Note also that the image size is the highest resolution currently available in Australia.
- It is not possible to capture fine cracking from images: crack widths of less than 2.5 mm can be difficult to observe even with high resolution images due to the high travel speeds. Cracking of this width can also be difficult to observe from a manual footpath-based assessment and impossible from a windscreen-based assessment.
- Kerbs and roadside footpaths can be obscured by parked cars: surveys of heavily-parked streets should be conducted when the extent of paring is light. However, in some cases the rating of the condition of kerb and roadside footpaths may have to be based on what is visible on either side of a parked vehicle.

4 DETAILS OF VALIDATION TRIAL

Prior to the validation trial, the equipment was validated against a 'ground truth' data set that is traceable back to national standards. Local checks were also performed to check for consistency of measurement.

For a longer-term contract, a benchmarking site would need to be established locally following consultation with MRWA staff. A validation would then be performed every six weeks to ensure that any issues are identified as early as possible and that the impact on any data collected in the interim is minimised. The final validation would typically be undertaken within 14 days of the completion of the survey. A number of daily checks would also be undertaken to ensure that the equipment is performing as expected.

An edited excerpt from the TSD Quality Plan, Version 1.1 (ARRB 2017) follows.

Laser Angle

The measurement system is highly sensitive to any differences in the mounting angles of the Doppler lasers. As such, the relative differences between the lasers must be known. Additionally, and to ensure that the angles have remained unchanged during transit, or over extended use, a geometric calibration process should be undertaken regularly. It is suggested that a laser angle calibration or check be performed on a monthly basis.

The ideal criteria for a Doppler laser geometric calibration site are that it:

- is at least 1 km long (1.5 km preferable) – to provide sufficient data to perform offset calculation
- consists of a homogeneous pavement (same construction, surface type throughout, no bridges, culverts) – allows the collection of repeatable and consistent data on and below the surface
- has a smooth consistent surface, i.e. no dips, bumps, potholes, patches, ravelling, etc. – to ensure that the magnitude of the dynamic loading being applied to the pavement is as low as possible
- is as straight and flat as possible – ensures that the gyros, laser servo height and other data compensations are minimised and do not have an impact on the Doppler reading/calibration
- has a posted speed that allows TSD to survey below 80 km/h to minimise potential data loss
- has suitable turn around locations at the start and end of the site to minimise time between runs and internal and external temperature changes
- has a light-coloured surface – Doppler lasers work better on lighter-coloured surfaces (darker surfaces absorb more laser light); however, experience has shown that most asphalt or spray seal surfaces are acceptable
- is located near an existing distance calibration site
- as safe to operate on as possible – allows WHS requirements to be met.

Distance

A distance calibration is completed prior to each Doppler laser calibration. Ideally, the distance calibration site is near to, or the same as, the Doppler laser calibration site.

Distance calibrations are completed on a quarterly basis over a survey verified distance calibration site with a minimum length of 1 km, or sooner when the vehicle is near an agreed validation/calibration site. The process is described in more detail in the TSD User Manual.

Benchmarking

Benchmarking loops, or check loops, are run pre- and post-Doppler laser calibration. The primary purpose of the benchmarking is to maintain confidence in the TSD calibration, operational processes and stability of the system throughout the survey. Utilising the same sites over the long term also allows a history to be built up; the impact of seasons, long-term climate cycles, temperature changes, etc. can also be analysed.

The criteria for a benchmarking site are that it is:

- 5 to 25 km long – must be long enough to exhibit a range of measurements necessary to perform a statistical analysis; it must also enable at least three repeat runs pre- and post-laser geometric calibration to be undertaken on the same day (the time between runs should be also minimised as this will limit internal and external temperature changes and possibly provide extra time to undertake additional runs, trials, research, etc.)
- ideally allow travel at varying and moderate speeds (up to 90 km/h) with suitable turn around locations so that the TSD can safely survey below 70 km/h if necessary to minimise potential data loss
- unaffected by traffic, i.e. peak hour traffic, parking restrictions, traffic lights, urban areas, etc.
- within 15 minutes of existing distance/laser angle calibration sites
- likely to stay ‘untouched’ for five years to build up a good site history, i.e. no resealing or rehabilitation work.

5 DATA COLLECTION AND PROCESSING AND DELIVERABLES AND NEXT STEPS

Key element of the data collection and processing are as follows:

- In late October 2016, MRWA was supplied with the schedule for data collection and processing including the roads to be surveyed by date, the personnel involved, and when data would be available to the road agency.
- The data was collected during the period 7 November to 13 November 2016.
- The schedule was circulated to MRWA during testing and updated weekly.
- The data collected during the survey was supplied to MRWA in the database format in February 2017.
- The data collected by the lasers was pre-processed within the Greenwood software program ‘TSD for Windows’ to correct for variances associated with the laser positioning, e.g. mounting angle, beam alignment, etc.
- The data was then post-processed utilising the ARRB Hawkeye Toolkit to provide linear and geo-referencing information, event tagging and road section identification, as well as alignment to other data streams.
- All raw data and the means of reprocessing the data from the annual survey will be retained for a period of seven years.

5.1 Deliverables

Following the data collection and processing ARRB supplied MRWA with a Microsoft Access database, titled: PSS16174_MRWA_TSD_TRIAL_2016-12-08 and ARRB provided access to all attributes via Hawkeye Insight[7] on 2 February 2017.

The database includes all data attributes as listed in Appendix A.

[7] Hawkeye Insight is a cloud based data viewing tool developed by ARRB.

6 CONCLUSION: POTENTIAL USE OF TSD DATA

As discussed in the Introduction, road agencies across Australia and New Zealand have recognised that there is significant potential to derive benefits from the collection of the full complement of high-speed data such as that undertaken and delivered through this TSD trial for MRWA. While this data is collected through the emerging technology of the TSD, there is a vast store of historical structural and functional performance data that exists across WA and that needs to be harnessed to achieve the full benefits the TSD presents. There are a number of areas of interest and questions that have been raised in discussions with collaborating road agencies also receiving TSD data. These areas of interest have been synthesised into the following two areas, including the following questions that these broad areas would look to address to harness this investment.

- Benchmarking past, current and future network performance data to ensure MRWA maximises the TSD and other emerging technologies
  - What degree of change is expected/has been observed in the measured network condition arising from a change in data collection techniques (i.e. method of crack assessment), equipment or supplier over the history of its data collection?
  - Are the observed data trends and annual changes in all the network condition parameters sufficient to justify a new data collection strategy, and what options might be considered?
  - What degree of quality deflection and surface condition time series data is available from all of the available data that the agency possesses and what should be changed/modified?
  - What is the current relationship/correlation between the deflection data collected at differing intensity levels and can such a relationship/correlation be credibly developed between differing deflection data collection techniques and technology?
- Reviewing, collating and analysing the data store to enhance pavement asset management operations and deliver a sustainable framework for long-term strategic planning
  - Can a relationship between time series deflection data and alternative variables (primarily climate, age and traffic load) be identified/developed?
  - Can this data be used to generate or validate useful pavement strength prediction models which could be used in pavement modelling at the network level?
  - Does a relationship exist between poor functional condition, i.e. pavement roughness, inadequate strength?
  - How can functional and structural data best be employed in treatment selection?

These questions raise issues of data relevance, interrelationships, modelling and useability to the derivation of benefits in this investment. As a result of this trial TSD survey, MRWA is now in a position to assess the benefits of the data that has been collected in the past and to determine how this can assist to inform future data collection strategies. Furthermore, this review will provide clear direction regarding improvements that could be implemented within a sustainable asset management framework to assist with informed decision-making.

It is considered that there are two specific projects that MRWA could consider for further investigation as part of a suite of projects. Given ARRB's unique position working with other road agencies in data collected using the TSD, ARRB would be pleased to be part of the MRWA projects should they proceed. Given MRWA's interest in maximising this investment in a trial, it would be advisable to undertake these projects sequentially, as the outcomes of the first project would assist to inform both the scope and the objectives of the second project.

REFERENCES

American Society for Testing & Materials 2013, *Standard practice for computing ride number of roads from longitudinal profile measurements made by an inertial profile measuring device)*, ASTM E1489–08, ASTM, West Conshohocken, PA, USA.

American Society for Testing & Materials 2015, *Standard practice for computing international roughness index of roads from longitudinal profile measurements*, ASTM E1926-08, ASTM, West Conshohocken, PA, USA.

ARRB Group 2017, 'TSD quality plan combined NZTA TMR RMS', software, version 1.1, ARRB Group, Vermont South, Vic.

Austroads 2007, *Guide to asset management: part 5B: roughness,* 2nd edn, AGAM05B-07, Austroads, Sydney, NSW.

Austroads 2011, *Distance measurement validation of road condition monitoring vehicles*, test method, AGAM-T005, Austroads, Sydney, NSW.

Austroads 2012a, *Review of the traffic speed deflectometer: final project report*, by J Kelley & M Moffatt, AP-R395-12, Austroads, Sydney, NSW.

Austroads 2012b, *Benefits and risks of investing in network level deflection data collection*, by T Martin, AP-T217-12, Austroads, Sydney, NSW.

Austroads 2016a, *Pavement roughness measurement with an inertial profilometer*, test method AGAM-T001, Austroads, Sydney, NSW.

Austroads 2016b, *Pavement surface texture measurement with a laser profilometer*, test method AGAM-T013, Austroads, Sydney, NSW.

Austroads 2016c, *Pavement rutting measurement with a laser profilometer*, test method AGAM-T009, Austroads, Sydney, NSW.

Baltzer, S, Pratt, D, Weligamage, J, Adamsen, J & Hildebrand, G 2010, 'Continuous bearing capacity profile of 18,000 km Australian road network in five months', *ARRB conference, 24th, 2010, Melbourne, Victoria*, ARRB Group, Vermont South, Vic, 10 pp.

International Organization for Standardization 1997, *Characterization of pavement texture by use of surface profiles: part 1: determination of mean profile depth*, ISO 13473-1:1997(en), ISO, Geneva, Switzerland.

Qui, S, Wang, W, Wang, S & Wang, KPC 2016, 'Methodology for accurate AASHTO PP67-10-based cracking quantification using 1 mm 3D pavement images', *Journal of Computing in Civil Engineering*, vol. 31, no. 2.

Rasmussen, S, Krarup, J & Hildebrand, G 2002, 'Non-contact deflection measurement at high speed', in AG Correria & FEF Branco (eds), *Proceedings of the 6th international conference on the bearing capacity of roads, railways and airfields, Lisbon, Portugal*, pp. 53-60.

Roads and Maritime Services 2016, 'Use of pavement strength data', technical direction ATD 2016_001, RMS, Sydney, NSW.

Wix, R 2016, 'The traffic speed deflectometer: combining structural and functional pavement condition evaluation in Australia', *World congress on pavements and asset management*, *Baveno, Italy*.

Wix, R, Murnane, C & Moffatt, M 2016, 'Experience gained investigating, acquiring and operating the first Traffic Speed Deflectometer in Australia', *Transport Research Arena, 6th, 2016, Warsaw, Poland,* Transport Research Arena, Warsaw, Poland, 10 pp.

APPENDIX A DATA TABLES (TSD, PROFILE, CRACKING)

TSD	
FIELD	**DESCRIPTION**
id	Record id number
ARRB_ID	ARRB section ID
ROAD_NAME	Road name
ROAD_NUMBER	Road number
DIRN	Direction
REGION	Region
SLK_START	Start SLK reference
START_TRUE	Start TRUE reference
START_DESC	Start description
SLK_END	End SLK reference
END_TRUE	End TRUE reference
END_DESC	End description
DIST_FROM	Start sub chainage
DIST_TO	End sub chainage
LENGTH	Interval length
QUALITY	Greenwood data quality flags
ACCELERATION	Vehicle acceleration
AIR_TEMP	Air temperature
SURF_TEMP	Surface temperature
STRAIN_GAUGE_LEFT	Strain gauge left axle load
STRAIN_GAUGE_RIGHT	Strain gauge right axle load
SCI-300	Structural Condition Index 200 d0-d200 (curvature) (Roberts Muller model numerically integrated derived deflection bowl)
SCI-200	Structural Condition Index 300 d0-d300 (Roberts Muller model numerically integrated derived deflection bowl)
SCI-SUB	Structural Condition Index Subgrade (Roberts Muller model numerically integrated derived deflection bowl)
D0	Deflection calculation at 0 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D200	Deflection calculation at 200 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D300	Deflection calculation at 300 mm from load (Roberts Muller model numerically integrated derived deflection bowl
D450	Deflection calculation at 450 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D600	Deflection calculation at 600 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D750	Deflection calculation at 900 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D900	Deflection calculation at 750 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
D1200	Deflection calculation at 750 mm from load (Roberts Muller model numerically integrated derived deflection bowl)

TSD	
FIELD	**DESCRIPTION**
D1500	Deflection calculation at 750 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE100	Gradient slope measurement at 100 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE200	Gradient slope measurement at 200 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE300	Gradient slope measurement at 300 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE450	Gradient slope measurement at 450 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE600	Gradient slope measurement at 600 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
SLOPE900	Gradient slope measurement at 900 mm from load (Roberts Muller model numerically integrated derived deflection bowl)
RAW_SCI-200	Structural Condition Index 200 d0-d200 (curvature) (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SCI-300	Structural Condition Index 300 d0-d300 (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SCI-SUB	Structural Condition Index Subgrade (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D0	Deflection calculation at 0 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D200	Deflection calculation at 200 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D300	Deflection calculation at 300 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D450	Deflection calculation at 450 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D600	Deflection calculation at 600 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_D900	Deflection calculation at 900 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE100	Gradient slope measurement at 100 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE200	Gradient slope measurement at 200 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE300	Gradient slope measurement at 300 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE450	Gradient slope measurement at 450 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE600	Gradient slope measurement at 600 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
RAW_SLOPE900	Gradient slope measurement at 900 mm from load (Greenwood Euler-Bernoulli model derived deflection bowl)
GRADE	Grade
CROSS_SLOPE	Cross slope
H_CURV	Horizontal curvature
V_CURV	Vertical curvature
SPEED	Vehicle speed
EVENTS	Survey events

TSD	
FIELD	**DESCRIPTION**
START_LAT	Start latitude
START_LONG	Start longitude
START_ALT	Start altitude
END_LAT	End latitude
END_LONG	End longitude
END_ALT	End altitude
DATE	Survey date
TIME	Survey time
FILENAME	Survey filename
VEHICLE	Vehicle registration
OPERATOR	Operator names

PROFILE	
FIELD	**DESCRIPTION**
id	Record id number
ARRB_ID	ARRB section ID
ROAD_NAME	Road name
ROAD_NUMBER	Road number
DIRN	Direction
REGION	Region
SLK_START	Start SLK reference
START_TRUE	Start TRUE reference
START_DESC	Start description
SLK_END	End SLK reference
END_TRUE	End TRUE reference
END_DESC	End description
DIST_FROM	Start sub chainage
DIST_TO	End sub chainage
LENGTH	Interval length
IRI_IWP	IRI inner wheel path
IRI_OWP	IRI outer wheel path
LANE_IRI_QC	Lane IRI quarter-car model
LANE_IRI_HC	Lane IRI half-car model
NAASRA	NAASRA counts
HATI	Heavy articulate truck index
MPD_OWP	Mean profile depth outer wheel path
ETD_OWP	Estimated texture depth outer wheel path
MPD_BWP	Mean profile depth between wheel path
ETD_BWP	Estimated texture depth between wheel path
MPD_IWP	Mean profile depth inner wheel path
ETD_IWP	Estimated texture depth inner wheel path

PROFILE	
FIELD	**DESCRIPTION**
GRADE	Grade
CROSS_SLOPE	Cross slope
H_CURV	Horizontal curvature
V_CURV	Verticle curvature
RUT_OWP_AVE	Rutting depth outer wheel path (under 2m straight edge)
RUT_OWP_SD	Rutting standard deviation outer wheel path
RUT_OWP_mm5	Percent rutting readings <5 mm outer wheel path
RUT_OWP_mm5_10	Percent rutting readings >5 mm & <10 mm outer wheel path
RUT_OWP_mm10_15	Percent rutting readings >10 mm & <15 mm outer wheel path
RUT_OWP_mm15_20	Percent rutting readings >15 mm & <20 mm outer wheel path
RUT_OWP_mm20_25	Percent rutting readings >20 mm & <25 mm outer wheel path
RUT_OWP_mm25_30	Percent rutting readings >25 mm & <30 mm outer wheel path
RUT_OWP_mm30_35	Percent rutting readings >30 mm & <35 mm outer wheel path
RUT_OWP_mm35_40	Percent rutting readings >35 mm & <40 mm outer wheel path
RUT_OWP_mm40plus	Percent rutting readings >40 mm outer wheel path
RUT_IWP_AVE	Rutting depth inner wheel path (under 2m straight edge)
RUT_IWP_SD	Rutting standard deviation inner wheel path
RUT_IWP_mm5	Percent rutting readings <5 mm inner wheel path
RUT_IWP_mm5_10	Percent rutting readings >5 mm & <10 mm inner wheel path
RUT_IWP_mm10_15	Percent rutting readings >10 mm & <15 mm inner wheel path
RUT_IWP_mm15_20	Percent rutting readings >15 mm & <20 mm inner wheel path
RUT_IWP_mm20_25	Percent rutting readings >20 mm & <25 mm inner wheel path
RUT_IWP_mm25_30	Percent rutting readings >25 mm & <30 mm inner wheel path
RUT_IWP_mm30_35	Percent rutting readings >30 mm & <35 mm inner wheel path
RUT_IWP_mm35_40	Percent rutting readings >35 mm & <40 mm inner wheel path
RUT_IWP_mm40plus	Percent rutting readings >40 mm inner wheel path
RUT_LANE_AVE	Rutting depth lane wheelpath (under 2 m straight edge)
RUT_LANE_SD	Rutting standard deviation lane
RUT_LANE_mm5	Percent rutting readings < 5 mm lane
RUT_LANE_mm5_10	Percent rutting readings >5 mm & <10 mm lane
RUT_LANE_mm10_15	Percent rutting readings >10 mm & <15 mm lane
RUT_LANE_mm15_20	Percent rutting readings >15 mm & <20 mm lane
RUT_LANE_mm20_25	Percent rutting readings >20 mm & <25 mm lane
RUT_LANE_mm25_30	Percent rutting readings >25 mm & <30 mm lane
RUT_LANE_mm30_35	Percent rutting readings >30 mm & <35 mm lane
RUT_LANE_mm35_40	Percent rutting readings >35 mm & <40 mm lane
RUT_LANE_mm40plus	Percent rutting readings >40 mm lane
SPEED	Vehicle speed
EVENTS	Survey events
START_LAT	Start latitude

PROFILE	
FIELD	**DESCRIPTION**
START_LONG	Start longitude
START_ALT	Start altitude
END_LAT	End latitude
END_LONG	End longitude
END_ALT	End altitude
DATE	Survey date
TIME	Survey time
FILENAME	Survey filename
VEHICLE	Vehicle registration
OPERATOR	Operator names

CRACKING	
FIELD	**DESCRIPTION**
id	Record id number
ARRB_ID	ARRB section ID
ROAD_NAME	Road name
ROAD_NUMBER	Road number
DIRN	Direction
REGION	Region
SLK_START	Start SLK reference
START_TRUE	Start TRUE reference
START_DESC	Start description
SLK_END	End SLK reference
END_TRUE	End TRUE reference
END_DESC	End description
DIST_FROM	Start sub chainage
DIST_TO	End sub chainage
LENGTH	Interval length
CRACK_PCT	Percentage of cracked cells
WP_CRACK_LENGTH	Length of interval with cracking in either wheel path
OWP_TOTAL_CELLS	Total cells in outer wheel path
OWP_CRACK_CELLS	Total cracked cells in outer wheel path
OWP_LONG_CELLS	Total cells with longitudinal cracks in outer wheel path
OWP_TRAN_CELLS	Total cells with Transverse cracks in outer wheel path
OWP_CROC_CELLS	Total cells with crocodile cracks in outer wheel path
OWP_STRAIGHT_CELLS	Total cells with straight crack features in outer wheel path
OWP_PREDOMINANT_TYPE	Predominant crack type based on area in outer wheel path
OWP_CRACK_WIDTH_CELLS	Average crack width in outer wheel path
OWP_CRACK_INTENSITY_CELLS	Total crack length divided by total cracked cells in outer wheel path
OWP_CRACK_INTENSITY_SEGMENT	Total crack length divided by total cells in outer wheel path
BWP_TOTAL_CELLS	Total cells in between wheel path
BWP_CRACK_CELLS	Total cracked cells in between wheel path

CRACKING	
FIELD	**DESCRIPTION**
BWP_LONG_CELLS	Total cells with longitudinal cracks in between wheel path
BWP_TRAN_CELLS	Total cells with Transverse cracks in between wheel path
BWP_CROC_CELLS	Total cells with crocodile cracks in between wheel path
BWP_STRAIGHT_CELLS	Total cells with straight crack features in between wheel path
BWP_PREDOMINANT_TYPE	Predominant crack type based on area in between wheel path
BWP_CRACK_WIDTH_CELLS	Average crack width in between wheel path
BWP_CRACK_INTENSITY_CELLS	Total crack length divided by total cracked cells in between wheel path
BWP_CRACK_INTENSITY_SEGMENT	Total crack length divided by total cells in between wheel path
IWP_TOTAL_CELLS	Total cells in inner wheel path
IWP_CRACK_CELLS	Total cracked cells in inner wheel path
IWP_LONG_CELLS	Total cells with longitudinal cracks in inner wheel path
IWP_TRAN_CELLS	Total cells with Transverse cracks in inner wheel path
IWP_CROC_CELLS	Total cells with crocodile cracks in inner wheel path
IWP_STRAIGHT_CELLS	Total cells with straight crack features in inner wheel path
IWP_PREDOMINANT_TYPE	Predominant crack type based on area in inner wheel path
IWP_CRACK_WIDTH_CELLS	Average crack width in inner wheel path
IWP_CRACK_INTENSITY_CELLS	Total crack length divided by total cracked cells in inner wheel path
IWP_CRACK_INTENSITY_SEGMENT	Total crack length divided by total cells in inner wheel path
SPEED	Vehicle speed
EVENTS	Survey events
START_LAT	Start latitude
START_LONG	Start longitude
START_ALT	Start altitude
END_LAT	End latitude
END_LONG	End longitude
END_ALT	End altitude
DATE	Survey date
TIME	Survey time
FILENAME	Survey filename
VEHICLE	Vehicle registration
OPERATOR	Operator names