ANNUAL SUMMARY REPORT

Project Title:	P40 Benefits of Traffic Speed Deflectometer Data in Pavement Analysis (TSD and FWD correlation study and investigation to 'ground truth' instrumentation) (Year 2 – 2015/2016)
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P40 BENEFITS OF TRAFFIC SPEED DEFLECTOMETER DATA IN PAVEMENT ANALYSIS (TSD AND FWD CORRELATION STUDY AND INVESTIGATION TO 'GROUND TRUTH' INSTRUMENTATION)

SUMMARY

This report details the findings for Year 2 of the project, and is a continuation of the work from last year. The report is a continuation of work begun in 2015 into ways to utilise the Traffic Speed Deflectometer (TSD) as a detailed pavement structural evaluation tool. There are three parts in this study. Firstly, a correlation study to relate the Falling Weight Deflectometer (FWD) with the TSD. Secondly, the conduct of a trial field instrumentation installation to independently measure pavement surface motion. Thirdly, a comparison of TSD data obtained from successive years of surveying the Queensland road network.

Based on the data collected, global correlation relationships of maximum deflection (D_0) and deflection ratio (D_{250} / D_0) for the two deflection measuring devices are presented. The study covered a range of pavement types. The general trend indicates that it is possible to establish an approximately linear relationship. Further refinement can also be made using more complex correlation techniques.

For very stiff pavement sites (i.e. $D_{0\ TSD}$ < 0.2 mm) for a 50 kN load, the correlation relationship between the FWD and TSD is unclear. It is recommended that in the interim, the relationship should not be applied to a TSD deflection less than 0.2 mm.

In the second part of the study, a methodology to install in-pavement sensors to measure independent pavement response to FWD and rolling wheel loads was developed. The method was trialled on a section of road along the Bruce Highway (10A) near the Sunshine Coast. It was found that the deflection converted from a surface-embedded accelerometer agrees with the peak deflection measured by a FWD to within 10–12%.

In the third part of the study, TSD survey records measured in 2014 and 2015 were compared. The results indicate excellent repeatability between the data collected in consecutive years.

The study considered a limited number of pavement sites. Future studies could expand the number of pavement sites for each of the pavement types, and could potentially develop individual deflection correlation relationships. It has been demonstrated that the deflection basins of the FWD and TSD are fundamentally different. This difference can explain why the measured D_0 and D_{250} / D_0 values vary between the devices in the sites considered.

Measuring surface deflection from dynamic loads applied on pavements is a complex issue. The pavement structure, dynamic behaviour of the equipment, and the pavement materials characteristics result in different measured deflections between different deflection devices. This year, a simple approach was taken to correlate the FWD with the TSD. This is only the first step to compare the TSD with other common deflection measuring equipment. The site instrumentation methodology developed this year could be used in future studies to enhance knowledge of the TSD, and the pavement responses to the different types of loads applied by different deflection measuring equipment.

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FIGURES

1 INTRODUCTION

The traffic speed deflectometer (TSD) is a pavement evaluation device, manufactured by Greenwood Engineering in Denmark, which measures the pavement surface deflection at traffic speeds. ARRB Group acquired a TSD in 2014 and commenced annual deflection surveys in Queensland, New South Wales, and New Zealand. The TSD has proven to be a valuable network assessment tool because of its high production rate and maintaining measurement repeatability over a range of test speeds and road conditions.

Each year between April and August, the TSD was used to survey the Queensland state-road network. The total length of state-controlled roads surveyed in 2014 and 2015 were 10,800 km and 18,000 km respectively. The surveys represented a significant proportion of the sealed road network in Queensland. In April 2016, the TSD commenced the third year of network surveys in Queensland.

To explore how TSD data could be utilised beyond the network level at the project level, a project was established as part of the research program of the National Asset Centre of Excellence (NACoE) research agreement between the Department of Transport and Main Roads (TMR) and ARRB Group. The multi-year Project P40 – Benefits of Traffic Speed Deflectometer Data in Pavement Analysis – was established to investigate the benefits of the TSD in project-level pavement analysis.

In the first year of the study, it was found that the TSD could be a beneficial pavement evaluation tool for tasks beyond simple network screening. Engineers can estimate a full deflection basin based on TSD sensor measurements. As TSD measurements can be expressed as individual deflection basins, a range of existing pavement analysis tools can be used to relate the deflections to pavement properties. Some common software examples include the CIRCLY and EFROMD.

Different pavement deflection devices have been used in the past. Fundamental differences in deflection devices (such as the type of loading, loading speed, measurement and analysis technique) result in different recorded maximum deflections and deflection basin shapes. In the first year of the project, it was determined that correlations developed between the various devices are limited and should not be extrapolated to other pavements without further study. It was recommended that, on specific pavements, conducting side-by-side comparison of different deflection measurement devices and, where possible, ‘ground truth’ measurement obtained from instrumented sections be used to improve the understanding of TSD measurements. The project also identified different ways that TSD data can be used for project-level pavement evaluations. The findings show early promise for the use of TSD data for project-level applications.

This report presents the findings from the second year of the research study. Three major components of work were undertaken:

- A comparison of the outputs from the TSD and the falling weight deflectometer (FWD) on different types of pavement structures. This is presented in Section 2.
- The establishment of in-ground sensors in selected pavements, allowing the measurement of the pavement surface motion generated by applied loads. A key objective was to enable the development of a method to measure and compare the pavement surface motion caused by FWD, TSD and other heavy vehicle loads. This area of work is presented in Section 3.
- A comparison of selected TSD data collected over the last two years in Queensland. This comparison is presented in Section 4.

A summary and proposed future work are presented in Section 5 of this report.

2 COMPARISON OF TSD AND FWD

2.1 Selected Sites

To conduct side-by-side comparison of FWD and TSD deflection basins, some sites in South East Queensland were identified, as listed in Table 2.1. These sites represent a range of pavement types that is typical in Queensland. As far as practically possible the testing was conducted over the same period to minimise the effect of different environmental factors. Therefore in subsequent analysis of the measured data, external factors such as temperature and moisture conditions were assumed to be identical.

Table 2.1: List of FWD and TSD correlation sites

<table>
<tr><th>Road ID</th><th>Road name</th><th>Test-path and direction</th><th>Pavement structure</th><th>Testing date</th></tr>
<tr><td rowspan="3">211a and 211b (1)</td><td rowspan="3">Ipswich – Boonah Road</td><td>Southbound LWP
Ch. 1.95–2.31 km</td><td>Sprayed seal
265 mm foamed bitumen</td><td>19 Aug 2015</td></tr>
<tr><td>Southbound LWP
Ch. 4.95–5.25 km</td><td>Sprayed seal
265 mm foamed bitumen</td><td>19 Aug 2015</td></tr>
<tr><td>Southbound LWP
Ch. 10.23–10.68 km</td><td>Sprayed seal
265 mm foamed bitumen</td><td>19 Aug 2015</td></tr>
<tr><td>910</td><td>Centenary Highway</td><td>Northbound LWP
Ch. 2.7–4.92 km</td><td>220 mm granular base
150 mm granular subbase
100–140 mm granular lower subbase</td><td>20 Aug 2015</td></tr>
<tr><td>121</td><td>Deception Bay Road</td><td>Westbound LWP
Ch. 4.0–5.2 km</td><td>80–150 mm asphalt
300 mm granular</td><td>19 Nov 2015</td></tr>
<tr><td>40A</td><td>D’Aguilar Highway</td><td>Westbound LWP
Ch. 34–38.5 km</td><td>Sprayed seal
200 mm category 1 CTB</td><td>22 Nov 2015</td></tr>
<tr><td>10A</td><td rowspan="2">Bruce Highway</td><td>Southbound LWP
Ch. 50.975–51.175 km</td><td>255 mm asphalt
250 mm lean mix concrete</td><td>23 Nov 2015</td></tr>
<tr><td>10A</td><td>Northbound LWP
Ch. 23.5–29.22 km</td><td>Cross-sections vary. Typically
80–120 mm asphalt
250–375 mm granular</td><td>25 Nov 2015 &
26 Nov 2015</td></tr>
<tr><td>9905</td><td rowspan="2">Caboolture Connection Road</td><td>Westbound LWP
Ch. 2.7–4.95 km</td><td>130 mm asphalt
130 mm granular</td><td>24 Nov 2015 &
25 Nov 2015</td></tr>
<tr><td>9905</td><td>Eastbound LWP
Ch. 4.95–2.7 km</td><td>130 mm asphalt
130 mm granular</td><td>25 Nov 2015 &
26 Nov 2015</td></tr>
</table>

(1): 211a and 211b are the same road, but the TSD data was collected in two different passes.

The second part involves exploring ways that a ground-truth experiment can be undertaken. The ultimate goal was to compare the TSD deflection against measurements from reference sensors embedded in the ground, which is a more accurate validation method. There have been other similar studies conducted overseas, and the project team has taken the lessons learnt into considerations. A similar ground truth experiment has been conducted in the United States (e.g. Nazarian 2014).

2.2 Measurement Spacing

The TSD uses a series of Doppler lasers to measure the velocity of the pavement surface movement as a result of the nominal 50 kN loaded half-axle of the TSD device. The TSD collects data every 20 mm of travel along the road. However, the current Greenwood Engineering processing software is limited to reporting average values over a 10 m interval.

As part of New South Wales, New Zealand and Queensland TSD network surveys, the 10 m average velocities were used to derive an equivalent full deflection basin based on the method developed by Muller and Roberts (2013). The TSD deflection results reported and discussed in this report were similarly derived.

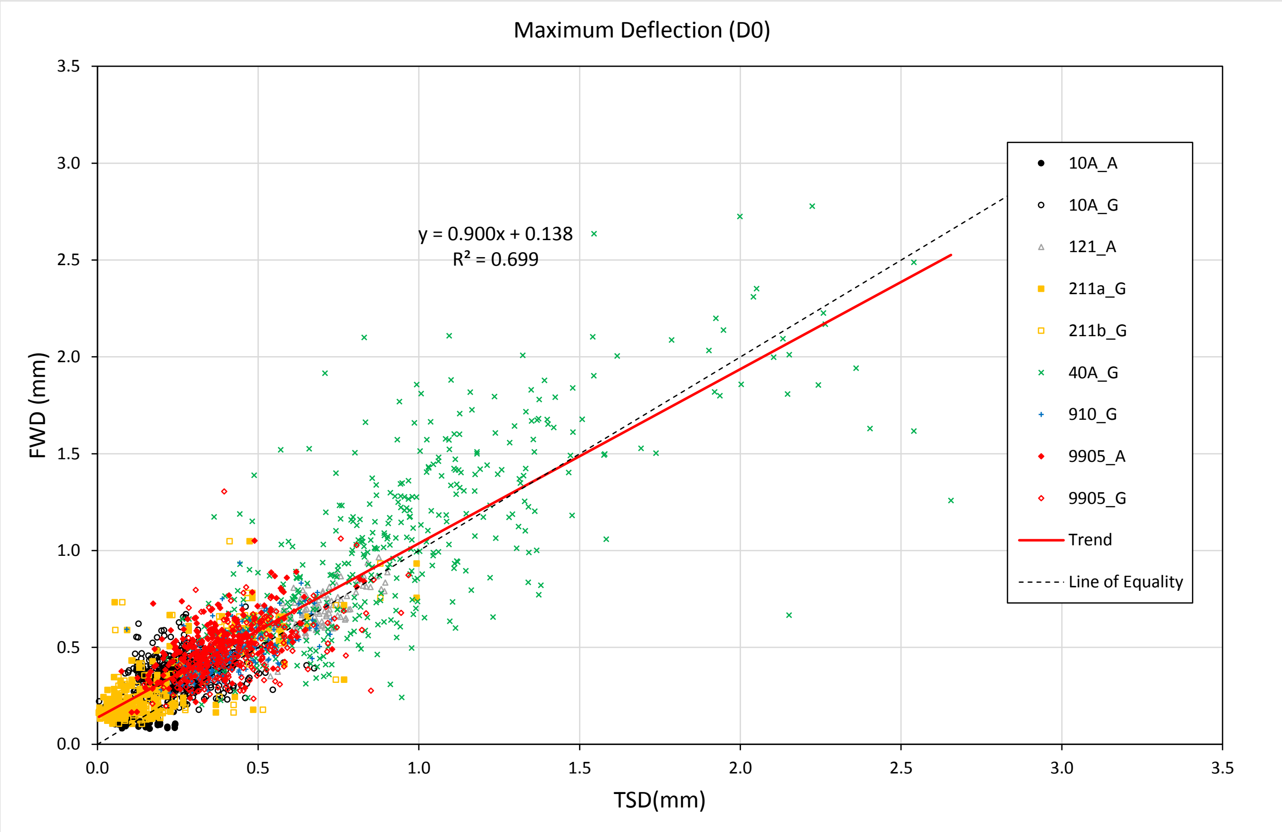
In contrast to TSD measurements, FWD testing is conducted statically at fixed locations, with pre-defined spacing between each deflection sensor. The FWD deflection was collected at 5 m or 10 m spacing.

2.3 Comparison of FWD and TSD Deflections

On each of the sites listed in Table 2.1, FWD and TSD data were collected. FWD testing was conducted with a target load of 50 kN, and all FWD deflection results reported here have been (linearly) normalised to this load level. Similarly, the TSD applied a static rolling load of nominally 50 kN.

Maximum deflections measured by the FWD and TSD (for a normalised load of 50 kN) for all test sections are plotted in Figure 2.1. The results show that there is a significant linear correlation between the maximum deflection measured by the FWD and TSD over a range of pavement types. However, one would expect that the correlation differs for different pavement types. Individual correlation relationships can be developed accordingly. It can also be observed that the correlation is weak for stiff pavement sites where the maximum TSD deflection is less than 0.2 mm.

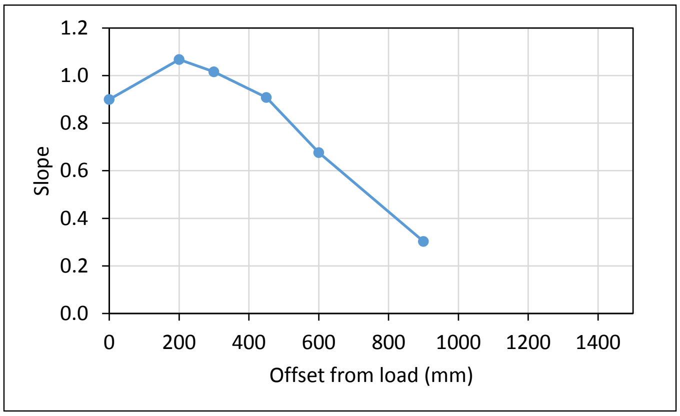
Figure 2.1: Linear correlation of deflection measured under the load by the FWD and TSD



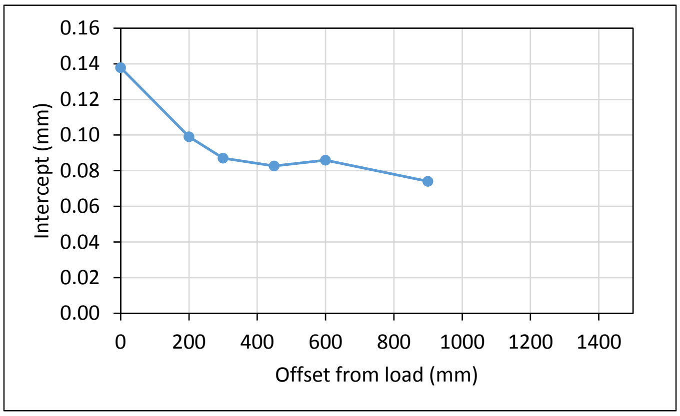
Note: G = gazettal direction and A = anti-gazettal direction in the legend

In addition to the correlation of the maximum deflection between the FWD and the TSD, similar comparisons of deflection measured at different offsets from the load were carried out. The slope, intercept, and coefficient of determination (R^2) from this linear regression are shown in Figure 2.2. There is a significant change in the slope value beyond an offset distance of 450 mm, which suggests that the shape of the deflection basin differed significantly between the FWD and the TSD beyond this point. The deviation is also confirmed by the fact that the R^2 value was maintained above 0.7 for an offset distance less than 300 mm.

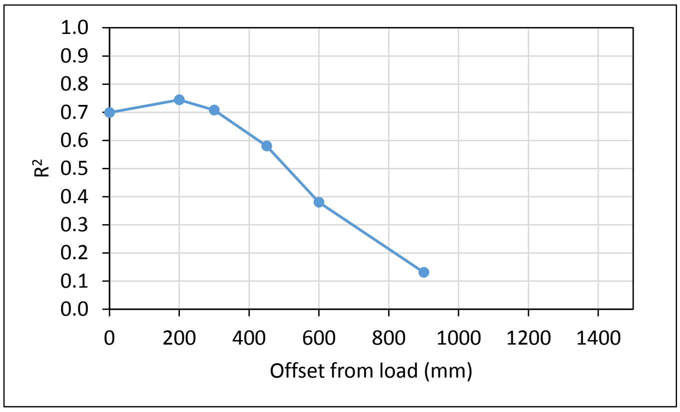
Figure 2.2: Linear regression results between the FWD and the TSD at different offset positions from the applied load



(a) Slope parameter of a linear regression



(b) Intercept parameter of a linear regression



(c) Coefficient of determination of a linear regression

All correlation data collected in this year are shown in Figure 2.1. Individual plots for each of the following pavement types are shown in Figure 2.3 to Figure 2.7:

- asphalt over granular pavement
- seal over foamed bitumen stabilised base pavement
- seal over cement treated base pavement
- seal over granular pavement
- heavy-duty asphalt over lean-mix concrete subbase pavement

Figure 2.3: TSD and FWD maximum deflection comparison for asphalt over granular pavement

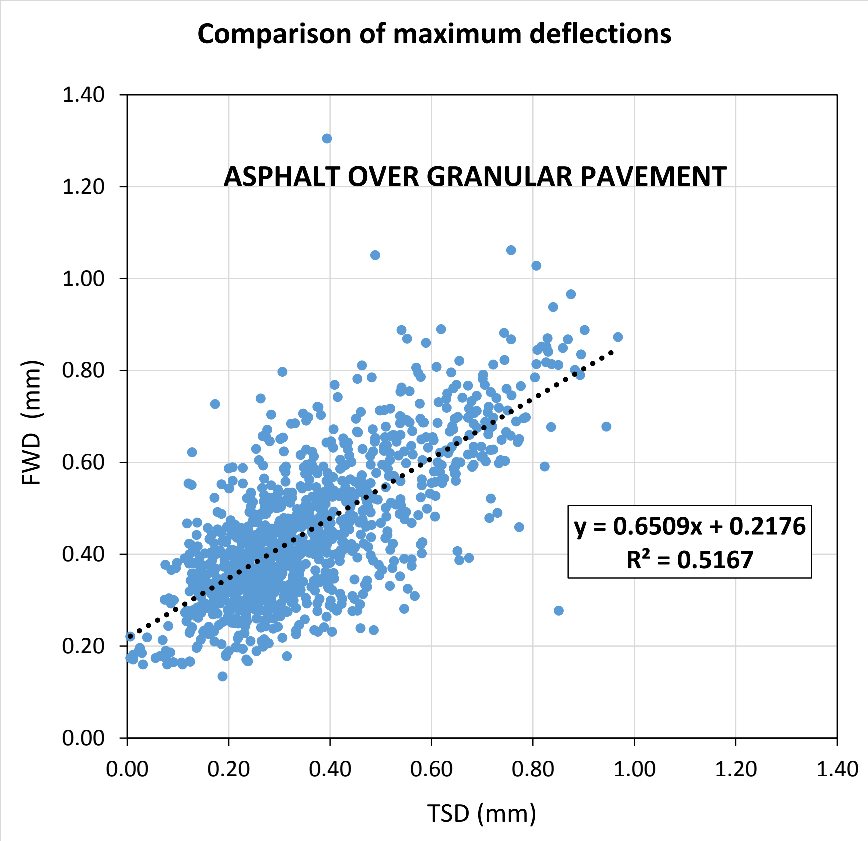


Figure 2.4: TSD and FWD maximum deflection comparison for seal over foamed bitumen stabilised base pavement

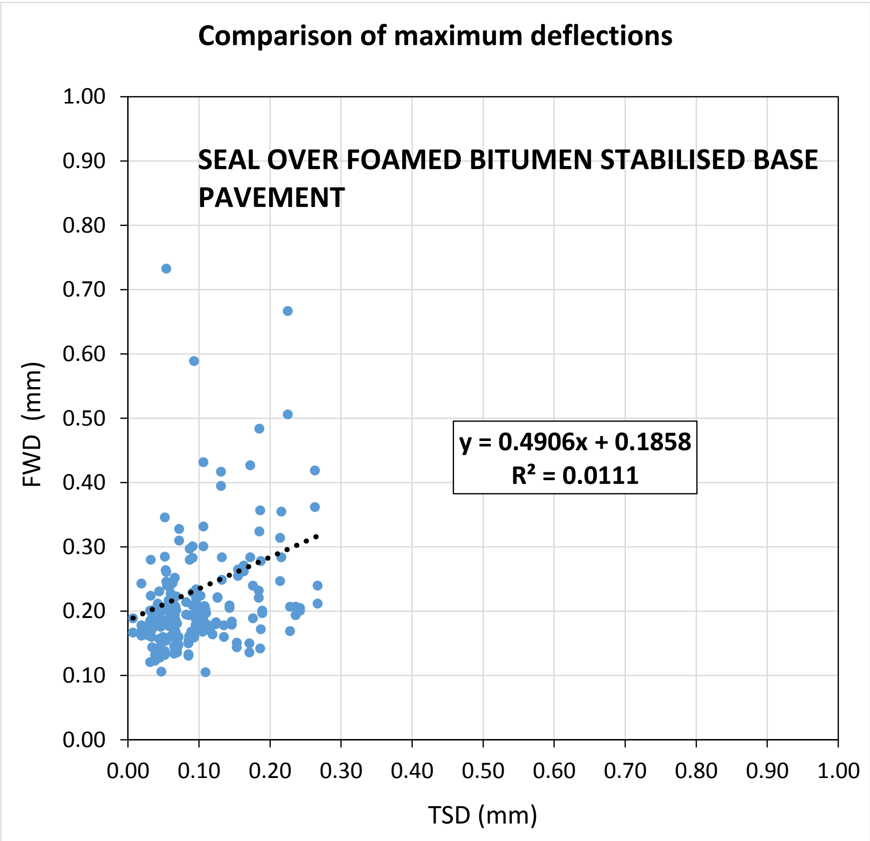


Figure 2.5: TSD and FWD maximum deflection comparison for seal over cement treated base pavement

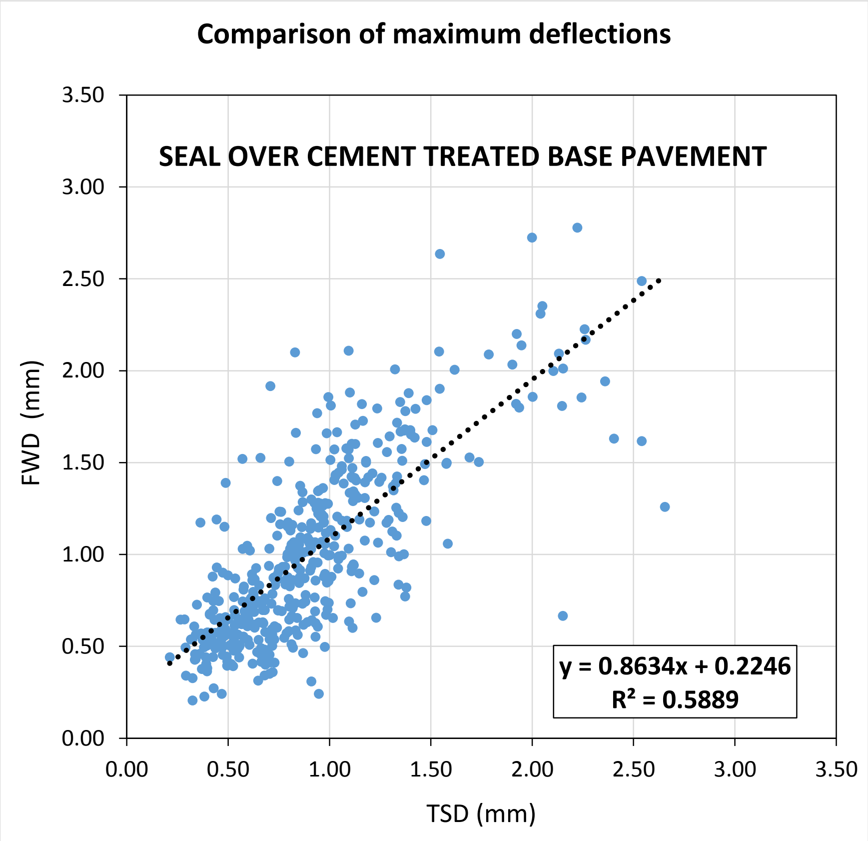


Figure 2.6: TSD and FWD maximum deflection comparison for seal over granular pavement

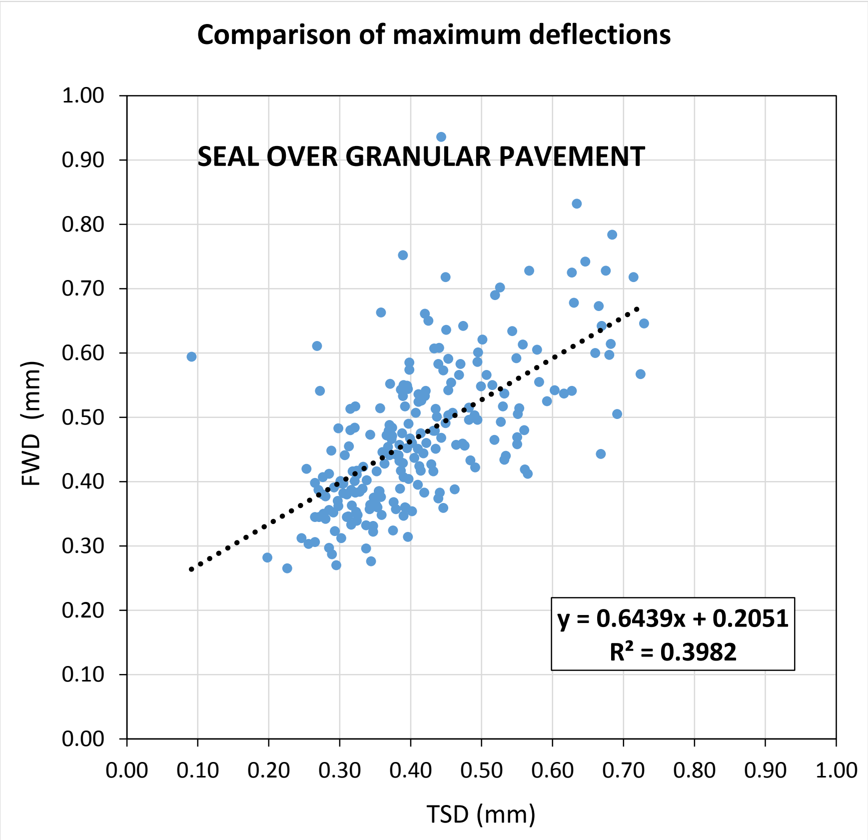
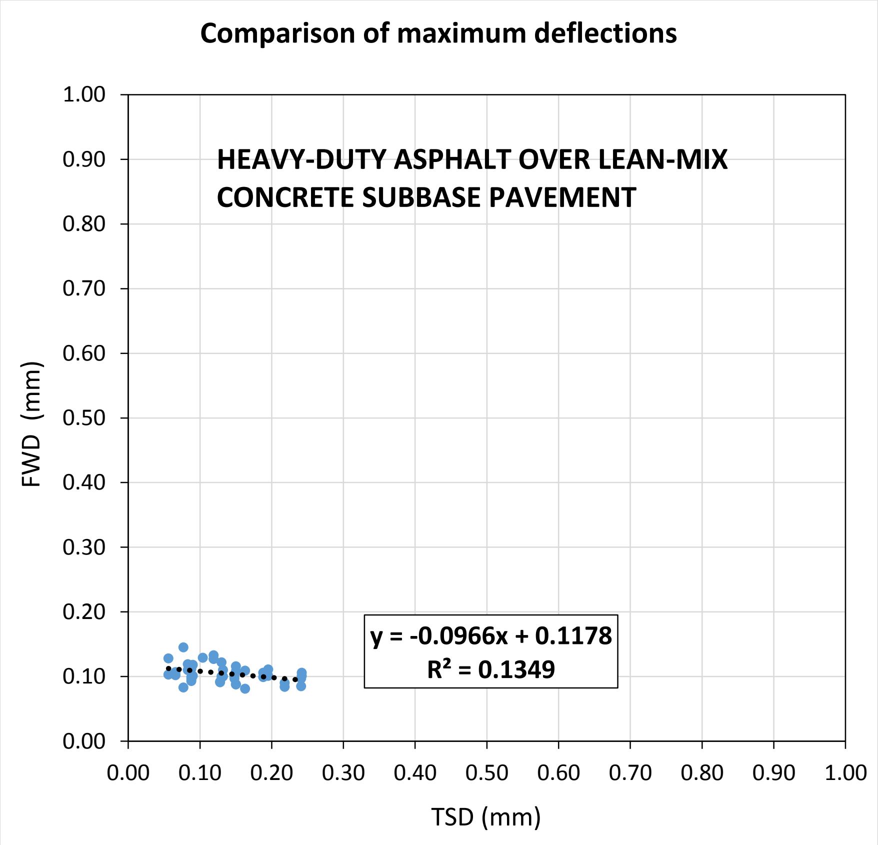
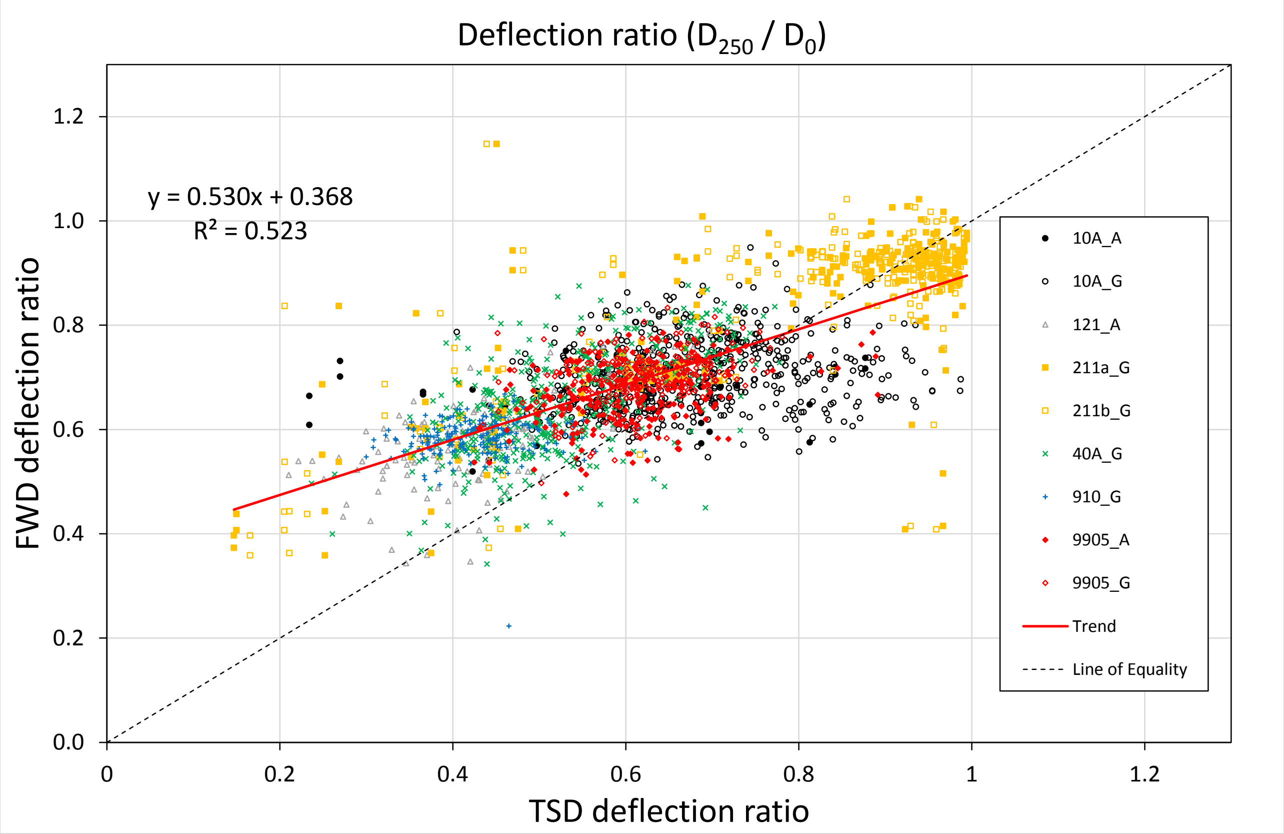


Figure 2.7: TSD and FWD maximum deflection comparison for heavy-duty asphalt over lean-mix concrete subbase pavement



The deflection ratio (D_{250} / D_0) is a measure used to distinguish different pavement types (Department of Transport and Main Roads 2012). The deflection ratios for all pavement sites are presented in Figure 2.8. This shows that deflection ratios measured by the FWD increase with material stiffness; this trend also applies to the TSD measurement.

Figure 2.8: Linear correlation of the deflection ratio (D_{250} / D_0) measured by the FWD and TSD



Note: G = gazettal direction and A = anti-gazettal direction in the legend

The deflection ratios measured from the FWD and TSD obtained in this study are summarised in Table 2.1 and compared with the indicative values for different pavement types.

Table 2.2: Indicative values for the deflection ratio

Pavement type	D_{250} / D_0 indicative range (1)	D_{250} / D_0 range (FWD from this study)	D_{250} / D_0 range (TSD from this study)	Road name
Granular < 1 x 10^6 ESA	0.5–0.7	0.5–0.6	0.4–0.5	Centenary Highway
Full depth asphalt	0.7–0.9	n/a	n/a	n/a
Full depth cement stabilised	0.85–0.95	0.65–0.75	0.5–0.6	D'Aguilar Highway Ipswich – Boonah Road (2)
Asphalt on granular	0.6–0.85	0.65–0.85	0.6–0.75	Deception Bay Road Caboolture Connection Road Bruce Highway (northbound)
Asphalt on cemented	0.85–0.95	n/a	n/a	Bruce Highway (southbound)

(1) Source: Brisbane City Council (2011).

(2) Foamed bitumen stabilised base.

The deflection ratios from the FWD for all pavement types fall within the indicative range, except for road 40A along D'Aguilar Highway. The cemented base pavement in Road 40A has a mean D_{250} / D_0 ratio of 0.65, which is much lower than anticipated. One possible explanation is that the cemented material has extensively cracked and reverted to the granular phase.

Pavements comprised of mainly granular materials have a lower ratio than pavements with bound base layers. In general, the deflection ratio measured by the TSD is lower than the ratio measured by the FWD.

2.4 Discussion and Summary

The first part of this study explored the correlation of the derived TSD deflection basins with the FWD basins, and was based on the examination of a limited number of sites. It was found that while a global linear correlation could be seen to exist, the correlation was dependent upon the type of pavement structure evaluated.

As demonstrated in Year 1 of the project, the deflection basins produced from TSD and FWD devices should theoretically differ. Further, differences between deflection basins ought to depend on the structure of the loaded pavement.

Using combined data from all test sites, a general equation to predict equivalent FWD D_0 deflections from measured TSD results was derived using linear regression. The R^2 for linear regression decreases significantly beyond an offset distance of around 400 mm.

For very stiff pavement sites (i.e. $D_{0\ TSD} < 0.2$ mm), the correlation between the FWD and TSD is unclear. It is recommended that in the interim, the relationship should not be applied to the deflection range below 0.2 mm.

There is a high degree of scattering in the FWD/TSD data comparison as shown in Figure 2.1. However, most of this scatter is related to road 40A, which is a pavement with a distressed cement treated base. Inspection of road condition data for this road confirmed that extensive and varied cracking has occurred within the test site. In such circumstances, it is reasonable to expect that deflection results will vary widely.

3 FIELD INSTRUMENTATION

3.1 Purpose of Field Instrumentation

Pavement deflection measurement devices, such as the FWD and TSD, measure the deflection response of the road surface that results from the application of a load on the surface. Due to the different nature of applying loads to the surface, it is widely accepted that deflections from an FWD and TSD may not necessarily be the same in all cases. An FWD applies a pulsed load through a rubber-based circular plate seated on the road surface. A TSD applies load via pneumatic tyres arranged in a dual-tyre axle group, travelling at a typical truck speed of around 70 – 80 km/h.

The effectiveness of the TSD velocity/deflection sensors in measuring the deflection of the road surface is difficult to ascertain as there are no readily available means of measuring the true response of the pavement surface when subjected to TSD applied loads.

The purpose of establishing field instrumentation is to provide an independent measure of the TSD loaded pavement surface responses to those recorded by the TSD. The ultimate goal is to compare the TSD deflection data against reference sensors embedded into the ground. This would ultimately provide a true TSD validation method.

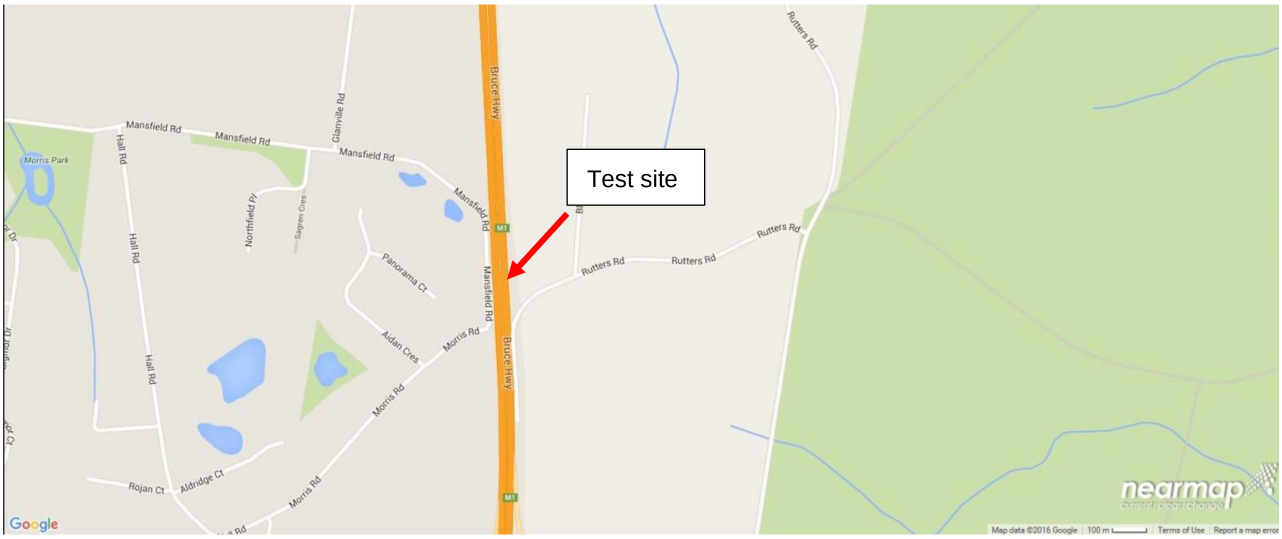
Other similar, albeit preliminary, studies have been conducted overseas (e.g. Kannemeyer, Lategan & Mckellar 2014, Nazarian 2014). Results from these studies were taken into consideration in formulating the field instrumentation established in Queensland.

3.2 Site Selection

Ideally, several sites would be instrumented representing a range of pavement structures. However, with the limited budget available in this year of the project, only a single preliminary installation and field trial was possible.

As part of the resurfacing maintenance work along Bruce Highway (10A), ARRB Group had the opportunity to instrument a section of the pavement. The pavement comprised 90 mm asphalt over cement treated subbase. The instrumented site was located in the outer southbound lane, and the general location of the test site is shown in Figure 3.1. The work was undertaken on the nights of 18 and 19 June 2016.

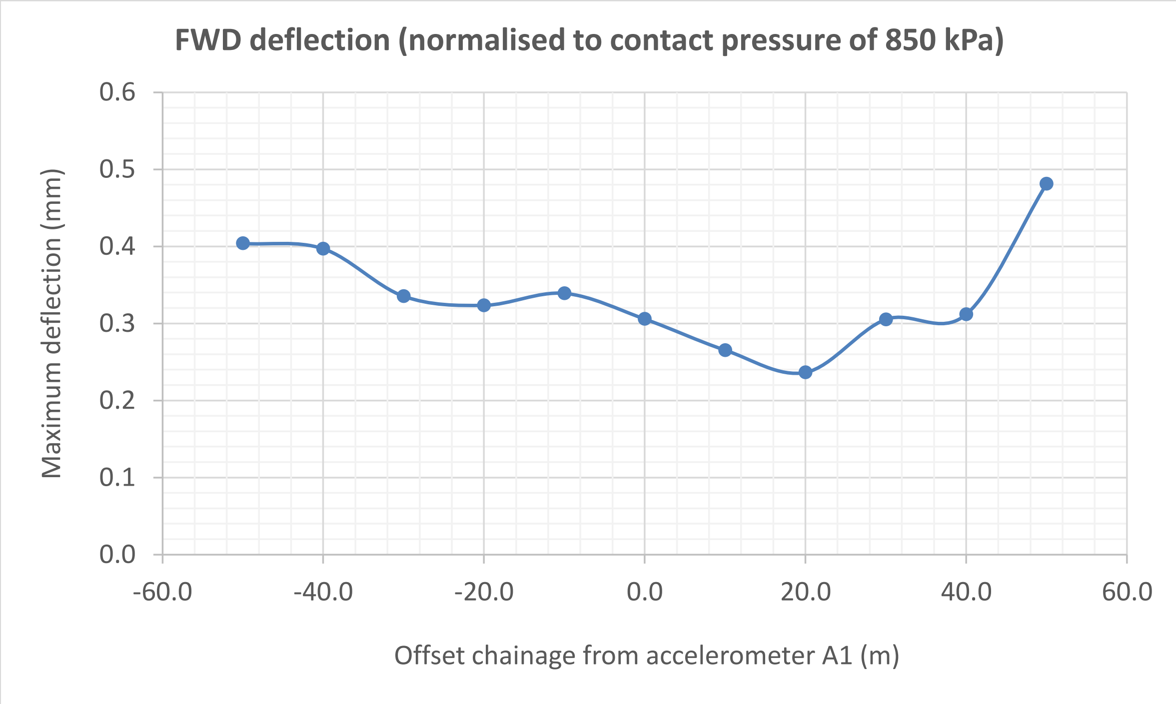
Figure 3.1: Field instrumentation location



Source: Nearmap 2016, 'Sunshine Coast, QLD', map data, nearmap, Sydney, NSW.

Based on the information provided by the resurfacing project team, a uniform section of road was selected. The FWD was used to determine the uniformity near the test section with FWD deflection measured at 10 m intervals. The maximum deflection profiles were measured 50 m before and 50 m away from the instrumented site. The FWD deflection results, shown in Figure 3.2, confirmed that the structural capacity of the site was fairly uniform with a normalised deflection of about 0.3 mm at 850 kPa.

Figure 3.2: Normalised maximum deflection profile across the vicinity of the instrumented site



3.3 Instrumentation Selection and Installation

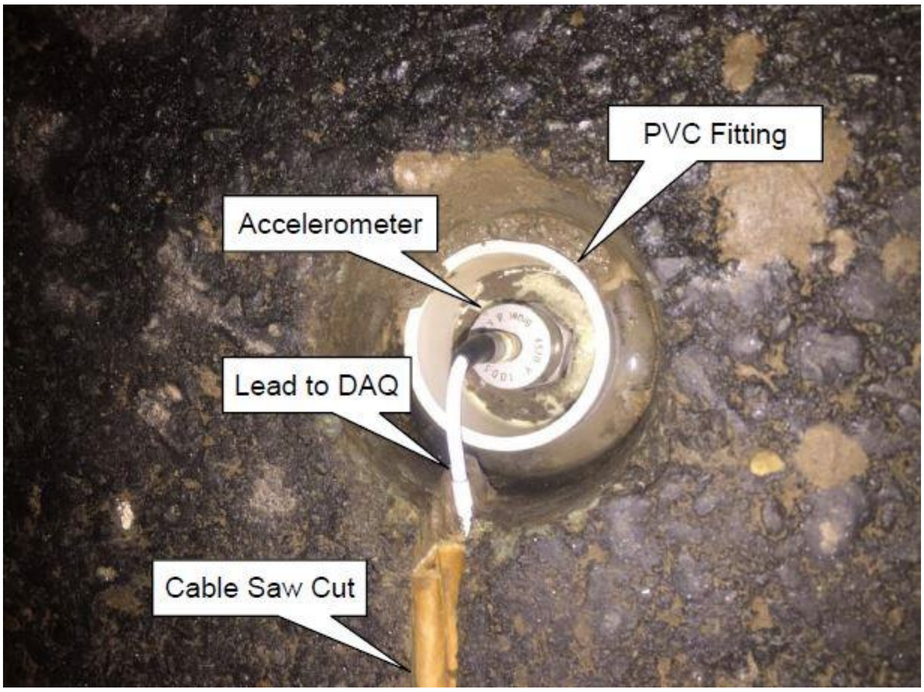
With a suitable site selected to conduct the preliminary field trial, the following short-term objectives for the trial were established:

- identification of the type of sensors suitable for measuring surface motions
- confirmation of the data acquisition parameters to be used for capturing the timing of a moving truck axle group
- selection of the appropriate data analysis method to convert raw data measurement to surface deflection
- based on the results, refinement of the test plan for the work in future years
- conduct of an experiment to compare the load pulse from a FWD
- measurement of the surface deflection at different offset distances. The furthest sensor located between 3.0 m to 3.5 m away from the first in-ground sensor has a similar offset distance to the reference Doppler laser on the TSD.

The original plan was to use the TSD as the test vehicle. However, the timing of the resurfacing work did not align with the TSD travel schedule. As a result, other heavy vehicles were used to apply rolling wheel loads during the preliminary trial.

The instrumentation was prepared and installed by SLR Consulting, which has extensive knowledge in making dynamic and acoustic measurements in the field. During the project, it was found that modern accelerometers could be used to measure over the required frequency range (5 to 50 Hz). An accelerometer such as the one shown in Figure 3.3 was chosen for the testing. It was screwed into a PVC fitting and fixed into a pre-drilled core hole. Five accelerometers at different offset distances were used in the trial experiment.

Figure 3.3: Core hole and accelerometer fitting



Source: SLR Consulting (2016).

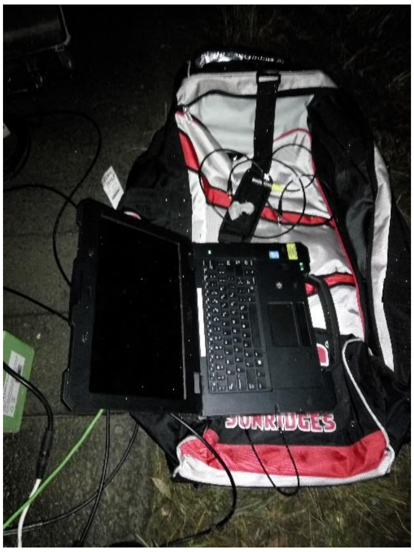
The installation involved drilling cores into the asphalt surface, installing sensors, making saw cuts for wires, and connecting signal wires to a computer-based data acquisition system. After sensor installation on the night of the testing, the data collected by the sensors while the pavement was loaded with the FWD and heavy vehicle pass-by was recorded. The various steps of the testing are shown in Figure 3.4. Details of the instrumentation set-up and data collected by SLR Consulting are provided in Appendix A.

Figure 3.4: Photographs during site preparation, instrumentation set-up and testing

(a) Coring

(b) Installation of sensors

(c) Saw cut



(d) PC-based data acquisition system

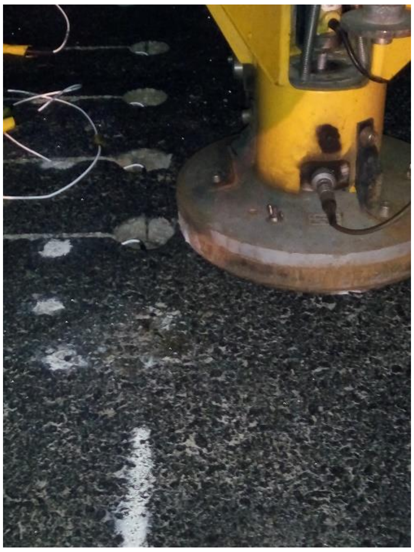
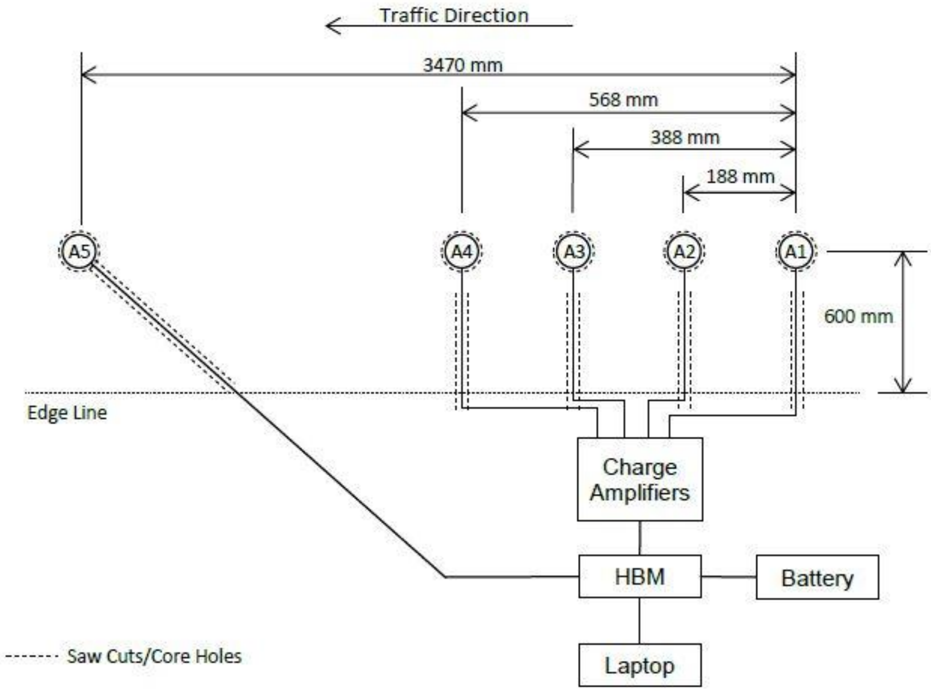
	
(e) Falling weight deflectometer	**(f) Test path for vehicle pass-by**

Figure 3.5 shows the site instrumentation set-up.

Figure 3.5: Instrumentation plan

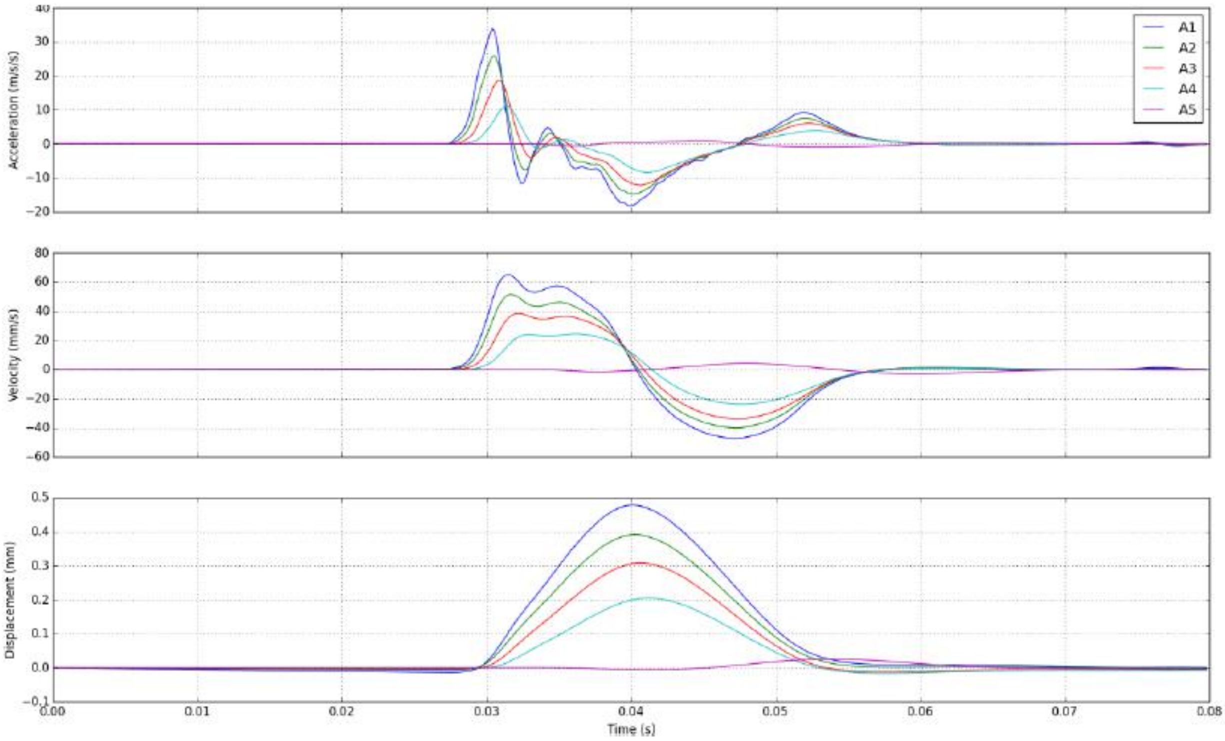


Source: SLR Consulting (2016).

Note: HBM = Signal condition unit SomatXR (Model MX1601B-R) manufactured by HBM.

Five accelerometers were embedded on the pavement surface. Each accelerometer measured the acceleration time history, and the velocity time history can be obtained by numerically integrating the acceleration time history. The displacement or deflection was then be obtained by integrating the velocity time history. Typical measured acceleration, velocity, and deflection time histories for the FWD are shown in Figure 3.6. ‘A1’ denotes the accelerometer that is closest to the FWD loading plate, and ‘A5’ denotes the accelerometer that is furthest from the FWD.

Figure 3.6: Typical FWD-generated pavement surface acceleration, velocity and displacements measured at the instrumented site



Source: SLR Consulting (2016).

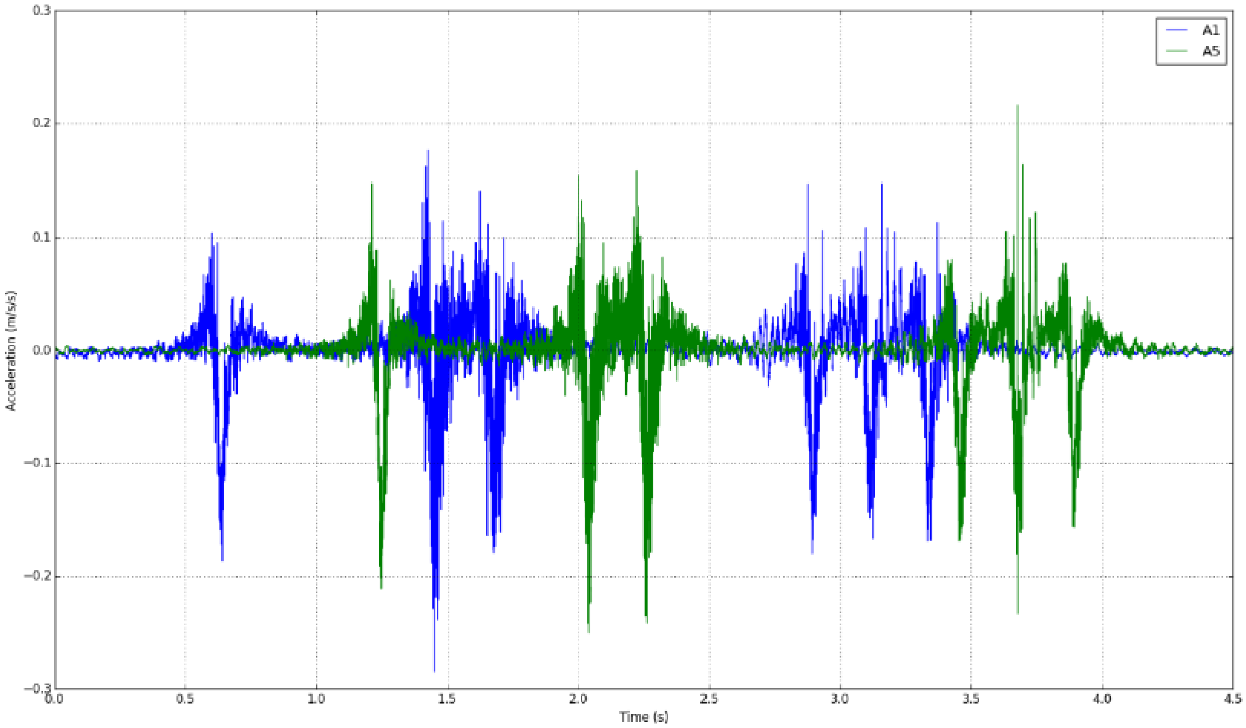
Frequency analysis indicated that the dominant frequency of an FWD drop lies at about 33 Hz. Furthermore, a comparison of the deflection converted from an accelerometer agrees with the peak deflection measured by an FWD within 10–12%. Some of the discrepancies can be explained by sensor alignment and the fact that the accelerometers were embedded at different depths below the pavement surface.

In addition to FWD loading, the pavement surface motion was measured during a pass-by of a semi-trailer. The test vehicle was a semi-trailer (total weight of 42 tonnes) driven over the site instrumentation at approximately 20 km/h. The resulting acceleration time histories from the closest (A1) and furthest (A5) accelerometer are shown in Figure 3.7. The peaks correspond to the single, tandem and triaxle groups of the semi-trailer respectively.

Of particular interest is the motion of the furthest sensor when the semi-trailer first entered the instrumentation array. This is important because the furthest sensor is similar in offset distance to the reference sensor used in the TSD. The study confirms that at 3.5 m away from the loading group, the motion was essentially zero (i.e. when the first axle of the semi-trailer travelled past the A1 accelerometer at about 1 second shown in Figure 3.7, there was negligible motion measured at the position of the A5 accelerometer). Therefore, it was concluded that for this particular pavement type, locating the reference sensor at 3.5 m away is appropriate.

The measurement suggests that the pavement response waveform is asymmetrical in the leading and trailing side of a wheel load. The frequency response also suggests that dynamic properties of the waveform are also dependent on the travel speed of the vehicle.

Figure 3.7: Acceleration data collected during a pass-by test of a semi-trailer



Source: SLR Consulting (2016).

4 COMPARISON OF TSD DEFLECTIONS ACROSS TWO YEARS OF NETWORK COLLECTIONS

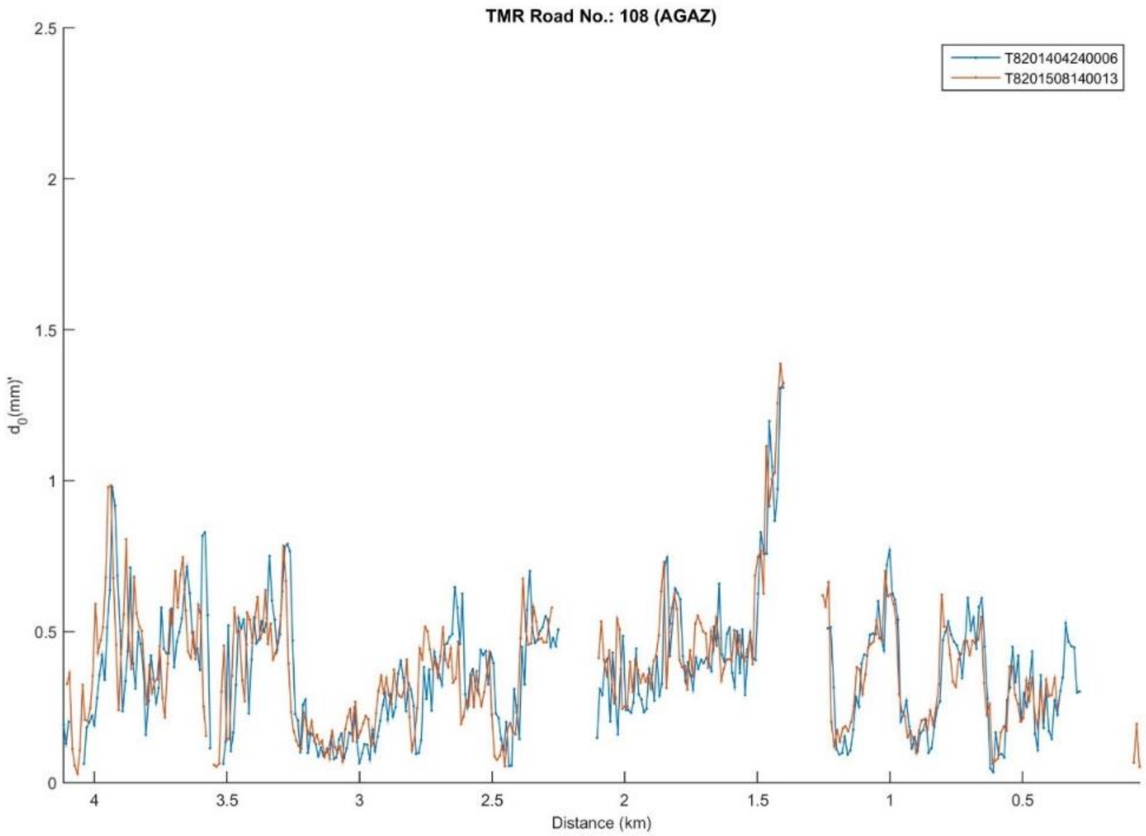
TSD surveys were conducted in Queensland in 2014 and 2015. In 2014 a total of 10,800 km of roads were surveyed. In 2015 a total of 18,000 km of roads were surveyed. 139 roads have been surveyed in both years with a total overlapping distance of around 9,500 km. A coverage map of the TSD surveys is shown in Figure 4.1.

Figure 4.1: TSD testing coverage map in 2014 and 2015

A small part of the project's scope was to compare the TSD measurements made during the 2014 and 2015 Queensland surveys. While there can be a range of factors affecting the magnitude of the deflections, the deflection profiles measured have excellent repeatability between the two years.

Overall, the deflections measured can be seen to be repeatable. An example of the deflection profiles collected in 2014 and 2015 along the Beenleigh – Redland Bay Road are shown in Figure 4.2.

Figure 4.2: TSD maximum deflections along Beenleigh – Redland Bay Road collected in 2014 and 2015



5 CONCLUSIONS AND PROPOSED FUTURE WORK

5.1 Conclusions

This report detailed the findings for the work undertaken in Year 2 of the NACoE P40 project. This continues the work to explore ways to utilise the TSD as a pavement structural evaluation tool. There were three parts in the study. Firstly, the outputs from the TSD and FWD were compared. Secondly, in-ground sensors were installed in a pilot exercise aimed at independently measuring the pavement response to FWD and rolling wheel loads. Thirdly, a comparison of TSD data collected in successive years within the Queensland state-road network was undertaken.

Based on the data collected in the first part of the study, global correlation relationships of maximum deflection (D_0) and deflection ratio (D_{250} / D_0) for FWD and TSD deflection measuring equipment are presented. The study covered a range of pavement types. It was determined that it is possible to establish a linear correlation relationship, and that the relationship can be refined with more complex correlation techniques.

The coefficients of linear regression (both slope and intercept) were found to decrease significantly beyond an offset distance of 400 mm. For very stiff pavement sites (i.e. $D_{0\ TSD}$ < 0.2 mm), the correlation between the FWD and TSD is unclear. It is recommended that in the interim, the relationship should not be applied to a deflection range of less than 0.2 mm. Pavements with deflections below this level would not typically be candidates for rehabilitation works.

In the second part of the study, a preliminary investigation into the independent measurement of the surface motion was undertaken. On a section of the Bruce Highway (10A), multiple accelerometers were embedded into an asphalt pavement. Double integration of the output of these sensors allowed pavement surface deflections resulting from an FWD and a semi-trailer load to be determined. In general, a comparison of the deflection obtained from the embedded accelerometers agreed with the peak deflection measured by an FWD within 10–12%.

It was concluded that the field instrumentation can measure impulse-type loading (i.e. FWD) as well as rolling wheel loading. Using the response generated by a semi-trailer loading, the study confirmed that at 3.5 m away from the loading group, the surface motion is essentially zero. This supports the current use of a similarly placed sensor in the TSD as a zero reference datum.

Selected records of TSD profiles measured in 2014 and 2015 were examined. Excellent repeatability between the data sets was found.

5.2 Proposed Future Work

The study was based on a limited number of pavement sites. Future studies could expand the number of pavement sites for each of the pavement types, and could potentially develop individual deflection correlation relationships for different pavement types. Deflection basins between FWD and TSD are different. This observation can partially explain the different D_0 and D_{250} / D_0 values measured by both devices.

Measuring surface deflection on pavements is a complex dynamic problem. The pavement structure and the dynamic behaviour of the equipment and the pavement materials result in different deflections from various devices. This year, a simple approach has been taken to compare the FWD with the TSD. This is only the first step to understanding the complex relationship. The site instrumentation methodology developed should be used in future work to improve understanding of the TSD.

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APPENDIX A SLR REPORT ON SITE INSTRUMENTATION

A.1 SLR Report

Pavement Deflection Measurement Trial

Pass-Bys and Impact Tests

Report Number 610.15594-R1

16 May 2016

ARRB Group Ltd
123 Sandgate Rd
Albion QLD 4010
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Version: Revision 2

Pavement Deflection Measurement Trial

Pass-Bys and Impact Tests

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1 INTRODUCTION

SLR Consulting Australia Pty Ltd (SLR) was engaged by ARRB Group Ltd (ARRB) to instrument a section of the southbound carriageway of the Bruce Highway for the purpose of measuring road pavement deflections due to vehicle pass-bys and impact loadings.

This report describes the instrumentation, data acquisition methods, testing plan and resultant measurements. The raw acceleration data is analysed and converted to velocity and displacement traces.

1.1 Test Location and Date

The instrumentation and test work was undertaken on the nights of the 18th and 19th of April 2016, coinciding with resurfacing maintenance works lead by DownerMouchel on the section of the southbound carriage way of the Bruce Highway located between Pumicestone Road and Steven Irwin Way. The approximate location of the instrumentation works is shown in **Figure 1**. All instrumentation and testing was completed in the slow lane (i.e. the left-most lane in the direction of traffic).

Figure 1 Instrumentation Location (Show in Red)

1.2 Objectives

The tests are part of a preliminary field trial to compare deflections obtained from accelerometers embedded in the pavement to those obtained from other testing devices, such as the Falling Weight Deflectometer (FWD). A Traffic Speed Deflectometer (TSD) was also part of the original plan, although scheduling conflicts meant that it could not be obtained for the testing period. The results from this trial will be used to guide future instrumentation work, such as appropriate sensor selection and determination of appropriate data analysis methods.

1.3 Falling Weight Deflectometer (FWD)

A FWD is a trailer-mounted testing device which is used to measure pavement surface deflections in response to an impact loading. It consists of a mechanism that is capable of automatically dropping different weights onto a 300 mm circular load bearing pad, as well as nine geophones arranged in a linear pattern at increasing distances away from the centre of the pad. An on-board data acquisition system records the geophones' signals and converts them into displacements.

The geophone arrangement and loading bearing pad are shown in **Figure 2**. The distance of each geophone from the centre of the loading pad is given in **Table 1**.

Figure 2 FWD Loading Pad and Geophone Arrangement

Table 1 FWD Geophone Distances from Centre of Load Bearing Pad

Number	Distance from Centre of Load Bearing Pad (mm)
1	0[1]
2	200
3	300
4	450
5	600
6	750
7	900
8	1200
9	1500

1. Geophone is concentric with load bearing pad

2 INSTRUMENTATION

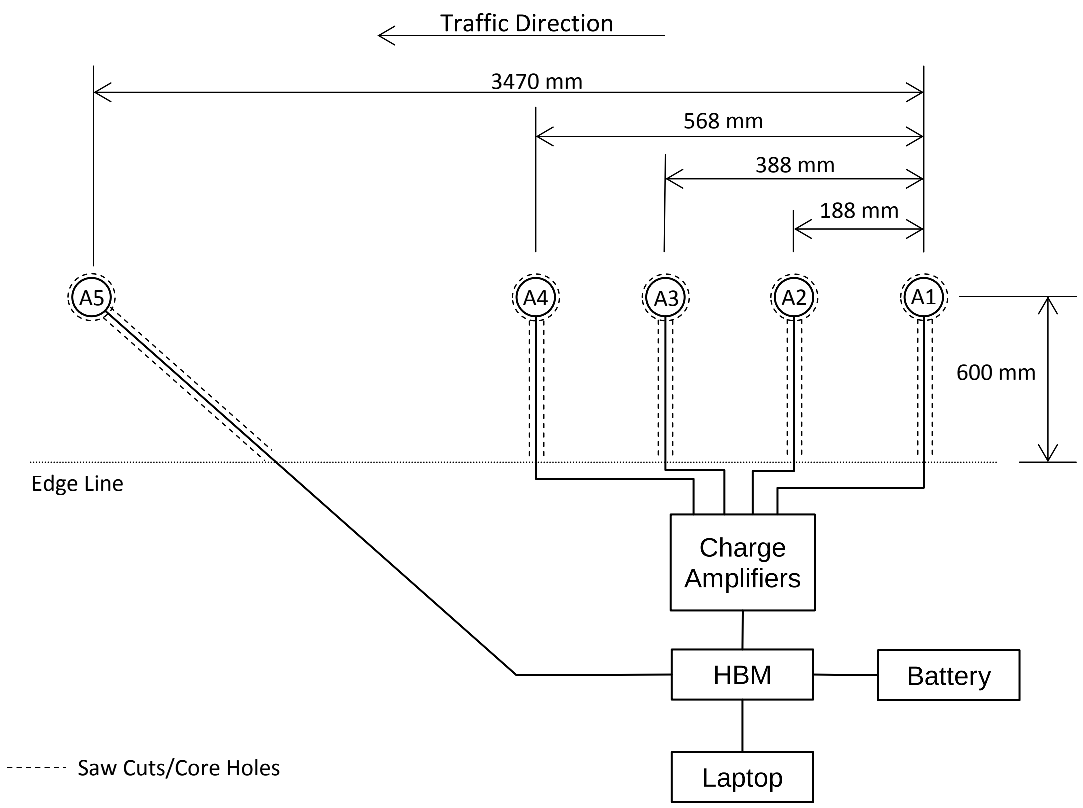
The data acquisition system and the accelerometer types used are briefly discussed in this section.

2.1 Instrumentation Plan

The basic instrumentation plan is shown in **Figure 3**. Details of the accelerometers used and the data acquisition system are provided in the following sections. The accelerometers are labelled as A1 to A5, from right to left (ie in the direction of traffic flow) and were 600 mm offset from the (not yet painted) edge line.

Core holes were required to secure the accelerometers into the pavement. Each hole was 64 mm in diameter and approximately 80 mm deep. Saw cuts were also required to allow for safe routing of cables to the edge of the road, where they were then connected to the data acquisition system. Locations of saw cuts and core holes are shown using dashed lines in the instrumentation plan. The core holes were cut in line with the expected wheel path.

Figure 3 Instrumentation Plan



2.2 Accelerometers

A total of five uniaxial accelerometers were used as part of the measurement setup. Two different types were used. The type and properties of each accelerometer are given in **Table 2**.

Table 2 Accelerometers Specifications

Name	Type	Sensitivity	Frequency Range
A1 - A4	Brüel & Kjær 4370 Charge Accelerometer	100 pC/g	0.1 to 4800 Hz
A5	PCB 393B04 ICP Accelerometer	1000 mV/g	0.06 to 450 Hz

PVC pipe fittings were epoxy glued into the holes which had been dried and cleaned with compressed air. The fittings were prepared in the office to aid in securing the accelerometers in place; a threaded stud has been epoxy glued onto the bottom of the fittings. The accelerometers could then be securely placed into the hole for testing, then quickly removed and reinstalled for the next night's testing. The core-hole and fitting setup are shown in **Figure 4** and **Figure 5**.

Figure 4 Core Hole and Accelerometer Fitting

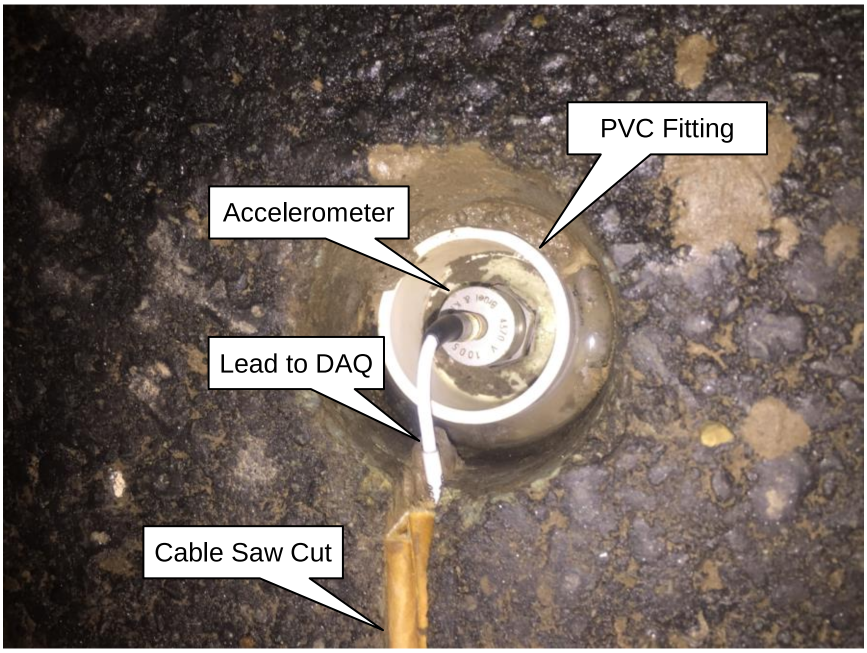
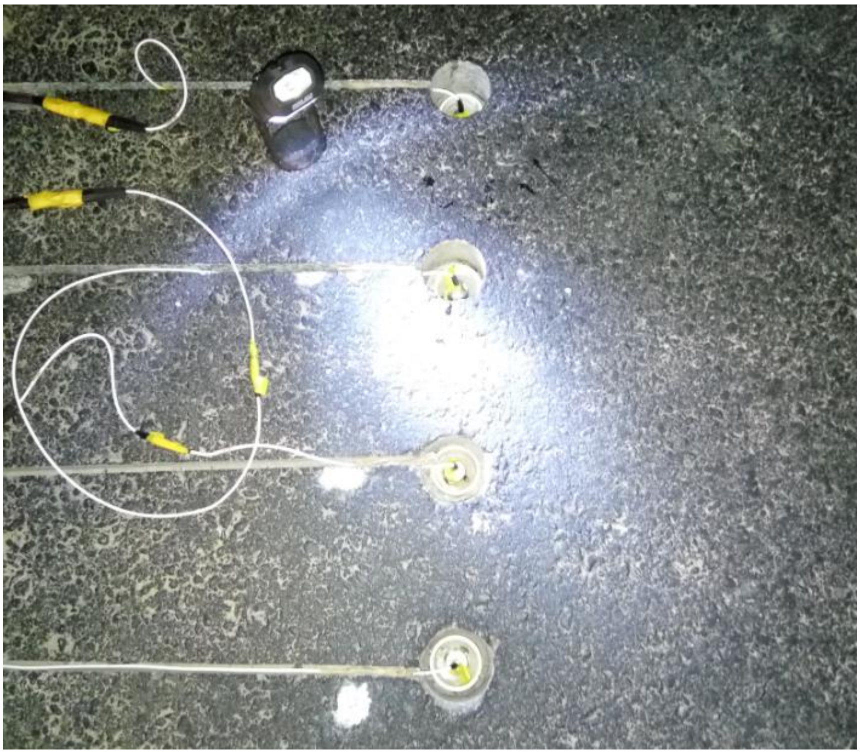


Figure 5 Core Holes and Accelerometers A1-A4



2.3 Core Profiles

Two typical core profiles are shown in **Figure 6**. The majority of the core profile consists of asphalt layers. The black layer is a rubber-like binding material used when laying down a new layer of asphalt. This layer is likely to behave in a viscoelastic manner. As the accelerometers are installed underneath this layer, there is a risk of acceleration measurements being lower than those measured at the surface of the road pavement (eg using the FWD).

Figure 6 Typical Core Profiles at Instrumentation Site

2.4 Data Acquisition

A HBM SomatXR MX1601B-R system connected to a laptop was used to record acceleration signals during testing. The laptop was running Catman version 4.1.1, allowing for the signals to be visualised in real time during the test. The sampling rate and low-pass filter cut-off were set differently on each night, as shown in **Table 3**.

Table 3 Sampling Rate and Low-Pass Filter Cut-Offs for Each Night

Date	Sampling Rate	Low-Pass Cut-Off
18th April	500 Hz	50 Hz
19th April	5000 Hz	1000 Hz

As A1 to A4 are charge type accelerometers, their signals were first passed through a charge conditioning amplifier. The Brüel & Kjær Type 2635 was used with a sensitivity of 100 mV/(m/s^2) and a band-pass filter with a usable frequency bandwidth of 0.2 Hz and 1 kHz, respectively.

The signal from accelerometer A5 was fed directly into the HBM system, with sensitivity set at 100 mV/(m/s^2).

3 TEST SETUP AND RESULTS

3.1 FWD Impact Tests

3.1.1 Setup

The FWD was used to perform a total of six impact tests (three drops per test) at three different locations. The position of the FWD relative to the accelerometers for locations 1, 2 and 3 are shown in **Figure 7**, **Figure 8** and **Figure 9**, respectively. The black dots represent the location of the FWD geophones and the number following the D indicates the radial distance from the impact location.

Figure 7 FWD Location 1, Tests 1 – 3

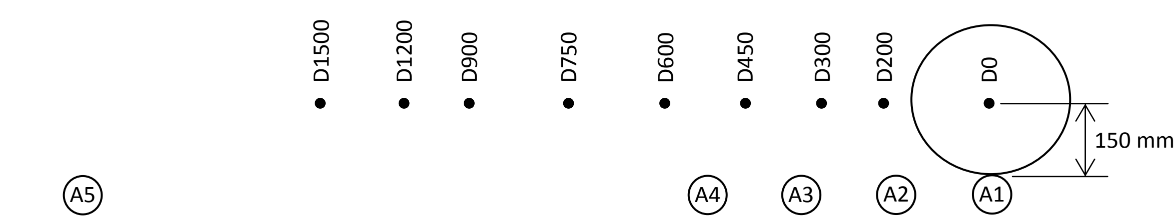
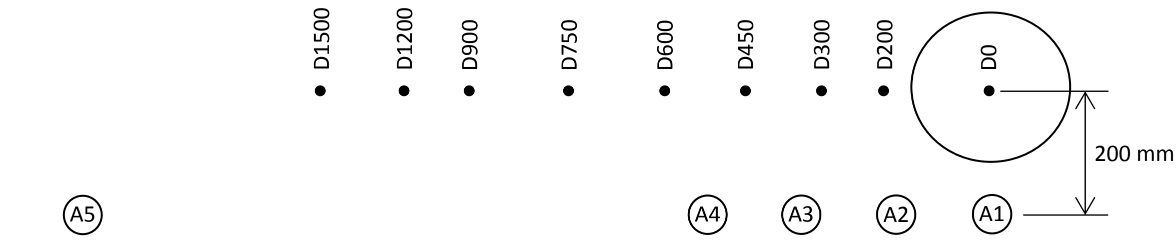


Figure 8 FWD Location 2, Test 4

Figure 9 FWD Location 3, Tests 5 – 6



The position, loading and the maximum displacement reported by the FWD for each test are shown in **Table 4**.

Table 4 FWD Test Positions and Loading

Test Number	Position	Loading (kN)	FWD D0 Displacement (mm)
1	Location 1	60	0.328
2	Location 1	60	0.327
3	Location 1	100	0.530
4	Location 2	40	0.186
5	Location 3	60	0.327
6	Location 3	100	0.518

3.1.2 Analysis Methodology

Only the final drop from each test was cut out for analysis. The data was de-trended by removing the mean and any underlying linear component. This was required as any drift in the data would result in increasing errors when integrated (eg quadratic error with linear drift). The acceleration data was not passed through any additional filters. The de-trended acceleration trace was then integrated using the trapezoidal rule to obtain velocity. The same procedure is completed on the velocity trace to obtain the final displacement trace.

3.1.3 Results and Discussion

The maximum deflection as calculated from the accelerometers' measurements are given in **Table 5**. The FWD displacements are taken at either 182 mm or 200 mm from the centre of the load bearing plate to match the distance to the nearest accelerometer. The 182 mm results are linearly interpolated from D0 and D200 results. The FWD results are slightly lower than the accelerometer based results. Typically the results are within a 10% range.

Table 5 Comparison of Accelerometer and FWD Deflection Results

Test ID	Distance from Load (mm)	FWD Deflection (mm)	Accelerometer Based Deflection (mm)	Similarity (%)
1	182	0.256	0.282	9%
2	182	0.256	0.280	9%
3	182	0.420	0.477	12%
4	182	0.132	0.160	17%
5	200	0.247	0.255	3%
6	200	0.402	0.446	10%

The acceleration, velocity and displacement traces for test 3 are shown in

Figure 10 (following page) as a typical example. An increasing offset of the peak is visible as the accelerometers are at increasing distances away from the impact point. Note that positive values indicate downwards movement of the pavement.

The traces for test 6 are shown in **Figure 11** (following page). This test has the same loading as test 3 although with an increased offset (see **Section 3.1.1**). The shape is identical with peak values decreasing slightly.

Figure 10 Impact Test 3 – Acceleration, Velocity and Displacement Traces

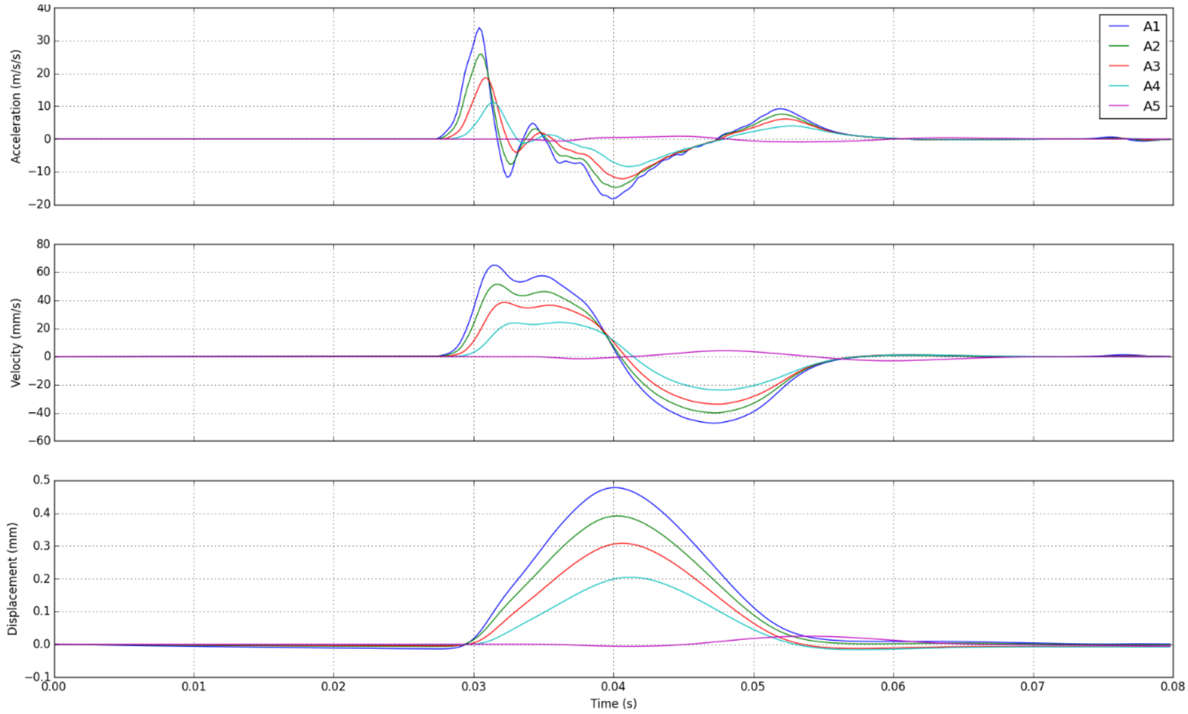
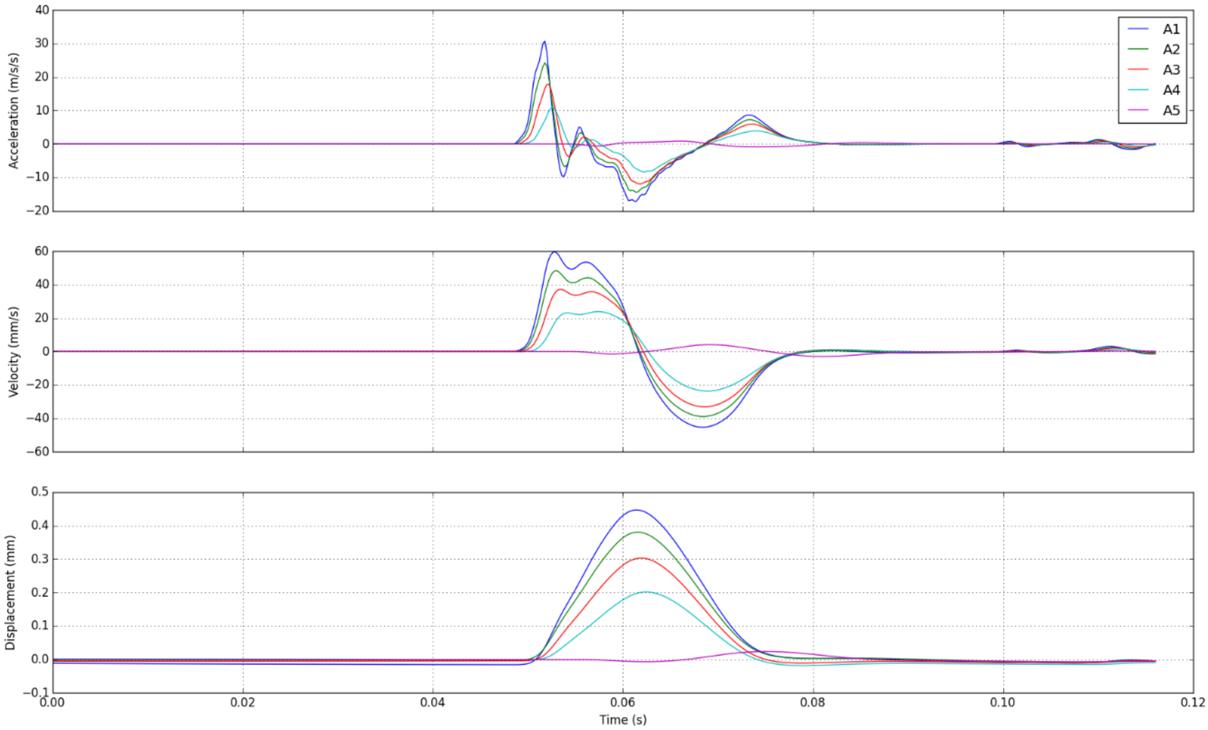
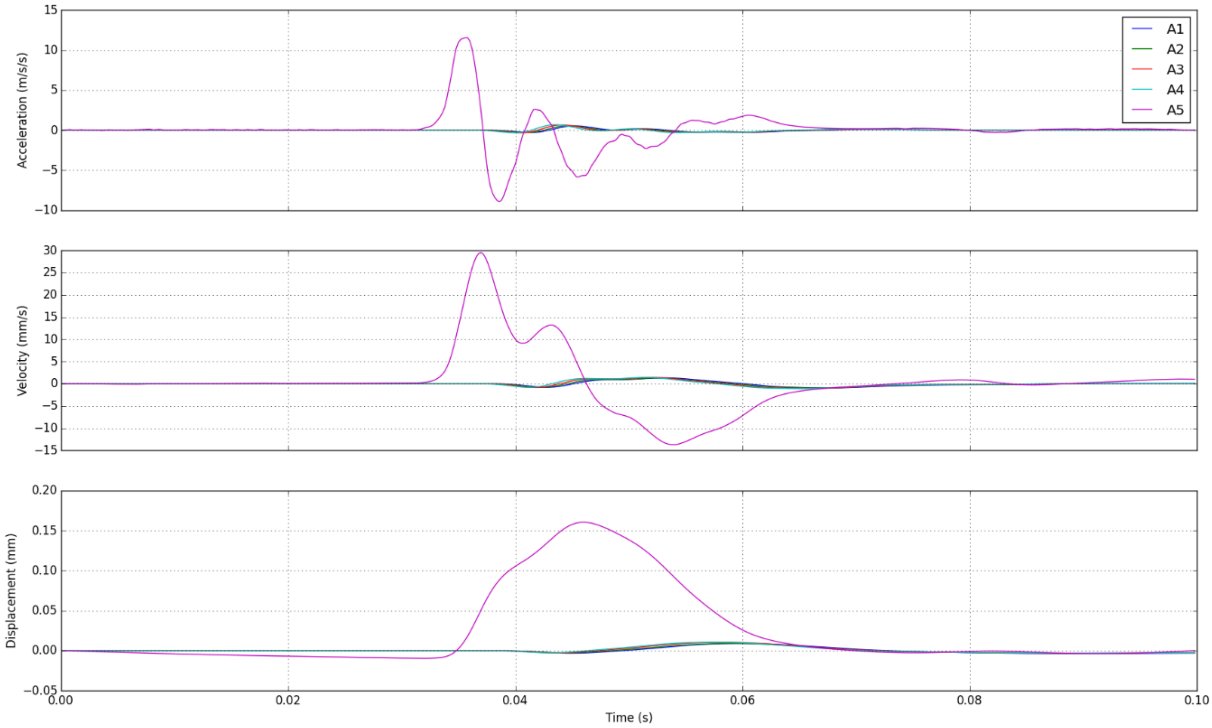


Figure 11 Impact Test 6 – Acceleration, Velocity and Displacement Traces



The traces for test 4 are shown in **Figure 12**. Here A5 has the highest value due to the positioning of the impact loading.

Figure 12 Impact Test 4 – Acceleration, Velocity and Displacement Traces

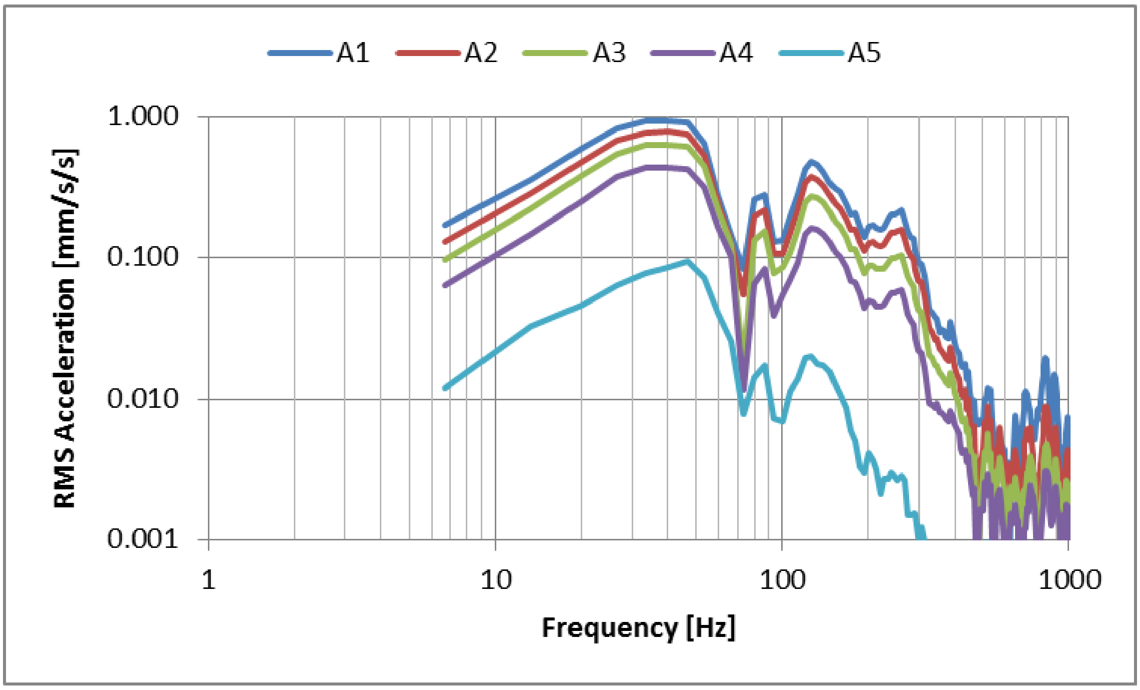


3.1.4 Impact Acceleration Spectra

Figure 10 to **Figure 12** show that the initial impact closely resembles a half-sine with an approximate duration of 15 ms. This can be related to a dominant frequency of approximately 33 Hz (ie 1/(0.015x2)).

Acceleration impact spectra are shown in **Figure 14**. The spectra shown are RMS spectra and have a frequency resolution of 6.66 Hz. The spectra show dominant energy in the 30 Hz to 40 Hz band which is consistent with the half-sine pulse lengths. The amplitudes reduce with increasing distance from the drop weight (as did the amplitudes in the time domain). The spectra indicate that vibration acceleration drops of rapidly at frequencies greater than 300 Hz.

Figure 13 Typical acceleration spectra for an impact.



3.2 Vehicle Pass-Bys

3.2.1 Setup

Vehicles from the resurfacing works were used as part of the pass by tests as the TSD was not available during testing. The axle loadings for each vehicle were generally unknown. The vehicles were instructed to drive with the outer wheel path in line with the accelerometers. The focus of this section will be on the last pass-by of a six axle semi-trailer with a reported total weight of 42 tonne.

3.2.2 Analysis Methodology

As will be shown in the next section, vehicle pass-bys result in lower magnitudes and a longer transient time as compared to the FWD impact tests. This is because the pass-by is a gradual loading as opposed to the FWD's impulse type loading. This is especially relevant for low-speed pass-bys.

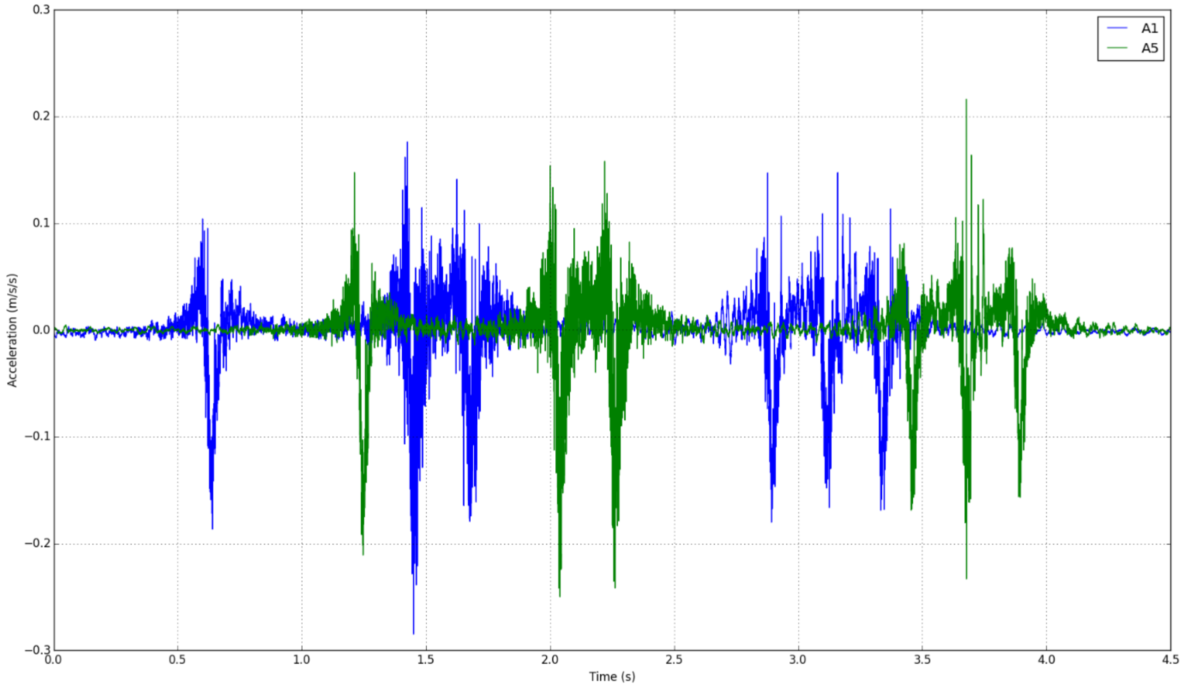
Due to the longer integration time and much lower signal-to-noise ratio the integrated results contain a higher amount of drift error. This is primarily due to increased noise at low frequencies (1/f noise). Although applying a high-pass filter with a low cut-off prior to integration aids in reducing this error, it also results in lower maximum displacements. Due to the sensitivity of the results, high-pass filtering during processing was avoided. A low-pass filter with a 25 Hz cut-off was applied to remove high frequency noise (this had no effect on the displacement results).

Exactly the same signal processing steps were followed as for the FWDs, with one additional step. Low frequency displacement data was manually removed and a spline was fit to the remaining data. This spline was then subtracted away from the displacement data. See the results in the next section for more detail.

3.2.3 Results and Discussion

The raw A1 and A5 acceleration signals for the last pass-by are shown below in **Figure 14**. The estimated speed of the vehicle was calculated to be around 20 km/h using the time offset of the signals and the known distance between accelerometers. There are six distinctive bumps, each corresponding to one of the vehicles six axles. The magnitudes of each are roughly equivalent, resulting in an axle loading of roughly 42/6 = 7 ton per axle, or 70 kN per axle (ie 35 kN per wheelset).

Figure 14 Acceleration Data for Last Semi-Trailer Pass-By (A1 and A5)



The transient associated with the first axle was cut out and analysed. The acceleration, velocity and displacement traces are shown in **Figure 15**. The integration results in a significant amount of drift in the displacement results. As discussed in **Section 3.2.2**, a 4th order spline is fit into the underlying data and then subtracted away. This process is shown in **Figure 16**.

Figure 15 Semi-trailer Pass-by Trace – First Axle Transient

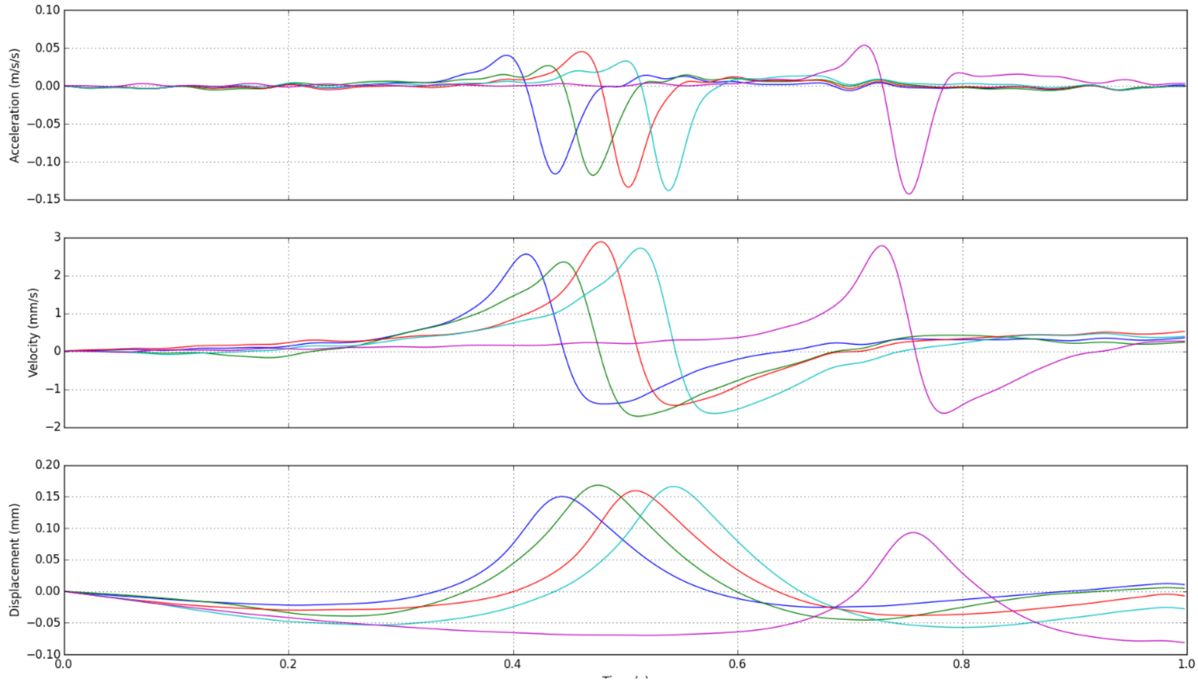
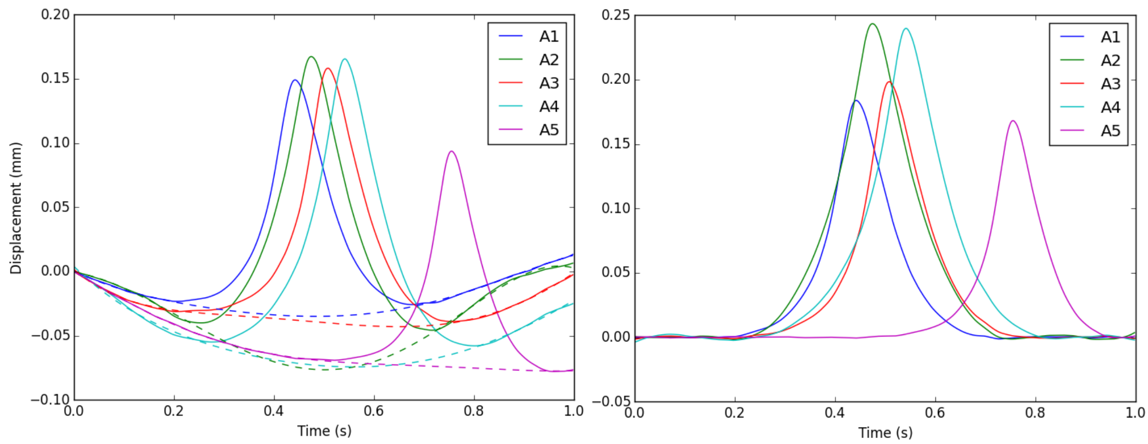


Figure 16 Correction of Displacement Data Using Curve Fit Spline (left: uncorrected data, right: spline corrected data)



The maximum found for each accelerometer showed some dependence on the choice of spline order but was deemed negligible. The mean maximum deflection for the accelerometer group is around 0.2 mm regardless of the chosen spline order. A simpler approach of subtracting the maximum and minimum displacement for each accelerometer (using the uncorrected displacement data) then taking the mean similarly gives a mean maximum deflection of around 0.2 mm.

3.3 Pass-by Acceleration Spectra

Figure 17 shows the acceleration spectra of the first axle transit of the semi-trailer using the unfiltered acceleration data. The frequency resolution is 1 Hz. The dominant energy is well below 10 Hz and lower compared to the 30 Hz to 40 Hz observed during the impact tests. This is also reflected in the longer pulse durations of approximately 100 ms as shown in **Figure 16**. The four spectra have almost identical amplitudes. The spectra diverge at low frequencies (1 Hz) which is due to 1/f noise. The bandpass filtered data is shown in **Figure 18** and shows no divergence at low frequencies. Also, this data drops off rapidly above the filter's upper corner frequency of 25 Hz.

Figure 17 Unfiltered Acceleration spectra for first axle transit of the semi trailer.

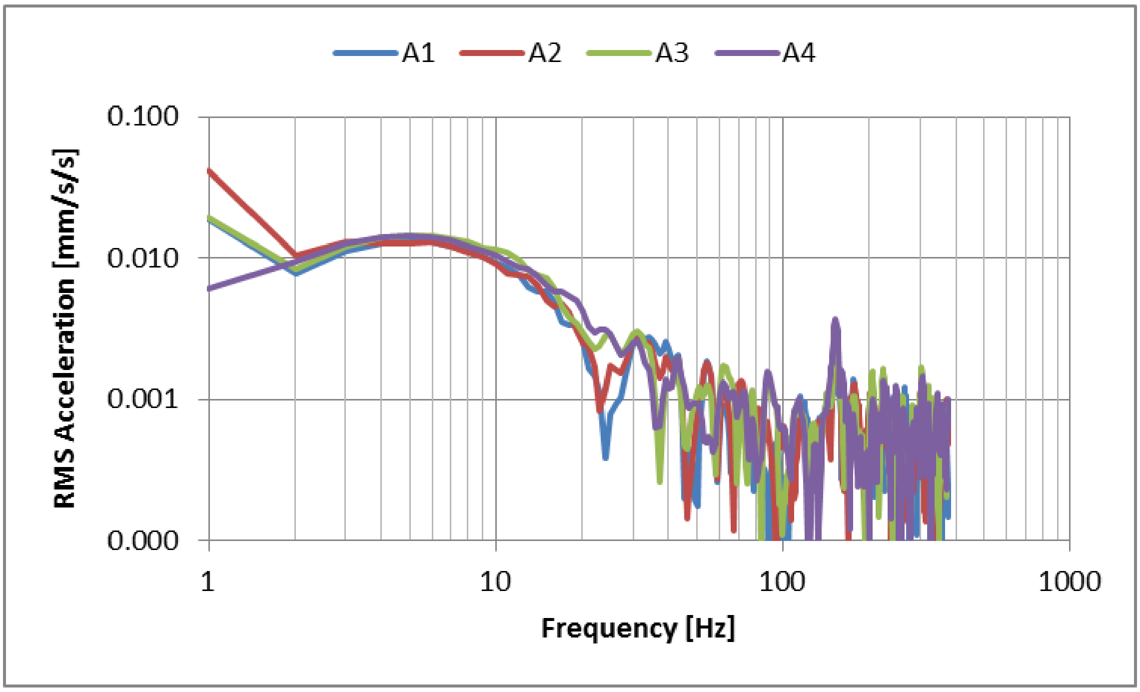
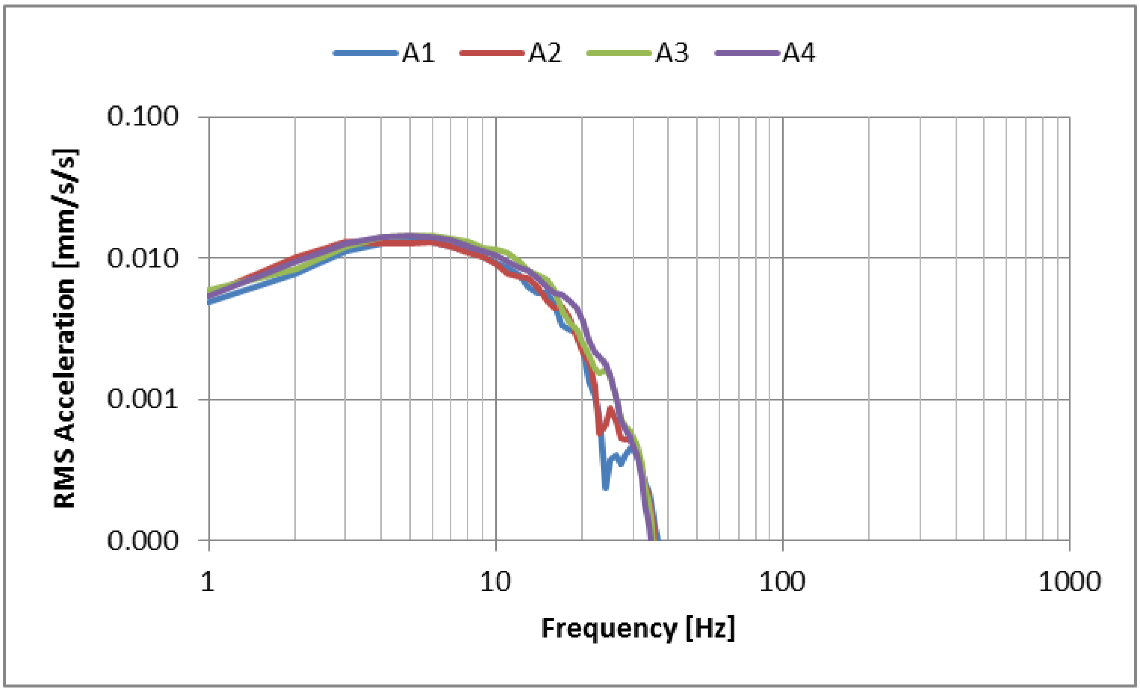


Figure 18 Filtered Acceleration spectra for first axle transit of the semi-trailer.



3.4 Comparison of FWD and Pass-By Results

The FWD results are clearer and more consistent than those recorded for a pass-by. Smaller acceleration magnitudes associated with pass-bys result in noisier acceleration readings. Additionally, during a pass-by the measured acceleration traces are 'contaminated' by residual vibration from the other axles. Coupled with the longer transient time, this results in a larger amount of drift error during the integration process. Although the displacement time traces can be corrected, there is still some variability in the end result. Faster pass-bys will result in shorter transient times reducing in less accumulation of drift error during integration and therefore increase the quality of the data.

Although the pass-by deflection value could not be compared to any other reference, it is a realistic result as it's slightly smaller than the 0.3 mm measured by the FWD for a 60 kN load. As asphalt is a viscoelastic material it is expected that a slower loading will result in lower maximum deflections. The presence of the rubber-like binding layer could also exacerbate this issue.

4 DATA

Results for all FWD tests and the vehicle-pass by were transferred to ARRB.

Each set of FWD test results are given in a separate file with the following column structure:

- Column 1: Time
- Columns 2-6: Acceleration for A1 to A5 (mm/s^2)
- Columns 7-11: Velocity for A1 to A5 (mm/s)
- Columns 12-16: Displacement for A1 to A5 (mm)

The semi pass-by test results are separated into the first, second and third axle groups, with the following column structure:

- Column 1: Time
- Columns 2-9: Unfiltered and Filtered (LP 25 Hz) Acceleration for A1 to A4 (mm/s^2)
- Columns 10-13 Velocity for A1 to A4 (mm/s)
- Columns 14-17: Displacement for A1 to A4 (mm)

As the A5 signal occurs at a significant time shift, the A5 results are given separately. The column structure is as follows:

- Column 1: Time
- Columns 2-3: Unfiltered and Filtered (LP 25 Hz) Acceleration for A5 (mm/s^2)
- Column 4: Velocity for A5 (mm/s)
- Column 5: Displacement for A5 (mm)

Table 6 lists the filenames and corresponding information. Note that the semi-pass by results are only integrated and not spline-corrected.

Table 6 Listing of Data Files

Filename	Information
test**X**_drop3.csv	Last drop for FWD test **X** (see Figure 10 to **Figure 12** for tests 3, 6 and 4)
semi_axle**X**.csv	Semi pass-by for axle group **X** (see **Figure 15** for first axle group), A1 to A4
semi_axle**X**_A5.csv	Semi pass-by for axle group **X** (see **Figure 15** for first axle group), A5 only

5 CONCLUSIONS

SLR have instrumented a section of road and measured pavement deflections due to vehicle pass-bys and impact loadings. The instrumentation, test and analysis procedures undertaken were proven to be successful.

Analysis of the results shows that short-term, impulse-like events result in clearer and more reliable displacement readings due to the introduction of less error during the integration process. Deflections calculated from accelerometer readings corresponded well to the FWD impact test results.

The measured pass-by deflections were of lower magnitude and longer duration compared to the FWD. This requires more complex post-processing procedures. The pass-by data could not be directly compared to measurement values from a second, independent system.

SLR have the following recommendations for future instrumentation tests:

- All coring and saw cutting of the test site should preferably be done at least one day prior to instrumentation to allow surfaces to dry.
- Use of the TSD for controlled pass-bys would provide a reference deflection value for comparison purposes.
- Faster pass-by times (or greater vehicle speeds) will reduce the length of the transients and accumulated drift error which will increase the quality of the data.