
# Implementation of Ground Penetrating Radar (GPR) in Western Australia

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March 2024

Final

# Version Control

| Report version no. | Date | Released to client by | Nature of revision |
|---|---|---|---|
| **1** | 18/03/2024 | AUR | Final |


## Acknowledgements

The author would like to acknowledge the collaborative input of the Main Roads Western Australia officers, in particular, Lalinda Karunaratne.





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# Summary

Main Roads Western Australia (Main Roads) spends significant amounts of money each year in destructive testing (e.g. test pits, coring) to verify the depth of the in situ pavement. The traffic control requirements for these testing methods involve significant traffic disruptions to the road users. Moreover, these test methods do not always provide sufficient information. Ground penetrating radar (GPR) is a non-destructive testing technique which provides a continuous image of the subsurface. GPR data can be used to optimise destructive geotechnical testing, and make informed decisions at a project- and network-level. It can also be combined with other pavement forensic testing techniques (e.g. Falling Weight Deflectometer (FWD), Traffic Speed Deflectometer (TSD)) as part of a pavement management system. A major benefit of GPR is that it can be operated at high traffic speeds (i.e. 80–120 km/h). Adopting GPR technology can result in cost savings, improved certainty with respect to existing pavement conditions prior to executing work and enhanced quality of the services Main Roads provides to the people of Western Australia. Therefore, the capability and availability of GPR in Western Australia (WA) needed to be investigated, to assess its potential for implementation on the Western Australian road network.

This study found that the use of GPR is limited across all Australian transport and road agencies including Main Roads, due to the following limitations:

- high cost, depending on the nature of the project
- difficulty in delineating different layers due to contamination of materials at layer interfaces (e.g. basecourse and subbase)
- challenges associated with detecting moisture in fine clays
- attenuation of signals in aggregates that have a high iron content, thus decreasing the accuracy of the results.

It was found that GPR is useful for:

- identifying the pavement layer thickness, noting the above limitations
- detecting the variability of pavement configurations across the project length
- assessing high moisture areas and/or voids within the pavement structure
- identifying cracks and other pavement surface defects.

The accuracy of GPR is dependent on several factors such as speed of testing, antenna type and frequency and material properties. Dipole (ground-coupled) and horn (air-coupled) antennae are available for testing with a range of frequencies from 10 MHz to 6 GHz. It has been reported in the literature that the error is generally about ±5% and up to 98% accuracy can be achieved if the GPR results are calibrated using the results obtained using traditional geotechnical investigation methods.

A market survey, conducted as a part of this project, suggested that most of the GPR contractors in Australia operate from the east coast and travel to Western Australia as required. Therefore, in order to achieve the best value-for-money outcome, Main Roads will need to have a clear understanding of a project's objectives, desired accuracy levels and deliverables from the project inception stage. They will also need to develop in-house knowledge and skills related to the conduct of GPR surveys to process, integrate and interpret large datasets to meet project requirements. The potential challenges for Main Roads in the implementation of GPR on its road network are the availability of the contractors, equipment and the inherent limitations of the GPR technology (e.g. frequency, performance in wet weather, speed of testing, accuracy, errors in interpretations, calibration issues and cost). Lessons learned from the critical evaluation of the GPR data provided by Main Roads suggest that the GPR surveys, and associated coring for the correlation and validation of the results, must be planned as a single project. The information related to the location of the core samples and GPR readings must be in the same reporting system and preferably collected with high-accuracy GPS equipment.

It is recommended that Stage 2 of the project proceed, with field trials conducted to assess the feasibility of using GPR on Western Australian road network, including a comparison of the results obtained using with the results of geotechnical testing in terms of cost and accuracy of the results. The scope of work and guidelines for the conduct of field trials must be prepared and the results of the field trials documented.

There is a need to develop more user-friendly software so that the GPR data can be converted into information which is meaningful to pavement engineers, and can be used in conjunction with other pavement survey data. Main Roads should consider funding initiatives aimed at achieving innovative GPR data collection and interpretation practices.

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# 1 Introduction and Scope

## 1.1 Project Background

Ground penetrating radar (GPR) surveys have the potential to provide high-resolution imagery of the subsurface, including pavement layer thickness, air voids, variability in the pavement configuration across the section length and the location of high moisture contents, etc. The major benefit associated with GPR investigations is that it is a non-destructive test that generates a continuous subsurface profile which can be compared with the discontinuous snapshots of the subsurface profiles obtained from destructive geotechnical investigations such as coring and trenching.

The data collected by the GPR can be used to optimise destructive geotechnical investigations such as test pits and pavement cores. Moreover, the correlation of the GPR data with geotechnical investigation can enhance confidence in the accuracy, or otherwise, of the GPR results.

Current GPR technology supports the collection of continuous data at traffic speeds of 80–100 km/h. The introduction of this technology on the Western Australian road network will provide an opportunity for Main Roads Western Australia (Main Roads) to include lower costs compared with destructive pavement investigations, reduced traffic disruptions, and an improved quality of work through the adoption of more efficient pavement rehabilitation treatment designs (e.g. accurate assessment of milling depth) and enhanced asset management practices (e.g. improved accuracy of forward work plans by using GPR data in a pavement management system.

## 1.2 Scope and Objectives

The aim of WARRIP project 2021-004 *Implementation of GPR in WA* was to investigate the feasibility of implementing GPR testing on the Western Australian road network in order to assess the effectiveness of GPR and its potential benefits to Main Roads in terms of: (1) cost savings, and (2) a reduction in the uncertainty regarding the composition of the State's road network.

The scope of works included the following:

- Improve technical capability of Main Roads by improving understanding of the GPR technology and the availability of the GPR contractors in WA.
- Provide recommendations to Main Roads for further assessment of the GPR capability to improve quality of work and reduce costs.

## 1.3 Structure of the Report

This report presents the findings of the investigations into the potential implementation of GPR on the Western Australian road network. The structure of the report is as follows:

- Section 1 – an overview of the project objectives and scope.
- Section 2 – the outcome of the literature review and discussion of the key findings.
- Section 3 – an overview of the availability of GPR technology in WA and the potential challenges associated with the adoption of GPR technology in pavement investigations.
- Section 4 – the outcome of the critical evaluation of the GPR data provided by Main Roads.
- Section 5 – conclusions.
- Section 6 – recommendations.

# 2 Literature Review

This section reports the results of a literature review undertaken at the commencement of the project. It entailed a study of national and international practices related to the application of GPR technology in pavement construction, maintenance, and rehabilitation. It also included the current usage of GPR by other transport and road agencies (TRAs) in Australia and overseas and the associated cost benefits. The purpose of the literature review was to demonstrate the capabilities and limitations of GPR technology in terms of its potential application as a non-destructive testing tool.

## 2.1 GPR Technology

Non-destructive test (NDT) methods are used to assess the current condition of a pavement and to identify possible maintenance requirements. They are a cost-effective means of testing that involve rapid data acquisition and the generation of a semi-continuous compilation of information specific to the inspected infrastructure.

GPR is a non-destructive tool used in many applications such as geological mapping, environmental monitoring, pavement investigations and archaeological prospection. Amongst the wide range of available NDT methods, GPR is recognised as one of the most effective and powerful non-destructive methods used to examine the subsurface conditions in a pavement for maintenance and rehabilitation applications (Eriksen et al. 2006).

GPR technology has the capacity to continuously collect large amounts of data along extensive sections of pavement at traffic speeds of up to 110 km/h. The working principles of a GPR system are based on the transmission and reception of short electromagnetic (EM) signals in a given frequency band. These EM signals are transmitted through the air to penetrate the road surface and travel into the pavements substructure. The rate at which these EM-signals are reflected allows for an estimation of most of the physical and geometrical properties in the subsurface. After collection, the GPR raw data is analysed and interpreted, ideally by an expert, to provide useful information for asset decision making.

Analogous to other non-destructive test methods, collected GPR data requires calibration against physical measurements obtained from the destructive works (i.e. boreholes, test pits, trenches or cores) in order to validate the results. The key factors for successful GPR utilisation include:

- project background information, objectives and proper planning and performance of the field work
- control on the core locations and depths and proper equipment calibration (Fauchard et al. 2003; Li et al. 2014; Plati & Loizos 2013; Saarenketo & Scullion 2000)
- accurate determination, or estimation, of the dielectric constant of pavement materials to assist in the accurate analysis of GPR data (Evans et al. 2007).

### 2.1.1 GPR Hardware and Arrangements

A GPR system is comprises an antenna (a core component of the system), a data acquisition system, a distance measuring instrument and an optional GPS fitted to a survey vehicle or cart. Based on the types of antennae and their arrangements, there are three types of GPR systems:

- GPR with horn antenna
- GPR with dipole antenna
- GPR with antennae array multi-channel.

These systems can be set up in the following configurations based on the transmitter and receiver designs:

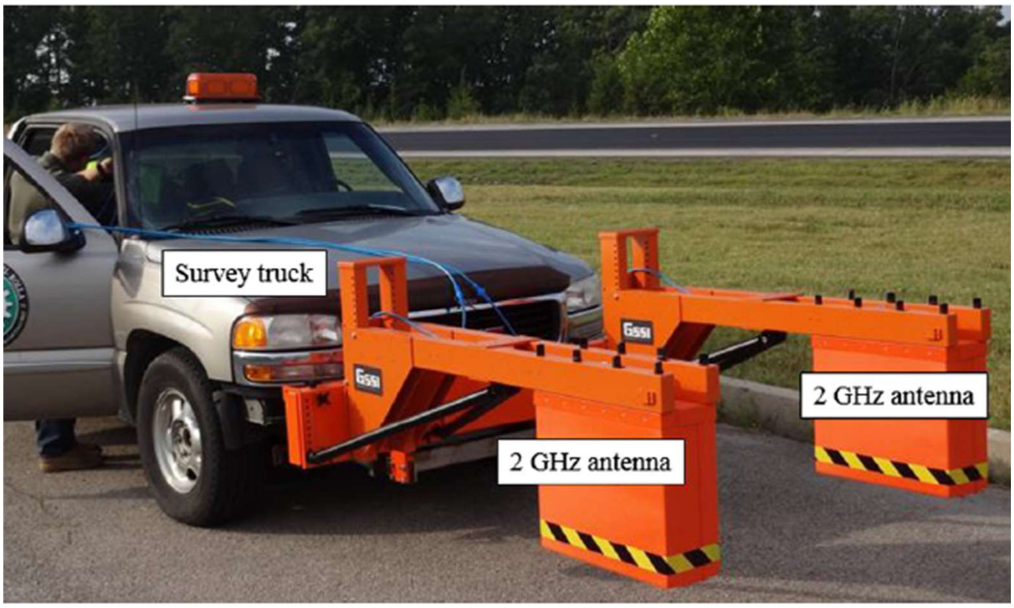
- monostatic system, which uses the same antenna as the transmitter and receiver
- bistatic system, which uses one antenna for transmission and another for reception
- multi-static system, which uses a single antenna or multiple antennae as transmitters and multiple antennae as receivers.

### GPR horn antenna

The GPR systems with horn antennae were specifically designed to be used in the evaluation of transport infrastructure as they can operate at traffic speeds ranging up to 80 to 120 km/h. The antennae, termed 'air-coupled' (or air-launched) are mounted on a vehicle where they are suspended above the surface of the road at a distance typically 0.4 to 0.6 m (Solla, Perez-Gracia & Fontul 2021). Figure 2.1 shows survey vehicle with two mounted high-frequency antennae.

The horn antennae operate at high frequencies typically ranging from 1 to 2.5 GHz that correspond to penetration depths of 50 mm and 25 mm respectively. These frequencies are common for use in asphalt and concrete condition assessments, determination of pavement layer thickness and locating embedded reinforcing bars (Annan et al. 2016).

**Figure 2.1: Survey vehicle with two mounted high-frequency antennae**




Source: Khamzin et al. (2017).

### GPR with dipole antennae

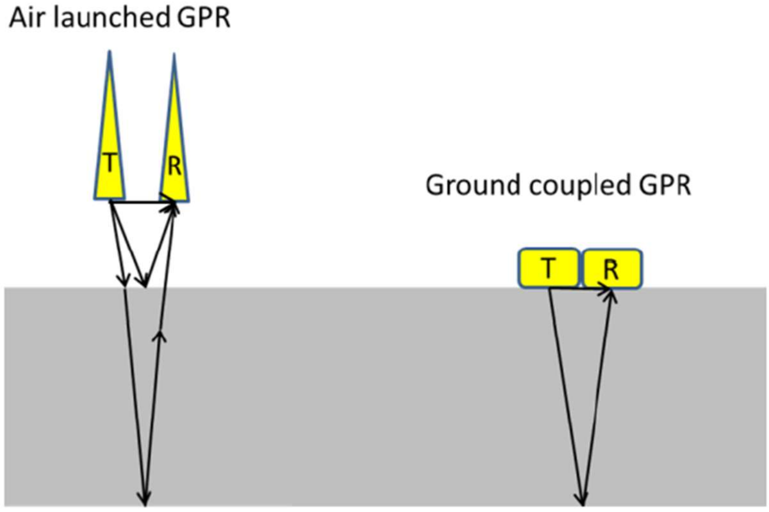
GPR systems that have dipole antennae are designed to be in contact with the road surface or suspended slightly above it. These systems are therefore only suitable for testing at maximum speeds of 40 to 60 km/h. In this arrangement the EM-signal is ground-coupled (see Figure 2.2) which introduces a stronger signal into the pavement. This allows for greater penetration depths and provides higher resolution of details over much smaller areas than signals emitted by an air-coupled system.

Dipole antennae operate across a wide range of frequencies but generally between 10 MHz and 6 GHz. For transport infrastructure applications, the optimum results are obtained using a central frequency of 400 MHz to 2.5 GHz.

Experience suggests that ground-coupled GPR measurements are generally more effective as subsurface reflections are enhanced, leading to greater penetration depth (lateral spatial resolution of air-coupled signals is known to degrade rapidly (Diamanti & Annan 2017)). Additionally, it can be argued that the data acquisition is faster in an air-coupled system due to the antennae being clear of the ground. However, literature review suggested that ground-coupled systems have been deployed on vehicles moving at highway speeds (Annan et al. 2016).

Figure 2.2 shows typical air-launched and ground-coupled GPR systems.

**Figure 2.2: Air-launched and ground-coupled GPR systems**




Key: T: Transmitter, R: Receiver.
Source: Diamanti and Annan (2017).

### GPR with antennae array multi-channel

A GPR system with an array of multi-channel antennae uses single or multiple antennae as transmitters and multiple antennae as receivers. The multi-channel configurations can include both air- and ground-coupled antennae that are closely spaced and simultaneously recording. Commonly, these systems are composed of four to 16 couples of transmitting and receiving channels mounted in a parallel broadside configuration with a crossline trace spacing of 40 to 120 mm. This system enables faster data collection by increasing the extension of the investigated area per time unit. It can also produce 3D images.

## 2.1.2 Operating Principles

### General

Short bursts of electromagnetic (EM) signals are transmitted from the GPR antennae as the instrument is moved across a surface. These signals propagate downward, through the surface and sub-surfaces with a velocity that is a function of the dielectric constants of the materials through which it propagates. When the signal encounters an interface where there is a change in the dielectric constant, a portion of the energy is reflected back to the receiver. The reflected signals' travel time, amplitude and phase of the signal is recorded by the receiver (Khamzin et al. 2017).

In all GPR systems the penetration depth is inversely proportional to the wave frequency, meaning that the loss of penetration depth because of an increase in an antenna frequency is offset by an increase in image resolution. For example, Solla et al. (2021) reported that the penetration depth from a 1.5 GHz antenna was 0.50 m while a 400 MHz antenna will penetrate up to a depth of 2.00 m.

In simple terms, low frequencies have high penetration depths but low resolution, and high frequencies have lower penetration but higher resolution.

### Dielectric constant

The dielectric constant of a material governs the speed and reflection amplitude of the EM-signals. Therefore, accurate estimation of the material's dielectric constants is critical for the successful interpretation of the GPR data. The dielectric properties of materials are required in order to:

- calculate the thicknesses of pavement structural layers and subgrade soil layers
- determine the moisture content
- calculate the asphalt air voids content

- estimate the moisture susceptibility and sensitivity, which is directly related to the permanent deformation of the unbound materials
- assess the compressibility of subgrade soils
- assess the homogeneity and fatigue of the bound layers.

In many road infrastructure projects, particularly during the quality assurance and quality control (QA and QC) phase of the project, high-quality data is required to ensure compliance and achieve the quality objectives (e.g. to verify the structural integrity, quality of asphalt layer bonding, permanent deformation in asphalt pavements, etc.).

According to Khamzin et al. (2017) the dielectric constant of a material is influenced by many parameters, including:

- type of material (i.e. mineralogy, electrochemical interaction)
- structure and properties of material (i.e. porosity, density, particle shape)
- pavement condition and integrity
- temperature
- pore fluid content.

The dielectric constant of the material can be determined in different ways:

- Use published values from various sources (Table 2.1).
- Correlate GPR data with the results of core samples at known locations (preferably with ground-coupled systems).
- Use the surface reflection method, where the amplitude of a reflected signal from the pavement surface is compared with that of a signal reflected from a copper plate on the pavement surface (air-launched antenna only).
- Use common midpoint (CMP), which involves the separation of the transmitter and receiver parts of the antenna by keeping the same halfway point between the transmitter and the receiver. This is achieved by moving the GPR antennae away from each other around their common midpoint.

Table 2.1 summarises the dielectric values of different pavement and subgrade materials reported in the literature.

**Table 2.1: Dielectric values of common pavement-related materials**

| Material | Saarenketo (2006) Dielectric constant | Davis & Annan (1989) Dielectric constant | Robinson et al. (2013) Dielectric constant |
|---|---|---|---|
| Air | 1 | 1 | 1 |
| Asphalt | 4–8 | – | – |
| Concrete | 8–10 | – | 80 |
| Water (fresh) | 81 | 80 | 80 |
| Water (saline) | – | 80 | – |
| Sand (dry) | 4–6 | 3–5 | 5 |
| Sand (wet) | – | 20–30 | – |
| Limestone | | 4–8 | – |
| Gravel | 4–7 | – | – |
| Shale | – | 5–15 | – |
| Silt | 16–30 | 5–30 | – |
| Silty sand | 7–10 | | – |
| Clay | 25–40 | 4–40 | – |
| Clay (wet) | – | – | 10 |
| Granite | 5–7 | 4–6 | 5 |

Sources: Davis & Annan (1989); Saarenketo (2006); Robinson et al. (2013).

The ranges of dielectric constants for road-making materials considerably overlap and depend on the specific materials being examined. Saarenketo (2006) reported a range of dielectric constants for silt, ranging from 16 to 30, whereas Davis and Annan (1989) reported a wider range, 5 to 30, indicating that some of the silts examined by Davis and Annan were significantly different to those examined by Saarenketo (2006). Similarly, Saarenketo (2006) reported a range of dielectric constants for clay, ranging from 25 to 40, whereas Davis and Annan (1989) reported a wider range, 4 to 40. On the other hand, dielectric constants of other materials (e.g. air, water, granite and dry sand) reported by different researchers were within similar range.

### Attenuation

Attenuation is the depletion of the strength of an EM-signal as it moves through a material. The attenuation rate is predominantly a function of a material's moisture content and salinity. For example, dry and intact asphalt tends to have low attenuation rates while moist and porous asphalt tends to experience higher attenuation rates.

The pavement quality (e.g. bonding between asphalt layers, moisture entrapment in deboned asphalt layers and porous asphalt mix, construction integrity, etc.) also influences the intermediate and base layer reflection amplitudes. Lower-quality pavements often result in decreased reflection amplitudes while higher-quality pavements correspond with better quality signals (Khamzin et al. 2017).

### Sampling density

The sampling density in a GPR system is the number of readings taken per unit length of the section surveyed. Saarenketo & Scullion (1995) established that a recommended good sampling density for measuring longitudinal sections of roads is 10 scans per meter for both air- and ground-coupled systems. This sampling density is sufficient to provide adequate information about cracks, crack propagation and segregation in bound pavements. However, Saarenketo (2006) recommended 40 scans per meter sampling density when measuring road cross-sections and conducting bridge deck surveys.

### Data collection speed

The effect of data collection speed was investigated by the Texas Transportation Institute. The GPR tests carried out over a large aluminium reflector at different speeds up to 70 km/h showed that speed had no major influence on the amplitude reflection (Scullion, Lau & Chen 1992).

Hopman and Beuving (2002) compared GPR data collected by Dutch GPR contractors at different speeds with the drill core data. The results indicated that the mean error increased with data collection speed: the mean error at low speeds was 5% while at a speed of 80 km/h the error was 9%.

A GPR system used for high-speed data acquisition and storage was evaluated as a part of railway ballast investigations. The GPR system was mounted beneath an inspection train. The inspection train collected data related to railway ballast conditions at sampling intervals of less than 50 mm at line speeds of 100 km/h. The quality of the data collected at high speed was validated against a slow-speed trolley-based GPR survey and a good level of correlation was found between the datasets (Eriksen et al. 2006).

### Antenna configurations

The GPR antenna frequency used for the survey determines the depth of signal penetration and resolution of the subsurface image. Generally, the higher frequency signals provide a better resolution (i.e. more precise indication of depth) but have a lower penetration depth (Venkateswarlu & Tewari 2014).

As the antenna frequency has a major impact on the investigation depth and precision of the data acquired, multiple GPR antennae could be coupled to meet the project specific requirements. Saarenteko (2006) reported that these multichannel systems offered several advantages due to the simultaneous use of the high-frequency antenna (higher resolution at shallow depth near the pavement surface) and lower-frequency antenna (with greater signal penetration to explore deeper horizons). Similarly, multiple channels allow the use of the antenna array techniques to determine the signal velocities (Davis et al. 1994; Emilsson, Englund

& Friborg 2002; Mesher et al. 1995) and data collection using many antennae with the same frequency to collect several survey lines simultaneously. This facilitates the preparation of a 3D model of the surveyed area or structure (Davidson & Chase 1998; Manacorda et al. 2002).

The most important parameters to be taken into consideration when designing a GPR antenna configuration for a specific application are:

- operating frequency
- sampling interval or sampling density
- antenna orientation and separation
- electrical properties of the in situ materials
- resolution frequency
- clutter frequency
- external interferences.

Queensland Department of Transport and Main Roads (TMR) (2020) *Pavement rehabilitation manual* provides a brief overview of the GPR equipment, calibration and signals' depth of penetration for a range of frequencies. The depth of penetration can range up to about 0.5 m, with a ground-coupled 1.5 GHz antenna, and 3 to 4 m with a 400 MHz antenna, and even deeper with lower-frequency antennae.

## 2.2 GPR Applications in Pavements

### 2.2.1 Pavement Investigation, Structure, Condition Monitoring and Rehabilitation

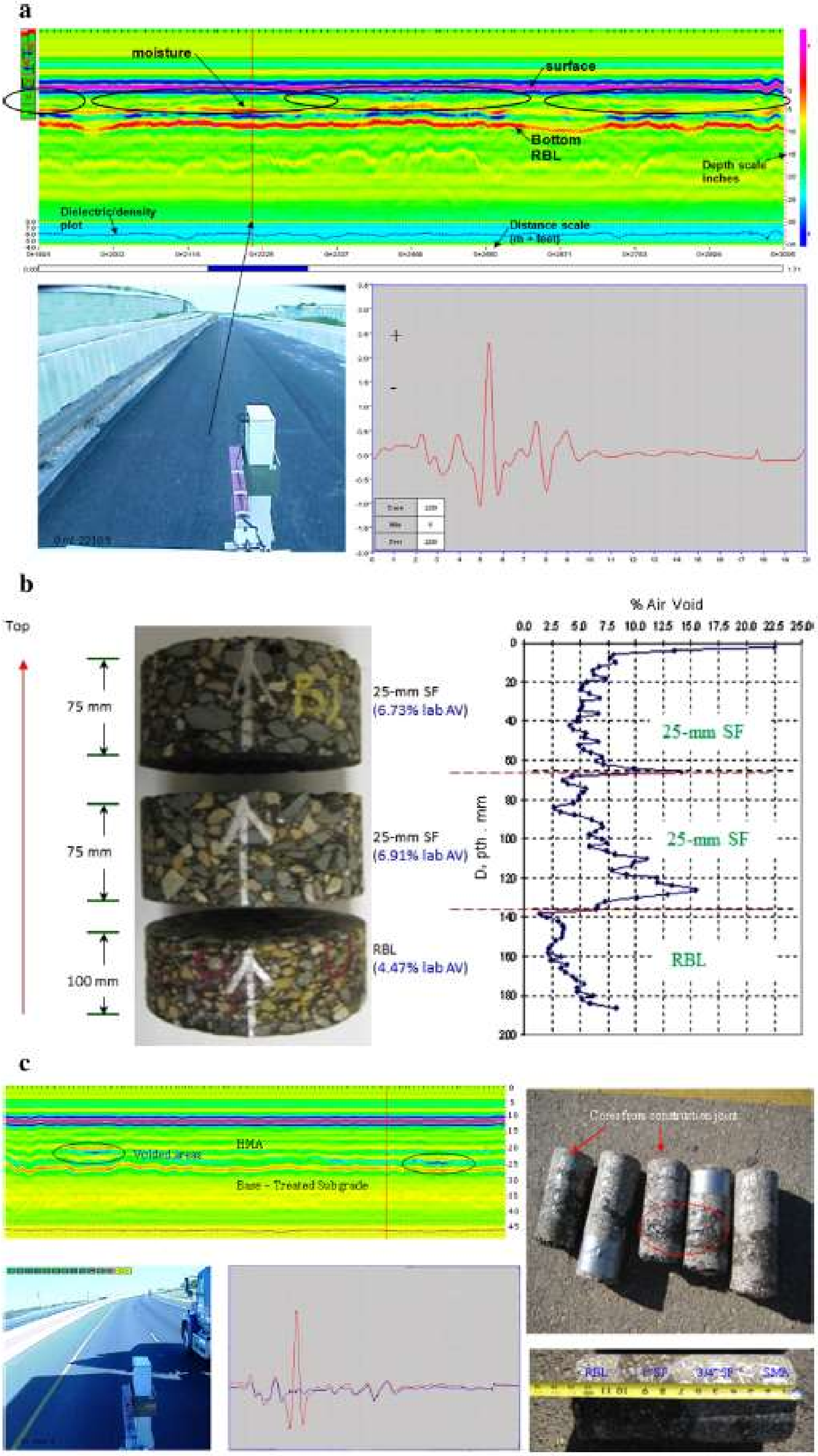
The use of GPR in road infrastructure covers a wide range of applications, including identification of pavement profile for new and existing roads, pavement evaluation and rehabilitation design of existing roads, and the verification of various pavement properties to aid QA and QC during the construction of new pavements. Several researchers have investigated GPR application for inspection and the evaluation of pavement structure, condition and distress, e.g. Angio, Pinelli & Benedetto (2003); Diamanti and Redman (2012); Heitzman et al. (2013); Krysinski and Sudyka (2013); Li et al. (2014); Liu et al. (2021); Muller (2015); Diamanti and Annan (2017); Khamzin et al. (2017), Marecos et al. (2017a & b). The typical applications of GPR used in pavement investigations were as follows:

- measuring the thickness of the pavement layers
- monitoring the variation in pavement layer thicknesses over the length of a project site
- assisting in the analysis of rutting mechanisms
- determining and verifying the material properties
- locating subsurface anomalies (i.e. objects, large boulders, air voids, tree roots, etc.) and man-made features (i.e. public utility lines – communications, gas, electricity, water; abandoned objects – fuel tanks, concrete waste, etc.)
- locating subsurface pavement defects (i.e. stripping, delamination, trenches, patches, voids, cracks)
- detecting subsurface moisture
- locating significant changes of construction within a pavement's length
- assisting in establishing the milling depth for pavement resurfacing projects.

Cao, Labuz & Guzina (2011) proposed a model based on GPR scans over a wide range of pavement profiles to estimate the pavement layer thickness without prior assumption of the pavement condition through GPR measurements obtained at highway speeds. The interpreted layer thicknesses showed very low error compared to the core data.

Li et al. (2015) used GPR for the construction monitoring and evaluation of perpetual pavements in Texas (USA) up to a depth of 610 mm while travelling at speeds of up to 113 km/h without need for traffic closures. The pavement sections typically consisted of hotmix asphalt (HMA) layers of over 350 mm total thickness placed on a 200 mm thick lime- or cement-treated base and a well-compacted subgrade. The study was supplemented with coring and laboratory air voids measurements. The results confirmed that the GPR is useful in determining pavement layer thicknesses, assessing compaction uniformity, locating areas of moisture retention, identifying low density locations and localised voided areas and indicative assessment of vertical segregation and debonding problems within or at HMA layer interfaces. Additionally, the GPR was successfully used in assessing the quality of the construction joints (permeability problems at the joints). Figure 2.3 shows typical GPR results from this study.

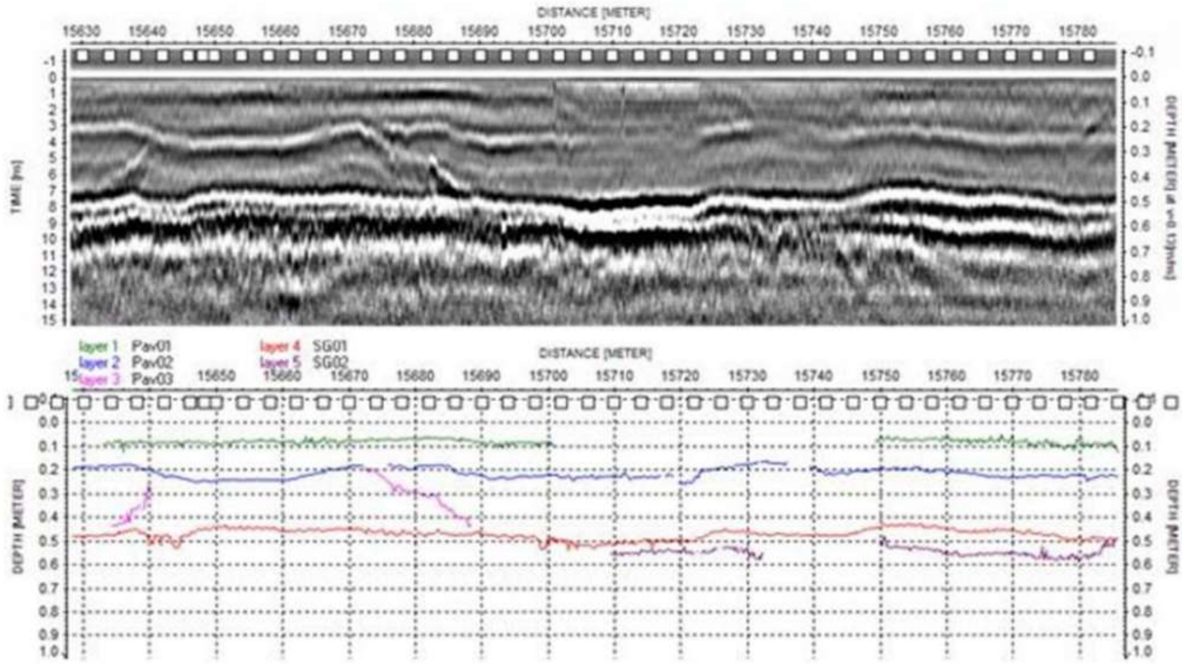
**Figure 2.3: Typical GPR results – detection of voids and moisture**




Key: a: forensic defects, b: coring and X-ray CT scanning indicating AV distribution, c: localised high voided areas and vertical segregation in cores.
Source: Li et al. (2015).

One of the most basic and successful applications of GPR for a road agency is the determination of pavement layer thicknesses. Figure 2.4 shows a typical example of two-dimensional radargram of a road pavement.

**Figure 2.4: Example of a two-dimensional radargram of a road pavement (top) and corresponding layer interpretation (bottom)**




Source: TMR (2020).

It is important to understand the local conditions (i.e. properties of in situ materials) and the capability of different antenna frequencies to address all requirements of a pavement investigation project. Marecos et al. (2017a) investigated the capability of joint use of the GPR antennae at different frequencies, i.e. ground- and air-coupled. They determined that the air-coupled antennae were more suitable for measuring the continuity of the pavement layers and should be selected when an evaluation of the layer thickness is needed. Ground-coupled antennae provided better signal to noise ratio. Therefore, they were preferred for detecting superficial cracks and debonding of asphalt layers. The penetration depth of GPR electromagnetic waves is limited in soils which have a high percentage of clay or high moisture content. In such cases, it may be useful to use different types of GPR antennae to improve the interpretation of the measured data.

Plati and Loizos (2013) estimated the in situ density and moisture content within HMA layers using GPR with air-coupled antennae of 1 GHz and 2 GHz frequencies. The results showed that the higher penetration depth of the 1 GHz antenna identified more areas of potential moisture within the HMA layer. There were limited differences between density or moisture content values using 1 GHz and 2 GHz antennae as the layer investigated consisted of the same HMA material. Therefore, the predicted results were independent of the antenna frequency. Despite a lot of work being undertaken worldwide related to GPR applications in pavements, there is no standardised procedure to address the specific pavement issues such as HMA density evaluation.

With the latest developments in GPR technology for identifying layer thicknesses, air voids and moisture content, GPR can be used for QA and QC related measurements such as to:

- determine the quality of asphalt layer bonding where significant amounts of moisture are trapped within the de-bonded areas (Heitzman et al. 2013)
- efficiently verify the existence of permanent deformation in the asphalt pavements.

The TMR *Pavement Rehabilitation Manual* (TMR 2020) provides guidelines when GPR data is used in pre-construction activities and/or pavement rehabilitation investigations, including:

- verify the accuracy of existing records
- determine the location and extent of consistent sections of the existing pavement

- use the estimated pavement layer thicknesses (calibrated against physical measurements) in conjunction with deflection data to undertake the mechanistic back analysis
- compare the GPR results with the visual surveys, deflection results or roughness results to determine if the anomalies detected by the GPR correlate with the pavement's visual condition, deflection properties or roughness.

During construction, the GPR investigations can facilitate the following:

- The contractor can ascertain the layer thickness to avoid penalties. The construction can be verified as being built to specifications and changes in the construction can be located.
- Determine whether the pavement in the shoulder is adequate for trafficking as part of temporary traffic diversions.
- Verify the location and depth of public utility plant (i.e. fibre optic or polyvinyl chloride/poly-pipe).
- Determine the location and extent of subgrade anomalies or obstacles.
- Detect, track and determine the size of the air voids.
- Detect the location of previous trenching: GPR can often differentiate materials disturbed previously from the surrounding undisturbed materials.

The use of GPR during the construction stage can assist the contractor in the following ways:

- select the pavement lots by identifying uniform sections
- schedule the project works
- allow more appropriate machinery to be selected early on
- reduce uncertainty based on enhanced information related to in situ materials
- identify poorly-constructed areas quicker and reduce associated delays and costs.

Noise modulated GPR (NM-GPR) is used for the assessment of calibrated road layer depth measurements and quantitative moisture mapping (Muller 2015). Khamzin et al. (2017) used 2 GHz air-launched front-mounted GPR units spaced 1.22 m apart to investigate to a depth of 762 mm. The antennae were positioned 457 mm above the pavement surface to provide optimal image pavement overlay to a depth of about 508 mm. The GPR system was calibrated by collecting data over a metal plate placed under the antennae. The average data collection speed was 60 km/h. The results indicated that the inspection of pavement segments with non-uniform thickness could be difficult. The air-launched GPR system equipped with the high-frequency antennae could be effectively used for QA and QC of new pavement with minor limitations.

Diamanti and Redman (2012) observed the crack responses in a variety of pavements (e.g. asphalt over concrete and asphalt over granular) with and without the visible surface cracking. This data was acquired using a ground-coupled GPR system at highway speeds. This study found that, although 250 MHz GPR is often more effective at detecting cracks and provides more distinctive response from vertical cracks than 1 GHz GPR, the 1 GHz GPR was more appropriate for crack characterisation because of its superior spatial resolution.

Krysinski and Sudyka (2013) studied the capability of the GPR for the pavement crack diagnosis by performing deep and wide analysis of the GPR signals observed in the presence of transverse cracks filled with foreign material or widespread zones of material degradation or lithological changes. The initial unopened cracks (new cracks) were not visible using the GPR equipment at higher frequencies due to the masking of signals generated in granulated medium like asphalt. It was noted that the lower frequencies allowed a better detection of large elements, while higher frequencies could outline details. Therefore, the use of different frequencies can be helpful in crack diagnosis. These observations can be useful in identifying hidden localised cracks and determining the crack properties like the range of depth, width, and shape, thus sometimes allowing a better understanding of the failure mechanism.

The *Pavement Rehabilitation Manual* (TMR 2020) verifies the assumptions as to the causes of pavement failure mechanisms (for example, detecting strong reflections indicative of excess moisture within a pavement may lead to conclusions regarding the rehabilitation strategy, and detecting soft spots in a subgrade may explain surface failures, and so on).

### 2.2.2 GPR Capability to Identify Top Asphalt Layer Thickness

One of the most successful applications of GPR on flexible pavement is estimating layer thickness which is an important parameter for newly-constructed roads in terms of QA and QC. For an existing pavement, it is used for condition assessment, predicting the remaining life (Zhao & Al-Qadi 2016), and estimating milling depth for resurfacing projects.

In radargram interpretation, the intensity of the signal at the interface indicates the quality or clarity of the interface (i.e. the more white or black the layer interface, the greater is the reflection amplitude, making it easier it is to pick the interface (Hadi & Preko 2013). Although antenna frequency may vary depending on the purpose of the project (and hence the equipment required), the literature review and consultation with selected GPR contractors indicated that the common frequency range (low to high) for pavement investigation is 400 MHz and 2.0 GHz. For top asphalt layer thickness, the more appropriate frequency range is higher (e.g. 2.0–2.5 GHz).

The GPR outputs are affected by user-defined parameters set during the processing stage. The stages of the processing include raw signal correction, removal of lower frequency harmonics, removal of antenna ringing, band-pass filtering, and signal gain. In addition to these stages, there are special processing steps such as vertical resolution enhancement, migration and time-to-depth conversion (Ciampoli et al. 2019). Multi-channel radar systems can be used for better results.

There are different methods for the determination of asphalt layer thickness using GPR data. These include:

- Two-way travel method – commonly used to determine asphalt layer thickness using single antenna GPR measurements.
- Common midpoint (CMP) method – is based on increasing an offset between the transmitter and receiver. An increase in the offset increases the two-way travel time in the layer. The extended common midpoint (XCMP) method assumes that the two antenna systems are all ground-coupled system.
- Common source method – which involves GPR measurements with one transmitter and at least two receivers.

### 2.2.3 Bridge and Culvert Investigation

Solla et al. (2021) provided a review of the best practices related to GPR application to transport structures. They noted that GPR is most used in internal bridge inspections due to its high practicality and rapid data collection with minimum intervention without affecting the structure’s integrity. Detection of internal damage can prevent the unpredictable and premature collapse of a structure. Solla et al. (2021) classified the use of GPR for bridge inspections into two categories based on the type of bridge (i.e. stone masonry and concrete).

For stone masonry arch bridges, the GPR can detect:

- unknown geometries such as hidden arches (Solla et al. 2010; Solla et al. 2011a; Solla et al. 2014)
- cavities and cracking in the masonry (Bergamo et al. 2015; Fauchard et al. 2013; Solla et al. 2011b; Trela, Wostmann & Kruschwitz 2008)
- moisture detection (Kalogeropoulos & Brühwiler 2011; Solla et al. 2012)
- bridge foundation condition (Arias et al. 2007; Solla et al. 2012; Sanchez-Aparicio et al. 2019)
- evidence of rehabilitation
- thickness of masonry (pavement, ring arch, spandrel walls) (Orbán & Gutermann 2009; Solla et al. 2014; Arias et al. 2007; Pérez-Gracia et al. 2011; Lubowiecka et al. 2011; Lubowiecka et al. 2009).

GPR surveying of concrete bridges is mainly focused on reinforced steel detection and mapping, estimation of deck thickness, damage detection such as cracking and delamination as well as foundation and pier assessment. GPR has been successfully used in a wide range of applications in concrete bridge inspection including:

- estimation of concrete cover depth (Hasan & Yazdani 2014; Hugenschmidt 2002)
- mapping reinforcing bars (deck and beams) (Hugenschmidt 2002; Hugenschmidt & Mastrangelo 2006; Beben, Mordak & Anigacz 2012; Rathod et al. 2019)

- location of utilities, deck joints and drain gate (Alani, Aboutalebi & Kilic 2013; Dinh, Gucunski & Zayed 2019; Hugenschmidt & Mastrangelo 2006; Slawski, Kosno & Swit 2016)
- damage detection on concrete (e.g. corrosion, cracking, spall, delamination) (Alani, Aboutalebi & Kilic 2013; Barnes Trottier & Forgeron 2008; Simi, Manacorda & Benedetto 2012; Dinh et al. 2019; Janku et al. 2019; Rhee, Choi & Kee 2019)
- moisture detection (Agred, Klysz & Balayssac 2018; Alani et al. 2013; Hasan & Yazdani 2014; Simi et al. 2012).

Solla et al. (2021) also highlighted potential limitations of the GPR related to concrete bridge inspections. Steel metal is a quasi-perfect reflector of the radar waves and this facilitates the detection of reinforced stee; however, deeper targets can be masked if it is a tight mesh. The spatial resolution of the antenna will affect the overlapping of these reflections with higher frequencies providing a higher resolution. The 3D data acquisition may incur an incorrect distance encoder calibration. The use of antenna arrays or automatic scanner systems makes the acquisition of 3D data easier.

In addition to concrete bridges, Muller (2003) reported that GPR can be used to inspect timber bridges for piping and rotting defects due to its ability to scan the entire girder length and obtain a 2D radargram image of the internal defects. The findings of field trials indicated an excellent correlation between the location and size of the predicted defects (i.e. piping, cracking and rotting) and those found after dissecting the girders. Wu et al. (2020) investigated the internal structure of timber bridge girders using GPR and identified the location and size of the defects (cracks and splits). The GPR results showed that all the 8 mm diameter metal bars were easily visible; however, the 5 mm diameter metal nails were unclear.

GPR can also be used to investigate if the trenches and culverts have been constructed according to the specifications (Lenngren, Bergstrom & Ersson, 2000).

## 2.3 GPR Accuracy and Limitations

### 2.3.1 Measurement Accuracy

Khamzin et al (2017) found that ground-coupled GPR data was consistent with air-coupled GPR data, suggesting that air-coupled GPR systems produce reliable data that can be rapidly and effectively used for the pavement condition assessment.

Data collected using an air-coupled (air-launched) system can be used for pavement layer thickness estimation for all types of pavements (i.e. granular (unbound and modified), cemented, asphalt and concrete) with an industry-accepted deviation of 10% without correlating with core samples and 5% if cores and design thickness records are available (Benedetto & Pajewski 2015). The accuracy of the GPR thickness predictions depends on the inspected layer. Some research suggested that the error was usually around 5% and in some cases around 2 or 3% (Angio et al. 2003). Davis et al. (1994) reported that the accuracy is less and the error increases to 10% for basecourse layers.

Cao et al. (2011) established that the GPR travel-time technique had an error of about ±7.5% compared to core data. Two primary sources of error in the traditional method based on travel time and the dielectric constants of the material to calculate layer thicknesses include:

- The dielectric constant values of in situ materials are selected based on empirical knowledge; making these assumptions can most likely reduce the accuracy of the estimated layer thickness.
- Identifying the peak may be overwhelmed by the ambient noise, thus multiplying the difficulty of identifying the travel time between interfaces.

Cao et al. (2011) identified the following issues associated with the use of this approach:

- One of the challenges an interpreter faces is determining if apparent changes in pavement layer thicknesses are real or simply caused by variations in pavement condition.
- A single GPR data file is collected for a length of pavement and this data is calibrated to just one dielectric constant when, in reality, there will be variations along the length of the pavement.
- The pavement thickness and its dielectric properties cannot be assumed homogeneous for extended pavement sections and can vary significantly within a relatively short distance.

- Confident inspection of pavement segments with non-uniform thickness could be difficult.

Lahouar et al. (2002) reported an average error of 6.8% in estimating the thickness of asphalt pavement layers ranging from 280 to 350 mm in thickness for an old pavement, and a 3.8% error for asphalt layer thicknesses ranging from 100 to 200 mm for a new pavement.

Rhee et al. (2021) investigated the limitations and capacity of GPR in detecting subsurface abnormalities and determining their depth under asphalt and concrete pavements in South Korea. This study was carried out using various types of pavements containing subsurface anomalies (e.g. cavity, steel plate, PE bottle, etc.). The effective survey depth in the asphalt pavement was found to be 1 to 1.5 m while it was less than 1.0 m in concrete pavements. The depth evaluation error was found to be in the range 0.03 to 0.27 m (7–27%) for investigating anomalies less than 1.0 m below road surface.

The most successful application of GPR is estimating layer thicknesses of flexible pavements using the two-way travel time method. However, as surface reflection cannot be obtained with enough accuracy, calibrating the dielectric constant using cores may be required to improve accuracy. The XCMP method can be used on air-coupled systems to estimate asphalt thickness without the need for dielectric constant calibration via coring (Zhao & Al-Qadi 2016).

### 2.3.2 GPR Limitations and Challenges

In GPR measurements of road pavements some specific problems with distance correlation occur. These are related to large length of profiles, high speed of the measuring vehicle, difficulties associated with heavy traffic, latency of the measuring system and parallax effect (Krysinski & Sudyka 2013).

Austroads (2019) outlines the disadvantages and limitations of using GPR as follows:

- Based on project-specific requirements, GPR investigations can be expensive.
- Data collection in wet weather conditions is not recommended as a film of surface water may affect the radar signal, making interpretation of the data more difficult.
- Field investigations (i.e. destructive geotechnical testing) are normally required to calibrate the system in order to obtain more accurate results.
- GPR data analysis and interpretation is time consuming; this affects the cost and the timeframe of an investigation.
- Analysis and interpretation require input from a GPR specialist and the person or team that is undertaking the pavement investigation.
- There are a limited number of qualified and experienced suppliers in the region.

In addition to these limitations there are other challenges associated with the appropriate use of GPR identified in literature. These include:

- The selection of the equipment (e.g. one survey line vs multiple survey lines) will affect the amount of area surveyed in a single pass.
- Lack of the evaluation criteria and data processing can be time consuming.
- The availability of the resources (i.e. GPR equipment and service providers).
- There are potential challenges associated with the signal attenuation and complex scattering phenomena due to the presence of high-conductivity and heterogeneous materials.
- Determining pavement strength with GPR based on the travel time of EM waves using the mechanical wave method (e.g. ultrasonic) and inferring material strength from stiffness.
- Determining the density of in situ materials.
- Identifying pavement layer thickness (i.e. boundaries between layers or material types) without a physical representative core sample or test pit for correlation.
- Investigating continuously reinforced concrete pavements, as GPR cannot penetrate metals.
- Measuring compaction of fill.
- Determining moisture content in certain soil types as fine clay particles make interpretation difficult.
- Using GPR in areas with aggregate manufactured from geological materials having high iron content, which can affect the attenuation of signals (e.g. material present in northern WA).

## 2.4 GPR Integration with Other Pavement Forensic Testing Techniques

### 2.4.1 General

As with many other geophysical techniques, the GPR survey results become much easier to understand and interpret and more reliable if there is other supporting data available. Roads can be surveyed using several non-destructive techniques such as the Benkelman Beam testing, Falling Weight Deflectometer (FWD), Traffic Speed Deflectometer (TSD) and profilometers. Similarly, the interpretation and use of deflection data needs layer thickness data so that the condition of the existing pavement can be assessed and back-calculation of layer moduli conducted (Domitrovic & Rukavina 2013).

The combination of GPR with other non-destructive pavement investigation techniques provides a powerful tool for the identification of distress in the existing pavement and the selection of an optimum rehabilitation treatment (Sarrenketo 2006). Geospatial views, developed to align and join the data gathered with NM-GPR, TSD and FWD, represent an important tool for understanding these complementary data in the context of the surrounding environment (Muller 2015).

### 2.4.2 Falling Weight Deflectometer (FWD)

The most popular integration of road survey techniques in pavement evaluation is the use of the GPR and FWD. The FWD measures deflection, with the data used to calculate the stresses and strains that are used in the development of a pavement model. To do this accurately, precise pavement structural thickness information is required. The GPR and FWD datasets can complement each other in the following ways:

- Changes in the thickness of the pavement layers are a major source of error when the results from FWD measurements are used to calculate the pavement layer moduli values. This becomes more important with thin asphalt pavements because layer moduli are more sensitive to layer thickness fluctuations (Irwin Yang & Substad 1989; Irwin Yang & Substad 1998). Furthermore, the layer moduli values determined using FWD and GPR data can be used as a quality check on the GPR interpretation and to exclude FWD data points that do not represent the pavement structure well.
- In the pavement condition evaluation, the FWD data helps to verify disintegration in the pavement layers and to understand if the problems are related to a specific pavement layer (Saarenketo & Scullion 2000). GPR data can be used to locate moisture-susceptible basecourses where the FWD data, collected during the dry summer months, would not indicate any problems.
- The FWD data provides information for GPR analysis about the subgrade materials (e.g. soil, bedrock). The shape of the deflection bowl, combined with the GPR data, indicates if the bedrock is present and close to the surface.

An effective approach to combining GPR and FWD survey results is to conduct the GPR measurement first and use that information to determine appropriate locations and station distance for the FWD measurements. This would ensure that the layer thickness would be sampled exactly where the intermittent FWD tests are done.

Marecos et al. (2017b) evaluated the bearing capacity of a flexible pavement (210 mm asphalt over 200 mm of thick unbound granular material) using the FWD and GPR. The pavement deflections and layer thicknesses were the main inputs to the layer modulus estimation through back-analysis. The thickness of the unbound layers had a small influence on the pavement response models, while the variations in the bituminous layer thickness had a high influence on the estimated bituminous layer moduli. The underestimation of the bound layer thickness resulted in the overestimation of the bound layer modulus. Considering the entire extent of the pavement under study, the results showed that the longitudinal variability of the bituminous layer thickness was high, 70% of the GPR estimated thickness was below the design thickness, and only 35% of the data had less than 5% variation. Therefore, if GPR-estimated thickness is not used, then almost two-third of the highway section under study would have significant errors in the pavement response models. The study reinforced the importance of using the GPR continuous assessment of layer thickness together with the FWD if an accurate structural evaluation of the existing pavements was to be achieved.

### 2.4.3 Traffic Speed Deflectometer (TSD)

The fact that the pavement can be monitored at high speed means that GPR into an important tool when combined with loading test devices such as the FWD and, more recently, with TSD.

For network-level investigations, in some countries the use of GPR is already considered mandatory for layer thickness assessment due to its ability to support pavement management system decisions. The joint interpretation of GPR and load test data, such as FWD and TSD, has also led to changes to the GPR system in order to better process the collected data. For this purpose, a dedicated GPR, a noise-modulated ground penetrating radar (NM-GPR), was developed in Australia (Solla et al. 2021).

Herronen, Matintupa & Saarenketo (2015) carried out integrated analysis of the GPR, laser scanner and TSD to evaluate pavement fatigue and remaining life. GPR was used to measure the thickness of the pavement layers, and micro- and macro-cracking in asphalt (using GPR surface reflection technique). Herronen et al. (2015) reported that, based on empirical data and experience, it is known that pavement distress starts to increase exponentially when the pavement strain exceeds 300 με, at which stage the remaining life is approximately 1 million axle loads. They analysed road data collected in Finland using the Road Doctor software and found that the pavement loses its strength dramatically and visual cracks started to appear when the strain level was higher than 400 με. Logically, it is very economical to rehabilitate the pavement when strains are at a level of 300 με. With the combination of modern data collection and joint analysis of the results the actual reason behind pavement deterioration can be identified.

Muller (2015) compared TSD and FWD data with GPR data for five test locations within Queensland, Australia. Overall, there was a clear correlation between the results of the three non-destructive testing techniques. Changes in the pavement structure, the presence of buried infrastructure and subsurface anomalies observed in the GPR response coincided with changes in the TSD and FWD responses. At some locations, the GPR data revealed relatively homogenous pavement layering when the TSD and FWD data indicated significant variation, indicating that a change in deflection is unrelated to the consistency of the pavement structure. This may be due to variation in the construction material, quality of construction, condition of the pavement layers, quantity of varying moisture and/or subgrade support. The findings supported the combined use of TSD and GPR, preferably collected simultaneously, for the rapid non-destructive assessment of flexible pavements.

## 2.5 GPR Implementation by Transport and Road Agencies

### 2.5.1 Australian Transport and Road Agencies

Overall, Australian transport and road agencies (TRAs) have limited exposure to GPR. The literature review indicated that GPR use by the TRAs is generally restricted to project-level studies and some field trials on selected sections with the intent to assess the capacity of GPR to investigate pavements. None of the TRAs have well-developed technical documentation related to GPR implementation on its road network.

The Austroads *Guide to Pavement Technology Part 5* (Austroads 2019) provides a brief overview of the applications of GPR for pavement investigation.

Main Roads' previous experience with GPR is limited to project-specific studies and field trials. Field trials involving two GPR contractors to assess the technical capability of GPR and availability of the equipment in WA have been recently carried out on a selected section of the Mitchell Freeway.

*Engineering Road Note 16* (Main Roads 2021) mentions the use of GPR for investigative testing of the pavement; however, it does not provide any details related to equipment, capability and testing procedures.

None of the other Main Roads technical documents (e.g. ERN9, Specification 501, Main Roads Supplement to Austroads Guide to Road Design – Part 7) furnish any details related to the use of GPR on the Western Australian road network.

TMR's *Pavement Rehabilitation Manual* (TMR 2020) provides a brief discussion related to the use of GPR, including guidance for GPR calibration, advantages and disadvantages, and implementation in the preconstruction, construction and post-construction stages.

Transport for NSW's (TfNSW) *Supplement to Austroads Guide to Pavement Technology Part 5: Pavement Evaluation and Treatment Design* (TfNSW 2021) specifies that GPR surveys must be calibrated to the actual pavement layer profile by subsequent field investigation (e.g. pavement cores or test pits) targeting areas of change in GPR data. The GPR can be used to:

- Decide on the selection of the deflection test sites by identifying areas of variable pavement layers typical in urban areas and where previous patching has been undertaken. The FWD testing must target the areas of variable thickness and back-calculation modelling must be undertaken so that the FWD deflections are correctly aligned with the different pavement profiles determined from the pavement investigations and GPR.
- Carry out GPR surveys for layer thickness determination as stiffness results from the back-analysis are extremely sensitive to the layer thicknesses assumed for the analysis.

VicRoads' *Road Structures Inspection Manual* (VicRoads 2018) allows the use of GPR to determine the internal details of components such as voids and densities; however, the results should be taken as indicative only and may require intrusive exploration to confirm the GPR findings.

### 2.5.2 Overseas Transport Agencies

The American Society for Testing and Materials (ASTM International 2019) produced a standard guide on the appropriate use of GPR in transport infrastructure. The document summarises the equipment and field procedures for a GPR subsurface investigation as well as processing methods used to interpret GPR data.

The California Department of Transportation (Caltrans) (2016) implemented a new pavement management system based on GPR surveys of pavements at highway speeds. The PaveM software needs pavement-related data to establish an inventory of the underlying pavement structure based on the layer thickness and material types and surface condition of the entire state highway network. PaveM also incorporates data from Caltrans's annual automated highway pavement condition surveys (APCS) which collects pavement surface condition data at highway speeds using lasers and cameras.

The traffic speed GPR data was verified by comparing samples to blind test sections that were extensively cored and measured with a more accurate walking GPR unit. These quality assurance tests showed that the airborne GPR method provided accurate subsurface data for the entire network. The research team developed two software programs, iGPR and iCORE, during the quality assurance testing that were useful for the pavement designers when determining a project's pavement structure. The iGPR takes the processed GPR data and displays a layer thickness and pavement type along the route lane-by-lane. The iCORE program vets the core data taken from a pavement section then enters it into the iGPR program for comparison with the GPR data. PaveM analysis enables Caltrans to implement a proactive approach for prioritising, preserving, rehabilitating and maintaining the existing highway pavements.

The *Design Manuals for Roads and Bridges* (Highways England 2020a & 2020b) sets out requirements for the non-destructive testing of highways structures, specifically GPR testing for concrete and masonry bridges and for pavement assessment.

The European GPR Association (2016) has produced guidelines for the pavement structural surveys including the applications and limitations of GPR use on pavements, survey assessment, survey specification, location referencing, data quality and backup, and data reporting.

New Zealand Transport Agency (NZTA 1997) evaluated GPR as a non-destructive pavement investigation tool for its use in New Zealand between 1992 and 1995. The key findings of the research were as follows:

- Structural layers were successfully tracked where the construction integrity was good both in urban roads and state highways. The breaking up of bound material and intermixing of unbound materials caused serious issues in interpretations.
- Moisture assessment was possible for state highways. There were significant variations both within and between the pavement sections surveyed.

- Buried services were successfully identified.
- Consolidation of the subbase and subgrade materials was assessed and areas of disturbance and reduced consolidation plotted.
- Extensive areas of clay pumping within clay-rich subgrade were mapped. However, the surface condition of the pavement in these areas should be inspected to assess the relationship between the clay pumping and pavement deterioration.

NZTA also carried out pavement moisture measurement to determine what its optimum level is before drainage intervention is needed. The survey was carried out using low- and high-frequency GPR antennae (500 MHz and 2.2 GHz) at speeds of 60–80 km/h with 2D LIDAR coupled with the Road Doctor software to view the results (NZTA 2017). The survey output can be used in several ways for managing the assets. For network level the moisture damage index (MDI) can be outputted to GIS or Google Maps and colour coded to show high and low moisture areas. High moisture areas can be looked at more closely for the purposes of implementing appropriate improvement in drainage and waterproofing the surface.

Based on the research findings related to the level of GPR use in Australia and international practice, it can be concluded that:

- The use of GPR in Australian states is currently limited to the project-specific investigations.
- Caltrans makes extensive use of GPR data in developing its rehabilitation plans.

## 2.6 GPR Effectiveness and Potential Cost Savings

Multiple studies have been undertaken evaluating GPR as a reliable and efficient tool for assessing the structure, condition and integrity of the roadway pavement structures. The *Pavement Rehabilitation Manual* (TMR 2020) details the following advantages of using GPR for the pavement investigation:

- It is non-destructive – pavement integrity is maintained during data collection.
- Pavement and geotechnical investigations can be better organised and optimised and better targeted, thus increasing confidence and reducing risk.
- Back-analysis and rehabilitation treatment designs can be optimised to save costs.

The Manual also discusses how the value of GPR use for a project investigation will depend on an assessment of costs against benefits. When making this assessment, variability, function and the importance of the road should be considered. The higher the variability or importance of the road, the greater the justification for the GPR use.

As pavement and geotechnical investigation requirements vary from project to project and region to region, it is not possible to develop a relationship between cost savings, geotechnical investigations and GPR surveys. However, it is possible to compare the typical cost of the GPR testing with geotechnical and pavement investigations and calculate potential reductions in the investigation and testing costs.

Currently Main Roads carries out geotechnical investigations (e.g. test pits, coring) to determine pavement profile for rehabilitation and widening projects. Sometimes attaining the desired level of geotechnical investigation is not possible due to traffic disruption constraints on the highway (e.g. 500 m spacing between adjacent cores and/or test pits). Therefore, investigating the capability of the GPR for filling gaps in the geotechnical investigation can be beneficial.

It is suggested that a desktop exercise, using typical Main Roads pavement investigation (dippings) and material costs, be conducted using a GPR survey. The costs of rehabilitation treatment determined from the GPR surveys could be compared to cost of treatments determined from sampling the GPR survey at typical dipping spacings.

Liu et al. (2021) investigated the application of 3D GPR images in pavement monitoring and maintenance by combining it with the YOLO model (i.e. You Only Look Once). The internal defects in asphalt pavements, including cracking, void zones, raveling and settlement, were detected by 3D GPR. However, only conventional methods were used to detect surface conditions. The evaluation of economic benefits showed that the maintenance cost based on GPR detection was reduced by $49,398/km compared to traditional detection. As for environmental benefits, the energy consumption and carbon emissions of the maintenance program based on GPR detection was less than those of traditional detection by 792,106 MJ/km and 56,289 kg/km respectively.

The cost of a GPR survey and the associated analysis and interpretation can be significant when compared to the cost of the total investigation. When compared to the cost of the constructed project, however, the cost of using GPR is minimal.

Morcous and Erdogmus (2009) compared the GPR pavement investigation and traditional coring techniques in terms of initial and operating costs and benefits (i.e. accuracy, time and destructiveness) for a concrete pavement. This comparison was based on a 1 mile (1.6 km) assessment using eight cores for the traditional method and eight scans and two calibration cores for the GPR method. The following advantages were reported:

- Significant reduction in the number of drilled cores for pavement thickness measurement, which is a destructive technique that affects pavement durability.
- The GPR results provided an accuracy as high as 98.5% (~ 3 mm).
- GPR equipment had higher initial and operating cost than core drilling; however, the reduction of core drilling should result in lower pavement maintenance costs in the long term.

## 2.7 Potential Improvements in Existing Practice

GPR applications in roads has proven to be a useful tool to solve various kinds of road engineering problems. A very important factor in the future of GPR in road surveys is to establish the technique in routine road analysis and pavement design procedures. Saarenketo and Scullion (2000) proposed the following three future development areas of GPR for its enhanced applications in the road design, construction and maintenance areas:

- Development of user-friendly software packages in order to convert GPR data and other road survey data into information which is meaningful to pavement engineers.
- Gaining enhanced understanding of the electrical properties of the pavement materials and subgrade soils and their relationship to moisture, strength and deformation properties.
- Training for government road agencies, staff undertaking the surveys and other customers who are using GPR data.

The XCMP is an alternative to the traditional two-way travel time method to estimate asphalt pavement thickness because it can provide more accurate dielectric constant values without calibration. Integrating the XCMP method with a stepped-frequency 3-D GPR may result in an accurate prediction of asphalt layer thicknesses greater than 64 mm without any need for the dielectric constant calibration from coring (Zhao & Al-Qadi 2016).

Lenngren et al. (2000) suggested that the next step to GPR implementation in pavement investigation will be to make full use of multi-channel GPR. This will make it possible to not only measure a full section across the road in one measurement but also to acquire velocity information in every single measuring point. As the porosity and moisture content in road structures affect the velocity of the GPR wave, deviation in the GPR velocity might be a useful tool for locating deteriorated areas. In addition, velocity information can be used for calibrating GPR data so that the exact layer thickness can be determined without coring. The multi-channel GPR can also facilitate simultaneous measurements with more than one antenna frequency. In this way, high-frequency antenna can be used for objects near the surface while antenna with lower frequency can be used for deeper objects.

GPR technology generally requires an extensive amount of manual data analysis. GPR manufacturers should continue to improve data analysis software with the goal of providing real-time results that would be valuable for project- and network-level pavement assessment. If road agencies worldwide express an interest in NDT for pavement evaluation, the NDT industry would see the market potential and continue developing its equipment. Road agencies might consider providing research funding to support the development of software for GPR data for project- and network-level analyses (Heitzman et al. 2013).

# 3 Potential and Opportunities for Implementation of GPR in Western Australia

## 3.1 Introduction

Main Roads has limited exposure to the use of GPR in pavement engineering and asset management. Therefore, exploring the potential use of GPR technology in the Western Australian pavement industry is paramount.

Consistent with the intent of the project as documented in the project proposal, the investigation addressed the following items:

- Availability of the GPR contractors in Western Australia.
- Availability of the GPR technology in Western Australia (i.e. antennae, processing units, speed of testing, etc.).
- GPR capability in terms of pavement investigation surveys such as:
  - pavement layer thickness tracking
  - identification of high moisture areas
  - detection of voids
  - QA and QC related testing and measurements (e.g. moisture content, air void content, density)
  - identification of pavement distress (e.g. asphalt stripping, delamination, cracks).
- Accuracy of the GPR data and interpretations and limitations.
- Application of the GPR in scanning concrete structures/bridges.
- Key skills and expertise required for GPR field surveys.
- Technical training requirements for interpreting GPR datasets.
- Potential challenges for Main Roads in the implementation of the GPR on its road network.

This section summarises the key findings of the investigation into the potential use of GPR technology for the Western Australian pavement industry to enhance the quality of work and improve Main Roads' asset management practices.

It should be noted that the information provided in this report is based on telephone interviews with GPR contractors' representatives and data available on their websites. The information collected is collated and presented in a tabular format for readability. The Australian Road Research Board (ARRB) does not take any responsibility of the information supplied in this report.

## 3.2 Western Australian Market Survey

A market survey was carried out through telephone interviews of the representatives of the GPR contractors to explore the availability of GPR contractors and equipment in WA. The key findings of the survey are presented below.

### 3.2.1 GPR Contractors and Technology

Eight GPR contractors were identified through discussion with Main Roads, the literature review and internet searches. Table 3.1 provides the details of the identified GPR contractors.

**Table 3.1: Identified GPR contractors**

| Sr. no. | GPR contractors | Office locations in Australia | Comments |
|---|---|---|---|
| 1 | Contractor A | The Rocks NSW (head office), Warana QLD, Spearwood WA | Currently engaged in GPR surveys for Main Roads |
| 2 | Contractor B | Tingalpa QLD (head office), Bunbury WA | Currently engaged in GPR surveys for Main Roads |
| 3 | Contractor C | Brookvale NSW | |

| Sr. no. | GPR contractors | Office locations in Australia | Comments |
|---|---|---|---|
| 4 | Contractor D | Mont Albert North VIC and Tauranga New Zealand | |
| 5 | Contractor E | Yatala QLD (head office), Ambrose QLD, Dandenong VIC, Kemps Creek NSW, Lonsdale SA | |
| 6 | Contractor F | Silverwater NSW | |
| 7 | Contractor G | NSW, VIC, QLD, WA, NT | No more GPR services, subcontracting GPR work |
| 8 | Contractor H | Smithfield NSW | No background for pavement GPR survey |

Source: Discussion with the contractors' representatives and Main Roads Staff.

Based on the initial discussion with the contractors regarding their GPR capability related to road pavement investigation, four contractors were shortlisted for detailed discussion. They were contacted and interviewed based on a pre-designed questionnaire in order to investigate their availability and technical capability for pavement investigation in Western Australia.

The GPR contractors interviewed as part of this investigation are contractor A, B, C and D.

Note that ARRB's new TSD vehicle (iPAVe 3) is equipped with GPR as well as TSD and other typical pavement condition testing facilities. It has 11 lasers for complete deflection bowl prediction. This integrated intelligent vehicle provides an opportunity to carry out GPR surveys and collect TSD and other pavement forensic testing data simultaneously from the same sections of the pavement.

The responses of the GPR contractors are documented in Table 3.2 to Table 3.5 as follows:

- Table 3.2 – the response from GPR Contractor A.
- Table 3.3 – the response from GPR Contractor B.
- Table 3.4 – the response from GPR Contractor C.
- Table 3.5 – the response from GPR Contractor D.

**Table 3.2: GPR market survey – GPR Contractor A**

| Inquiry | Response from GPR Contractor A |
|---|---|
| Presence in WA(1) | Yes (based in Perth). |
| Office location in Australia | QLD and NSW. |
| Experience (years of GPR use) | 10 years of experience in GPR testing for road pavements. |
| Previous experience with SRA(2) | Accomplished GPR testing for TMR QLD, Brisbane City Council, VicRoads and Main Roads WA. |
| Availability for work | Available for work immediately as physically present in WA. |
| Availability of combined technology (TSD, FWD) | Contractor A carries out GPR and deflection surveys (FWD) on pavements, however, GPR and deflection is not integrated into one vehicle. |
| GPR equipment | Only 2D GPR is available with ground- and air-coupled antennae (dipole and horn antenna). |
| Available antennae frequencies | Several antenna frequencies are available. However, following frequencies are commonly used for road pavement investigation:<br>• 400 MHz for up to 2–2.5 m depth.<br>• 2 GHz for up to 20–30 mm depth. |
| Speed of testing (km/h) | 80–110 km/h (lower speeds are common). |
| Layer thickness measurement | Yes |
| Void detection | Yes |
| High moisture pockets | Yes (depends on selection of equipment and in situ material composition) |
| Moisture content | No |
| Air void content | Yes (indirect indicative calculation possible (not volume of voids) |
| Density measurement | No (never tried). |
| Pavement distress (e.g. asphalt stripping, delamination, cracks, etc.) | No (it is not Contractor A's core business) |
| QA & QC related testing | No |

| Inquiry | Response from GPR Contractor A |
|---|---|
| Expertise in interpretation | Contractor A has appropriately skilled staff for GPR data interpretation. |
| Accuracy of GPR results<br>(layer thickness tracking) | Generally good accuracy especially in layer thickness tracking of fine granular materials (bound and unbound). |
| Concrete structures/bridges | Not doing a lot of bridge scanning as it is not Contractor A's core business. |
| Others | – |
| Challenges of GPR implementation on WA road network<br>(Opinion based on experience) | • Targeting materials' dielectric constant – calibration of GPR thickness measurement through correlation with boreholes/cores.<br>• There are potential limitations of GPR technology in terms of depth of scanning, type of equipment, antenna frequency and speed of testing for network-level GPR implementation. However, there are insignificant limitations for project-level implementation. |

1. GPR contractor has an office in WA and is physically present with its survey equipment.
2. SRA: State Road Agency in Australia.

Source: Telephonic conversation with Contractor A's representative.

**Table 3.3: GPR market survey – GPR Contractor B**

| Inquiry | Response from GPR Contractor B |
|---|---|
| Presence in WA(1) | Yes, Contractor B has office in Bunbury WA. |
| Office location in Australia | Brisbane QLD (head office), Bunbury WA (regional office). |
| Experience (years of GPR use) | 12 years of experience in GPR survey for road pavements. |
| Previous experience with SRA(2) | Contractor B has carried out GPR surveys for pavements in different Australian states. Recently completed a GPR survey for Main Roads on a section of the Mitchell Freeway in WA. |
| Availability for work | Immediate availability as physically based in WA. |
| Availability of combined technology (TSD, FWD) | Contractor B provides GPR surveys with video capturing of the pavement surface for visual inspection. Currently, Contractor B has no deflection surveys capability. |
| GPR equipment | Ground- and air-coupled antennae are available with 2D GPR facility only. Both right and left wheel paths can be scanned. |
| Available antennae frequencies | A wide range of antennae frequencies are available for survey. The preferred frequencies for road pavement surveys are:<br>• 2 GHz for 1 m scanning depth for high resolution.<br>• 400 MHz for deeper penetration i.e. up to 2 m. |
| Speed of testing (km/h) | • Ground-coupled antenna (e.g. 400 MHz) = 50 km/h.<br>• Air-coupled antenna (e.g. 2 GHz) = 110 km/h. |
| Layer thickness measurement | Yes |
| Void detection | Yes |
| High moisture pockets | Yes. Depends on equipment used. For example, high moisture pockets can be detected by using ground-coupled antenna with 400 MHz frequency with speed of testing not more than 50 km/h. |
| Moisture content | Yes. Contractor B's software provides graphical presentation of moisture through data integration. Moisture detection is based on antenna frequency and speed of testing. Contractor B seeks support from their overseas office in complex interpretation. |
| Air void content | Yes (based on frequency, speed of testing and software used).<br>Contractor B may need support from its overseas office for such deliverables. |
| Density measurement | No |
| Pavement distress (e.g. asphalt stripping, delamination, cracks, etc.) | Yes (the system is based on camera just like visual inspection. Although it is not a substitute of a road profiler, however, it is better than visual inspections). Pavement distress could be mapped from frame-by-frame high resolution video recording. |
| QA & QC related testing | No |
| Expertise in interpretation | Skilled staff is available for GPR surveys and data interpretation in Australia. Contractor B is supported by its overseas office for complex interpretations if required with suitable tools and software packages. |
| Accuracy of GPR results<br>(layer thickness tracking) | Accuracy of results is based on choice of frequency for survey, variability of material composition, speed of testing etc. Experience shows that 2 GHz frequency antenna is quite accurate for 1 m depth and 400 MHz frequency for up to 2 m depth. |
| Concrete structures/bridges | Yes – bridge and concrete scanning capability is available. |

| Inquiry | Response from GPR Contractor B |
|---|---|
| Others | • Network level surveys: thickness, structures.<br>• Project level surveys: site investigation, thickness, reasons for damage.<br>• QC & QA: thickness, air voids content special structures.<br>• Forensic surveys: thickness, moisture susceptibility, transition structures.<br>• Pavement condition monitoring: pavement distress, moisture.<br>• Core calibration can be performed through core data integration to GPR data.<br>• Major benefit of GPR survey is continuous detailed profile of the survey target. |
| Challenges of GPR implementation on WA road network<br>(Opinion based on experience) | The major challenge in GPR implementation on pavements is related to the clarity of the project objectives and desired deliverables from the project inception stage in order to enable GPR surveyor to choose the right frequency, equipment and speed of testing. For example:<br>• For utility location: Pushcart GPR<br>• For pavement layer thickness tracking: air-coupled antenna<br>• For moisture detection: ground-coupled antenna. |

1. GPR contractor has an office in WA and is physically present with its survey equipment.
2. SRA: State Road Agency in Australia.

Source: Telephonic conversation with Contractor B's representative.

**Table 3.4: GPR market survey – GPR Contractor C**

| Inquiry | Response from GPR Contractor C |
|---|---|
| Presence in WA(1) | Contractor C has no office in WA. However, they can ship their products/equipment and gears overnight (these days shipping time is based on COVID restrictions) to WA for a GPR survey as required. |
| Office location in Australia | Sydney (NSW). |
| Experience (years of GPR use) | 40 years experience in GPR surveys and interpretations. |
| Previous experience with SRA(2) | Worked for several industry consultants and governmental organisations such as Sydney Trains, Services NSW, Australian Federal Police. |
| Availability for work | Generally immediate availability. |
| Availability of combined technology (TSD, FWD) | Contractor C has the capability to conduct a range of geophysical surveys such as GPR (2D & 3D), conductivity, resistivity and electromagnetic. However, Contractor C does not offer deflection surveys (e.g. TSD, FWD). |
| GPR equipment | Have a range of antennae that can be attached to survey vehicles based on project-specific requirements. |
| Available antennae frequencies | Highest available antenna frequency is 2.3 GHz. Other available frequencies are 1.6 GHz, 1.2 GHz, 750 MHz, 450 MHz, 160 MHz, 100 MHz, 80 MHz, 80 MHz (airborne), 25 MHz |
| Speed of testing (km/h) | As required (80–100 km/h is common). |
| Layer thickness measurement | Yes (layer thickness tracking is based on selection of right equipment (i.e. antenna frequency). |
| Void detection | Yes |
| High moisture pockets | Yes (generally based on contrast in dielectric properties of the materials. Moisture is easily detectable between bone dry and saturated materials, however, can be difficult to be detected in the middle conditions). |
| Moisture content | No |
| Air void content | No |
| Density measurement | No |
| Pavement distress (e.g. asphalt stripping, delamination, cracks, etc.) | Yes (e.g. asphalt delamination, stripping, cracks). However, detection of pavement distress is based on selection of equipment, processing software and skills of interpreter. |
| QA & QC related testing | Generally, it is possible to delineate between good and bad areas. No specific test results possible at this stage. |
| Expertise in interpretation | Skilled staff (geophysicist, geologist) available with a wide range of skills for professional interpretation of GPR data to meet project-specific requirements. |
| Accuracy of GPR results<br>(layer thickness tracking) | The GPR accuracy depends on antenna frequency and processing unit used. For example, with high-frequency antenna 10–20 mm accuracy could be achieved up to 400 mm depth. If depth of penetration increases to 2 m, the accuracy will be reduced to 100–200 mm. |
| Concrete structures/bridges | Yes (bridges can be scanned in 2D and 3D in high resolution based on antenna frequency used). |

| Inquiry | Response from GPR Contractor C |
|---|---|
| Others | • Contractor C has underwater and airborne GPR survey capability.<br>• Standalone antennae are available to be fitted to survey vehicle. |
| Challenges of GPR implementation on WA road network<br>(Opinion based on experience) | • Go deeper – lower frequency, shallow depth – higher frequency – higher tolerance.<br>• Based on project-specific requirements, a bunch of antennae with different frequencies can be set-up but it will be expensive to carry out a survey with several antennae and processing needs. Therefore, a clear understanding of project objectives and deliverables from the outset is critical.<br>• Interpretation skills are key to achieve desired project outcome.<br>• The hardest thing is the data integration. GPR data can be collected with multiple antennae frequencies. However, it can be challenging to integrate and interpret at later stages.<br>• GPR provider may promise a client to deliver a specific outcome without considering project details. For example, dataset integrity and interpretation capacity can be different for 2 m and 300 mm depth. These two depths need two different antennae for better results. The GPR survey requirements should be discussed and clarified at the project inception stage. |

3. GPR contractor has an office in WA and is physically present with its survey equipment.
4. SRA: State Road Agency in Australia.

Source: Telephonic conversation with Contractor C's representative.

**Table 3.5: GPR market survey – GPR Contractor D**

| Inquiry | Response from GPR Contractor D |
|---|---|
| Presence in WA(1) | Contractor D has no office in WA. However, they have done several GPR surveys in WA and are keen to carry out work in WA as required. |
| Office location in Australia | Victoria and New Zealand. |
| Experience (years of GPR use) | Eight years experience in GPR surveys and interpretations related to pavement investigation. Contractor D carries out GPR investigations in three major areas:<br>• Structural/bridge scanning<br>• Geotechnical rock scanning/borehole scanning<br>• Pavement investigation. |
| Previous experience with SRA(2) | Worked for VicRoads on several major projects |
| Availability for work | Immediate availability. |
| Availability of combined technology (TSD, FWD) | Contractor D provides GPR survey for roads, runways and ports pavements, bridge deck condition assessment, geological and utilities. |
| GPR equipment | Dipole and Horn antennae, 2D and 3D GPR surveys. |
| Available antennae frequencies | A wide range of frequencies are available i.e. 125 MHz, 200 MHz, 400 MHz, 1.0 GHz, 1.6 GHz, 2.0 GHz and 2.7 GHz.<br>• 400 MHz frequency antennae are good for pavement and subgrade investigation (generally for 1.5–2.0 m depth).<br>• Horn antennae are used for surveys to be carried out at traffic speeds. |
| Speed of testing (km/h) | As required (up to 110 km/h). Speed of testing depends on sample rate/points to be picked up and details required. |
| Layer thickness measurement | Yes |
| Void detection | Yes |
| High moisture pockets | Yes<br>(Moisture detection has limitations. It is easier to be identify moisture in new pavements as compared to old pavements. Similarly, it is challenging to identify moisture in granular pavements. Moisture can be mapped accurately in sand and clay layers due to the sharp dielectric contrast; however, in materials having similar characteristics the moisture is not identifiable). |
| Moisture content | No (what we get from GPR is relative moisture. It is not possible to report absolute moisture value in terms of percentage). |
| Air void content | No |
| Density measurement | No |
| Pavement distress (e.g. asphalt stripping, delamination, cracks, etc.) | Yes (it is based on use of right GPR equipment for the survey) |
| QA & QC related testing | No specific test results possible at this stage |

| Inquiry | Response from GPR Contractor D |
|---|---|
| Expertise in interpretation | Skilled staff (civil engineer with 20 years of experience in pavement engineering including several years in GPR surveying and interpretations) available. |
| Accuracy of GPR results (layer thickness tracking) | Accuracy of the GPR results is based on type of antenna and frequency used for survey. GPR systems with ground-coupled antennae are generally more accurate as compared to air-coupled antennae. Composition of in situ materials is critical for accuracy of results. The more homogeneous the material – more accurate the results. The materials having highly fines clay particles mislead interpretations in terms of moisture identification. |
| Concrete structures/bridges | Yes (specialised in structural scanning of concrete in 3D). |
| Others | – |
| Challenges of GPR implementation on WA road network (Opinion based on experience) | • Major challenge in implementing GPR at network level with the volume of data handling and utilisation. It is labour intensive to analyse large datasets and it requires many hours to interpret those datasets.<br>• Sometimes the intermix between the subgrade and subbase materials due to migration of silt and clay particles from the subgrade upward can mislead the interpretation. GPR interpretations are excellent in case of sharp contacts between different types of materials.<br>• Air-coupled antennae have less accuracy compared to ground-coupled antennae.<br>• It is crucial to have a specialist analyst for GPR interpretations, preferably a relevant engineering professional who can interpret GPR data collected in the field at higher level of confidence. |

1. GPR contractor has an office in WA and is physically present with its survey equipment.
2. SRA: State Road Agency in Australia.

Source: Telephonic conversation with Contractor D's representative.

### 3.2.2 Key Findings of the Market Survey

The key findings of the market survey can be summarised as follows:

- The discussions with GPR contractors indicated that most of them operate from the east coast and travel to WA with their equipment to undertake GPR surveys as required. Most of the contractors have not done any network-level GPR survey directly for any Australian TRA. This indicates that their exposure to GPR is limited.
- None of the contractors interviewed have deflection survey equipment (e.g. TSD, FWD) integrated with the GPR technology. However, some of them provide other geophysical surveys such as conductivity, resistivity, electromagnetic, etc. Based on the market survey, it can be assertively concluded that the effectiveness and accuracy of the GPR investigation in the pavement domain depends on following factors:
  - composition of the pavement and subgrade materials
  - type of the GPR antenna and frequency
  - availability of the processing unit, software and location determination equipment
  - speed of testing
  - operators' skills.
- It is crucial that Main Roads has a clear understanding of the objectives at the project inception stage. The GPR contractors must be informed clearly about the intent of the project, the deliverables, and the desired level of accuracy from the outset so that they can select the right equipment for the survey.
- The antennae frequencies play a pivotal role in the GPR investigation capability and accuracy. Table 3.6 summarises typical GPR antennae frequency ranges and their characteristics.

**Table 3.6: GPR antennae frequencies and their characteristics**

| Category | Frequency range | Characteristics | Expected penetration | Limitation | Appropriate use |
|---|---|---|---|---|---|
| Low | 200–300 (Commonly used low frequency is 250 MHz) | Lower the frequency longer the wave and deeper the penetration | Generally, up to 6 m (In Australia, it may be difficult to reach that depth due to composition of in situ materials) | Low frequencies are:<br>• Unable to pick smaller targets<br>• Provide limited details/information | Suitable for deep investigation |

| Category | Frequency range | Characteristics | Expected penetration | Limitation | Appropriate use |
|---|---|---|---|---|---|
| | | | | • Provide low resolution radargram (i.e. low quality outcome) | |
| Medium | 400–600 MHz | • Suitable to pick smaller targets in mid-to-shallow depth<br>• Considered an appropriate frequency range using single radar | Can penetrate:<br>• 3–4 m in sandy dry soil<br>• 300–500 mm in saturated clay | • This frequency range is not capable of penetrating as deeper at lower frequencies<br>• Low to medium resolution radargram (low to medium quality outcome) | Suitable for investigation at shallow to medium depth |
| High | 700–800 MHz | Low penetration depth | Can penetrate from 1 to 2 m depth | Can only explore shallow depth | Generally, capable to locate small targets at shallow depth |
| Very High | More than 1 GHz | • Higher the frequency – shorter the wave and shower the penetration<br>• Shallow penetration | Penetration depth based on frequency:<br>• 1.6 GHz = 400 mm<br>• 2.3 GHz = 200 mm | Can only explore very shallow depth | Appropriate frequency for very shallow depth and high-resolution application (i.e. high-quality outcome) |

- The ground-coupled (dipole) antenna is considered more accurate compared to the air-coupled (horn) antenna. Since different antennae frequencies have different capabilities in terms of depth of scanning and resolution of the radargram of the pavement, dual antenna and multiple arrays can be used to meet project-specific requirements and obtain best results from the pavement survey.
- The pavement layer thicknesses, voids and distress in asphalt pavements (i.e. stripping, delamination and cracks) can be detected with generally higher level of confidence if the right equipment is used and contrast with the dielectric constant of the materials is favourable. However, moisture detection can have issues in interpretation in the case of fine clay material. Generally, moisture is easily detectable in bone dry and saturated materials but it is difficult to be detected in the middle conditions.
- Currently, QA and QC testing using GPR is limited to delineating pavement sections into ‘good and bad areas’. It is not possible to generate numerical test results in terms of moisture content, density and air void content. Based on the literature review and discussions with the GPR contractors, it is clear that the GPR testing cannot replace laboratory testing conducted on materials collected from the site.
- The accuracy of the GPR depth measurement results is based on the frequency of GPR antenna and the penetration depth of signals. For example, based on feedback from the GPR contractors, with high frequency antenna 10–20 mm accuracy can be achieved for up to a 400 mm depth. If the depth of penetration increases to 2 m, the accuracy of the results will be reduced to 100–200 mm.
- Several GPR contractors have reported the availability of a wide range of equipment including:
  - antennae frequencies from 30 MHz to 2.7 GHz
  - multiple antennae fitted to the vehicle with multiple array arrangements based on project-specific requirements
  - processing unit, software and location determination equipment
  - capability of GPR data interpretation
  - airborne and underwater GPR surveys.
- The ability of GPR to investigate the desired parameters largely depends on the clarity of the project’s objectives from the inception stage. This information is key if the GPR contractor is to select an appropriate frequency for the survey and software for data analysis to achieve the desired results.
- GPR can be used to optimise geotechnical investigations by reducing testing needs and providing enhanced and continuous information related to the pavement subsurface structure and condition, including variability in pavement materials, buried services and transverse and longitudinal contacts between different types of pavements.
- Concrete scanning including 3D GPR surveys of concrete structures (e.g. bridges) is common. All the contractors reported that they are frequently undertaking concrete and bridge scanning with GPR.

- Main Roads will need to train its staff in GPR surveying and data interpretation in order to enable them to manage GPR projects efficiently and utilise the results in project- and network-level decision making to ensure value-for-money.

## 3.3 Potential Challenges

Potential challenges for Main Roads in the implementation of GPR on its road network are summarised as follows:

### 3.3.1 Availability of Contractors and Equipment

Based on historic use of GPR, not all GPR contractors provide pavement investigation services. Many of the GPR contractors offer their services for service location, concrete scanning, and archaeological and mining site investigations. Most of the GPR contractors are based on the east coast and travel to WA with their equipment when required. Undertaking jobs in WA has been challenging due to the recent travel restrictions related to COVID19. However, it is anticipated that this will improve with restrictions being eased.

### 3.3.2 Limitations of GPR Technology

GPR technology has limitations for its use in pavement investigations due to the penetration capability of different frequencies, the composition of materials and survey speed. GPR technology is not equally effective in all types of materials as it is based on the dielectric constant of in situ materials. It is generally more effective in sandy materials compared to clayey soil. Similarly, homogeneity of the material plays a major role in the accuracy of GPR results, i.e. the more homogenous the material – the more accurate the results. GPR survey results in heterogeneous materials are not accurate. Limitations of GPR technology can be summarised as follows:

- limitation of depth of scanning due to antenna frequency
- in situ ground conditions – variability of materials and contrast in the dielectric constant
- weather conditions – GPR data collection is not recommended during wet weather as a film of surface water may affect the radar signals
- speed of testing, i.e. reduced speed of survey to pick up more details
- measurement accuracy and errors in interpretation
- limitations in data collection and handling
- cost of network-level GPR surveys
- limitations in test results in terms of numerical values.

The GPR contractors reported that the accuracy of the results for moisture detection in the pavement can be improved if a ground-coupled antenna is used with a frequency of 400 MHz and speed of testing around 50 km/h. It should be noted that such an antenna type and speed of testing is not suitable for network-level GPR application. Higher-frequency antennae may not be able to detect moisture in the pavement at high traffic speeds (i.e. 110 km/h) and the GPR survey may end up providing pavement layer thicknesses only. Moreover, there may be issues associated with the depth of the signal penetration.

The major challenge in the layer thickness tracking in terms of delineating different pavement layers is contamination of materials at the layer interface. For instance, the contamination of the subbase layer with clay and silt-sized particles migrating from the subgrade upward into the overlying pavement layer makes it difficult to identify the exact contact of the two layers. It is not common to have sharp contacts of different pavement layers in the field.

### 3.3.3 GPR Calibration

GPR calibration with the results of testing of core samples, or other destructive testing, is important to ensure that the GPR data reflects the real picture of the subsurface conditions. One way to do that, as proposed by some of the contractors, is to core the pavement prior to a GPR survey so that core locations can be confirmed through video images that can be recorded as a part of the GPR surveys. It will allow an accurate integration of the geotechnical destructive testing data to GPR processing software for correlation and calibration. However, this approach does not seem ideal as one of the objectives of a GPR survey is to optimise geotechnical investigation by reducing core or test pit sites based on the pavement condition and variability as captured by the GPR.

Accurate core and/or test pit locations can be captured by a high-accuracy GPR and rechecked by their locations relative to other features within a road corridor. Multiple location controls such as SLK, GPS coordinates and chainages can be recorded and cross checked by plotting on the Google Earth image.

### 3.3.4 Clarity of Project Objectives

Clarity of the project objectives and deliverables is critical to outcome-focused GPR surveys. It is an inherent limitation of the GPR technology that all antenna frequencies cannot meet the specific needs for every project. The selection of the right equipment for the survey is based on clarity of the project objectives and deliverable requirements from the outset. These project-specific requirements include depth of scanning, required parameters and their level of accuracy (e.g. layer tracking, moisture detection, voids, pavement distress (stripping, layer delamination and cracks) and culvert detection, etc.) must be cascaded to the GPR survey contractor at the project inception stage in order to facilitate the selection of the appropriate equipment for the specific survey. For example:

- A ground-coupled antenna cannot be used for network-level survey.
- A ground-coupled antenna is the preferred option for moisture detection.
- Lower-frequency antennae (e.g. < 300 MHz) are required for deeper penetration (i.e. 2 m depth).
- Higher-frequency antennae (e.g. > 800 MHz or 1 GHz) are required for shallow penetration (i.e. 1 GHz for < 1 m or 2 GHz for 200 mm depth).

### 3.3.5 Availability of Knowledge and Skills

GPR implementation for pavement investigations ideally requires a professional pavement engineer who has expertise in pavement design, structure and material response to environmental and operational factors. Several years of experience of GPR interpretations is required to interpret GPR datasets with a high level of confidence. It is not only the availability of the equipment but also the availability of the right knowledge and skills which enhances the outcome of GPR surveys.

### 3.3.6 Main Roads Requirements for In-house Skills

For the best value-for-money, Main Roads needs good control over the GPR survey projects in terms of project planning, scope of work preparation, evaluation of the contractors' experience and interpretation of the GPR data for project- and network-level decision making. Main Roads will need to provide technical training to relevant staff in the accurate interpretation of GPR datasets, the management of contractors, and the use GPR survey outcome in day-to-day activities and operations. In terms of the availability of the GPR training, some GPR contractors in Australia offers in-house verification of competency assessment for industry GPR users in order to assess proper practice techniques for concrete scanning. However, as GPR use in the pavement domain is not widespread, the availability of specific training is also limited in this regard.

GPR-related technical training for dedicated Main Roads personnel is critical due to the lack of experience of GPR contractors related to pavement investigation and monitoring in WA. Main Roads initially may need to educate GPR contractors regarding the project objectives and specific issues related to their pavements, in order to enable them to choose the most appropriate equipment and survey parameters.

One of the critical elements in the implementation of GPR on the Main Roads network specifically for network-level analysis is the technical capability of personnel to handle and integrate large datasets and interpret these datasets to meet project requirements. Main Roads will therefore need to evaluate the technical skills of the contractor who will be conducting surveys and interpreting results.

### 3.3.7 GPR Survey Cost

GPR survey costs needs to be estimated for cost-benefit analysis. Based on project-specific requirements, multiple frequency antennae may be required in order to meet data collection needs. The large datasets associated with the network-level GPR surveys require a lot of manhours for processing the data. These requirements must be considered when estimating the costs of a GPR survey.

# 4 Critical Evaluation of GPR Survey Data

## 4.1 Introduction and Background

Contractor A and Contractor B were commissioned by Main Roads to carry out a GPR survey of a section of Mitchell Freeway, Perth, Western Australia. Contractor B also surveyed a section on the Canning Highway. The purpose of the surveys was to determine the layer thicknesses of the pavement sections for determining asphalt milling depth. GPR survey data was provided to ARRB to assess industry capability in terms of GPR surveys to measure the pavement profile on the Western Australian road network. The evaluation included a comparison of GPR results, antennae frequencies, processing software and interpretations.

This section of the report details the critical evaluation of GPR survey data from the Mitchell Freeway section carried out by two different contractors. The survey outcomes from the two contractors were compared with each other and correlated with the core data. The GPR surveys were managed by Main Roads.

Note that:

- Neither the GPR surveys nor the coring was undertaken as a part of this project. Unfortunately, the data provided for analysis was not sufficient and appropriate for investigating GPR capability for pavement applications.
- Pavement coring was carried out a year before the GPR survey were conducted. It should be noted that the coring was not undertaken for the purpose of correlating results but rather to determine the asphalt milling depth. The lower pavement layers (i.e. basecourse and subbase layers) were not targeted in the cores. Therefore, no correlation and comparison can be made for the validation of GPR results.
- As the intent of the GPR surveys was to establish asphalt milling depth, the project was scoped accordingly to track layer thicknesses without requiring additional information critical to evaluating GPR capability for the road pavement investigations, including information related to high moisture pockets, air voids, crack detection and pavement distress (e.g. asphalt layers delamination, stripping, etc.). Moreover, no interpretations and commentary was provided in the contractors' reports regarding GPR use for pavements in general, the selection process, the justification for the antennae frequencies used, and the limitations of the results.

GPR contractor reports provided to ARRB were evaluated based on the available information (data and interpretations) and the findings have been summarised logically without any assumptions. The intent of this section is, therefore, to evaluate capability of GPR technology for its application to road pavements.

## 4.2 Pavement Coring

The pavement coring carried out at the Mitchell Freeway and Canning Highway sites was managed by Main Roads, with the core data provided to GPR contractors for correlation and interpretation.

### 4.2.1 Mitchell Freeway – Core Data

Main Roads provided pavement coring data related to the investigations undertaken on the southbound carriageway of the Mitchell Freeway between Hodges Drive and Hepburn Avenue between SLK 17.8 and 26.3. The pavement coring was carried out by a contractor engaged by Main Roads. The purpose of the investigation was to assess the asphalt thickness for resurfacing requirements.

A total of 116 cores were undertaken from the Mitchell Freeway site from 2– June 2020. The pavement cores were extracted using a 100 mm diamond tip core. Details of the coring are as follows:

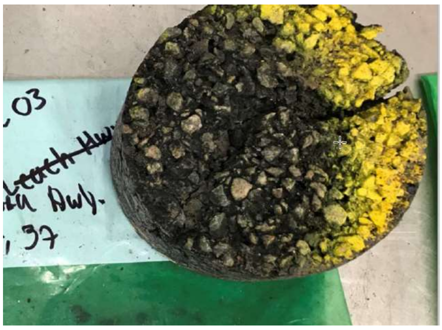
- Coring was carried out on lanes 1 and 3. Findings related to other lanes/areas were estimated; therefore localised inconsistencies and inaccuracies are expected.
- The core drilling reports did not provide any information related to core location; however, discussion with Main Roads led to the following conclusions:
  - Left lane (R2): coring conducted on targeted cracked areas (if any), close to the left wheelpath (LWP) to keep the operator away from live traffic.

  - Left shoulder: coring conducted close to the left lane edge line to keep the operator away from underlying services.
  - Right lane (R1): coring conducted on targeted cracked areas (if any), close to the right wheelpath (RWP) to keep the operator away from live traffic.
  - Right shoulder: coring conducted in the middle of the shoulder.
- The thickness of asphalt typically varied from 60–70 mm except from SLK 25.80 to 25.90, where the thickness varied from 155 mm to 325 mm.
- The asphalt surfacing was composed of 25–30 mm of 10 mm laterite mix open-graded asphalt (OGA) and 30–40 mm of DGA 10 or 7 mm granite mix.
- The basecourse comprised a crushed rock base (SLK 17.90 to 22.70), bitumen-stabilised limestone (SLK 22.80 to 25.60 and SLK 26.40 to 26.60) and hydrated cement-treated crush rock base (SLK 25.70 to 26.10, except for SLK 25.80–25.90, where pavement was asphalt).
- Multiple interconnected cracks were observed in the slow and fast lanes and meandering cracking was observed in multiple areas.
- Ravelling was apparent in the slow lane at SLK 19.50.

Figure 4.1 shows selected pavement cores from this investigation.

**Figure 4.1: Selected pavement cores**

SLK 26.40 (Shoulder) – Interconnected cracks



SLK 24.40 (Slow Lane) – Longitudinal crack

SLK 23.10 (Fast Lane) – Longitudinal crack

SLK 21.30 (Slow Lane) – Meandering crack

Source: Main Roads.

Table 4.1 provides details of the layer thicknesses in lanes 1 and 3.

**Table 4.1: Coring details – Mitchell Freeway**

| SLK | Lane reference | Asphalt thickness (mm) | SLK | Lane reference | Asphalt thickness (mm) |
|---|---|---|---|---|---|
| 26.40 | R2 | 60 | 26.00 | R1 | 70 |
| 26.10 | R2 | 70 | 25.60 | R1 | 70 |
| 26.00 | R2 | 60 | 25.30 | R1 | 55 |
| 25.90 | R2 | 70 | 25.10 | R1 | 40 |
| 25.80 | R2 | 55 | 25.00 | R1 | 50 |
| 25.70 | R2 | 60 | 24.70 | R1 | 60 |

| SLK | Lane reference | Asphalt thickness (mm) | SLK | Lane reference | Asphalt thickness (mm) |
|---|---|---|---|---|---|
| 25.60 | R2 | 60 | 24.50 | R1 | 50 |
| 25.50 | R2 | 60 | 24.30 | R1 | 60 |
| 25.00 | R2 | 60 | 24.20 | R1 | 65 |
| 24.60 | R2 | 50 | 24.00 | R1 | 55 |
| 24.40 | R2 | 50 | 23.80 | R1 | 60 |
| 24.10 | R2 | 55 | 23.60 | R1 | 60 |
| 23.90 | R2 | 60 | 23.30 | R1 | 70 |
| 23.70 | R2 | 60 | 23.10 | R1 | 60 |
| 23.40 | R2 | 70 | 22.70 | R1 | 55 |
| 23.20 | R2 | 60 | 22.50 | R1 | 60 |
| 22.90 | R2 | 60 | 22.30 | R1 | 50 |
| 22.80 | R2 | 60 | 22.00 | R1 | 65 |
| 22.40 | R2 | 60 | 21.80 | R1 | 65 |
| 22.20 | R2 | 60 | 21.60 | R1 | 50 |
| 21.90 | R2 | 70 | 21.40 | R1 | 65 |
| 21.70 | R2 | 65 | 21.10 | R1 | 60 |
| 21.50 | R2 | 65 | 20.80 | R1 | 55 |
| 21.30 | R2 | 60 | 20.60 | R1 | 55 |
| 21.20 | R2 | 60 | 20.40 | R1 | 55 |
| 20.80 | R2 | 65 | 19.90 | R1 | 60 |
| 20.70 | R2 | 65 | 19.70 | R1 | 50 |
| 20.50 | R2 | 65 | 19.40 | R1 | 60 |
| 20.30 | R2 | 75 | 19.20 | R1 | 75 |
| 20.00 | R2 | 85 | 19.00 | R1 | 60 |
| 19.60 | R2 | 45 | 18.80 | R1 | 65 |
| 19.50 | R2 | 40 | 18.60 | R1 | 65 |
| 19.30 | R2 | 55 | 18.40 | R1 | 65 |
| 19.10 | R2 | 70 | 18.20 | R1 | 65 |
| 18.70 | R2 | 65 | 18.00 | R1 | 60 |
| 18.50 | R2 | 75 | | | |
| 18.30 | R2 | 60 | | | |
| 18.00 | R2 | 60 | | | |
| 17.90 | R2 | 60 | | | |

Source: Main Roads.

### 4.2.2 Canning Highway – Core Data

Thirty-four cores were drilled on the Canning Highway site, with the project managed by the Main Roads Metropolitan Region. Table 4.2 provides coring details for Canning Highway section.

**Table 4.2: Coring details – Canning Highway**

| SLK | Lane reference | Asphalt thickness (mm) | SLK | Lane reference | Asphalt thickness (mm) |
|---|---|---|---|---|---|
| **Southbound** | | | **Northbound** | | |
| 0.93 | Fast lane | 50 | 0.98 | Fast lane | 80 |
| 1.13 | Fast lane | 80 | 1.18 | Fast lane | 100 |
| 1.33 | Fast lane | 30 | 1.38 | Fast lane | 75 |

| SLK | Lane reference | Asphalt thickness (mm) | SLK | Lane reference | Asphalt thickness (mm) |
|---|---|---|---|---|---|
| 1.53 | Fast lane | 65 | 1.58 | Fast lane | 130 |
| 1.73 | Fast lane | 80 | 1.78 | Fast lane | 55 |
| 1.93 | Fast lane | 115 | 1.98 | Fast lane | 65 |
| 2.13 | Fast lane | 60 | 2.18 | Fast lane | 95 |
| 2.33 | Fast lane | 80 | 2.38 | Fast lane | 80 |
| 2.53 | Fast lane | 70 | 1.03 | Slow lane | 60 |
| 2.73 | Fast lane | 105 | 1.23 | Slow lane | 75 |
| | | | 1.43 | Slow lane | 60 |
| | | | 1.63 | Slow lane | 80 |
| | | | 1.83 | Slow lane | 100 |
| | | | 2.03 | Slow lane | 85 |
| | | | 2.23 | Slow lane | 80 |
| | | | 2.43 | Slow lane | 80 |

Source: Main Roads.

## 4.3 Mitchell Freeway – GPR Data Evaluation

Main Roads used two different GPR contractors to investigate the same section of the Mitchell Freeway, with the GPR survey results correlated with pavement coring data. The purpose of the critical evaluation of the GPR surveys was to assess industry capability in terms of equipment availability (i.e. antennae type and frequencies, software and interpretation skills).

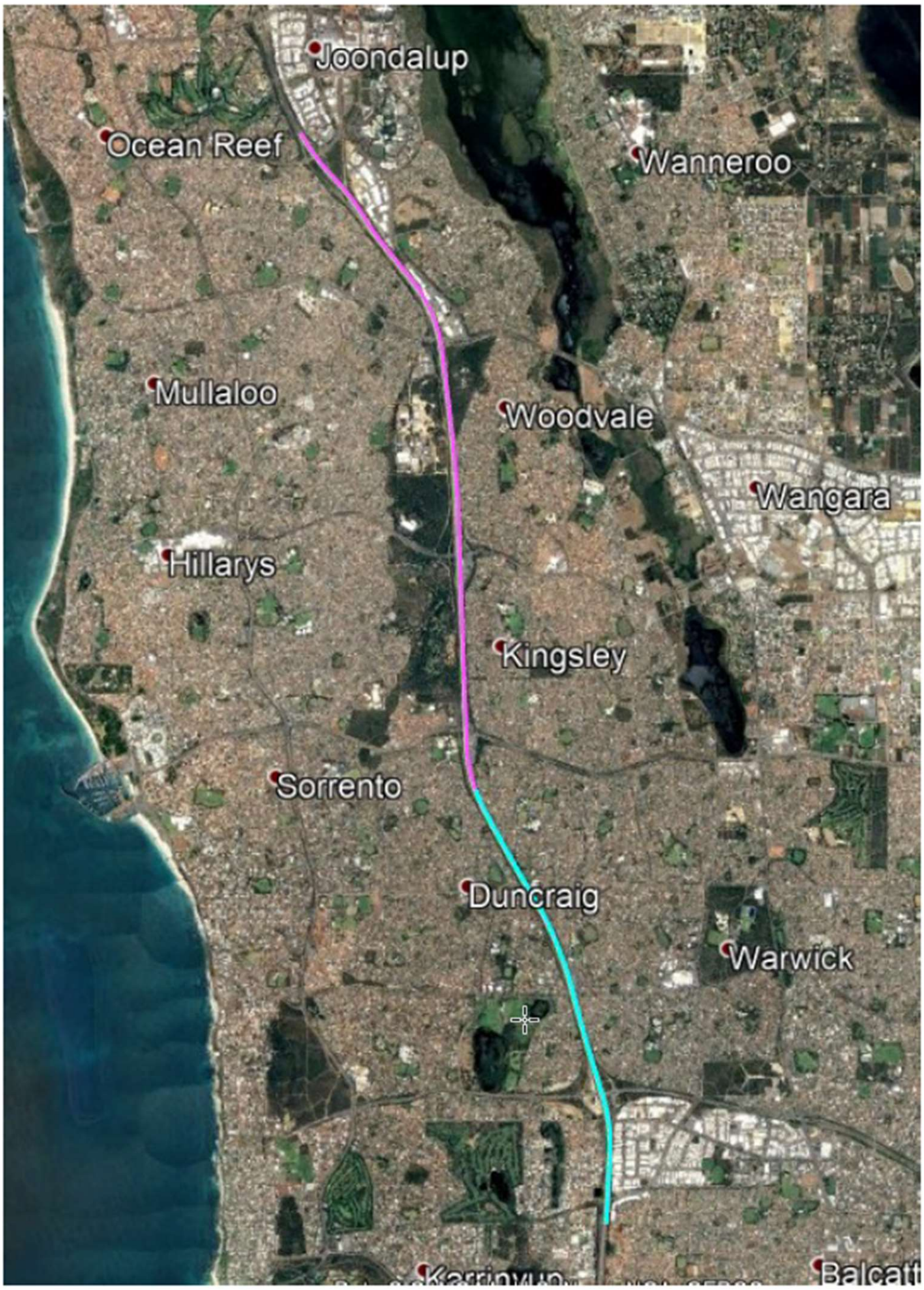
### 4.3.1 Contractor A GPR Data Evaluation

#### GPR survey details

Contractor A carried out GPR testing of approximately 33.5 km of the Mitchell Freeway and a 320 m length of a bridge section. The survey was conducted using a GSSI SIR30 recording system connected to antennae operating at centre frequencies of 1,000 MHz (air-coupled) and 1,500 MHz and 900 MHz (ground-coupled). The apparatus was mounted to the rear of the vehicle positioned approximately 500 mm above the nominal ground surface. Data was collected at a density of 10 scans/m at normal traffic speed. The GPR system was connected to the hub encoder and Xnav 500 IMU GPS (with accuracy levels up to 0.1 mm) to provide both linear offsets and coordinate-based location systems.

The survey was carried out on 3 July 2021 at night time without traffic control in place. The pavement was dry at the time of the survey. The survey distance was measured using a wheel-mounted encoder in order to control the acquisition of the data. The GPR was calibrated with core data provided by Main Roads for lanes 1 and 3. Figure 4.2 shows a satellite map of the location of the survey.

**Figure 4.2: Location of Mitchell Freeway survey**




Source: Main Roads/Contractor A's Report.

### GPR layer thickness tracking

The layer thicknesses were measured and reported at intervals of 1 m, 10 m and 100 m. A measuring interval of 10 m was used in the evaluation. Table 4.3 summarises the details of the measured thicknesses of the pavement layers.

**Table 4.3: Details of thickness of pavement layers measured by Contractor A GPR survey on Mitchell Freeway**

| ID | Layer 1/Asphalt thickness (mm) | | | | | Layer 2 thickness (mm) | | | | | Layer 3 thickness (mm) | | | | | Layer 4 thickness (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) |
| 1A1IWP (R1 IWP) | 35 | 191 | 101 | 30 | 30 | 164 | 425 | 251 | 47 | 19 | 335 | 763 | 536 | 76 | 14 | 623 | 932 | 755 | 76 | 10 |
| 1A1OWP (R1 OWP) | 30 | 236 | 91 | 33 | 37 | 149 | 428 | 230 | 48 | 21 | 350 | 670 | 495 | 48 | 10 | 579 | 773 | 657 | 61 | 9 |
| 1A3IWP (R2 IWP) | 33 | 161 | 89 | 29 | 33 | 143 | 405 | 209 | 43 | 20 | 354 | 666 | 479 | 49 | 10 | 518 | 910 | 663 | 94 | 14 |
| 1A3OWP (R2 OWP) | 34 | 176 | 95 | 30 | 31 | 150 | 466 | 216 | 49 | 23 | 349 | 681 | 490 | 51 | 10 | 545 | 878 | 657 | 71 | 11 |
| 1A5IWP (R3 IWP) | 30 | 169 | 95 | 28 | 29 | 133 | 306 | 218 | 36 | 17 | 363 | 587 | 463 | 44 | 9 | Not found | | | | |
| 1A5OWP (R3 OWP) | 32 | 197 | 102 | 32 | 32 | 141 | 354 | 242 | 39 | 16 | 362 | 635 | 475 | 46 | 10 | 522 | 922 | 642 | 109 | 17 |
| 1B1OWP | 144 | 167 | 156 | 7 | 4 | 322 | 364 | 345 | 15 | 4 | Not found | | | | | Not found | | | | |
| 1B1IWP | 126 | 176 | 155 | 17 | 11 | 318 | 440 | 362 | 38 | 10 | Not found | | | | | Not found | | | | |
| 1B3OWP | 72 | 167 | 142 | 29 | 20 | 323 | 433 | 353 | 34 | 10 | Not found | | | | | Not found | | | | |
| 1B3IWP | 126 | 173 | 159 | 15 | 9 | 317 | 439 | 365 | 42 | 12 | Not found | | | | | Not found | | | | |
| 2B2IWP | 137 | 207 | 160 | 20 | 13 | 304 | 401 | 350 | 32 | 9 | Not found | | | | | Not found | | | | |
| 2B2OWP | 103 | 158 | 144 | 16 | 11 | 310 | 359 | 335 | 18 | 5 | Not found | | | | | Not found | | | | |
| 2B4IWP | 138 | 199 | 162 | 25 | 15 | 309 | 399 | 340 | 34 | 10 | Not found | | | | | Not found | | | | |
| 2B4OWP | 140 | 191 | 152 | 15 | 10 | 305 | 404 | 343 | 34 | 10 | Not found | | | | | Not found | | | | |

Note: Data collection interval is 10 m.

Key: IWP: Inner wheelpath/RWP, OWP: Outer wheelpath/LWP.

Source: Main Roads/Contractor A Report (GPR survey at Mitchell Freeway).

A typical example of a radargram showing a section along the GPR line collected in lane 1 (fast lane) for layer thicknesses between chainages 800–900 m is shown in Figure 4.3. The horizontal axis on the GPR section represents the distance, in metres, along the line and the vertical axis represents the two-way time (TWT) in nanoseconds ‘ns’ for the radar signals. The depths of layers 1, 2 , 3 were approximately 150 mm, 325 mm and 500 mm respectively.

**Figure 4.3: Radargram of GPR section (1A3OWP)**

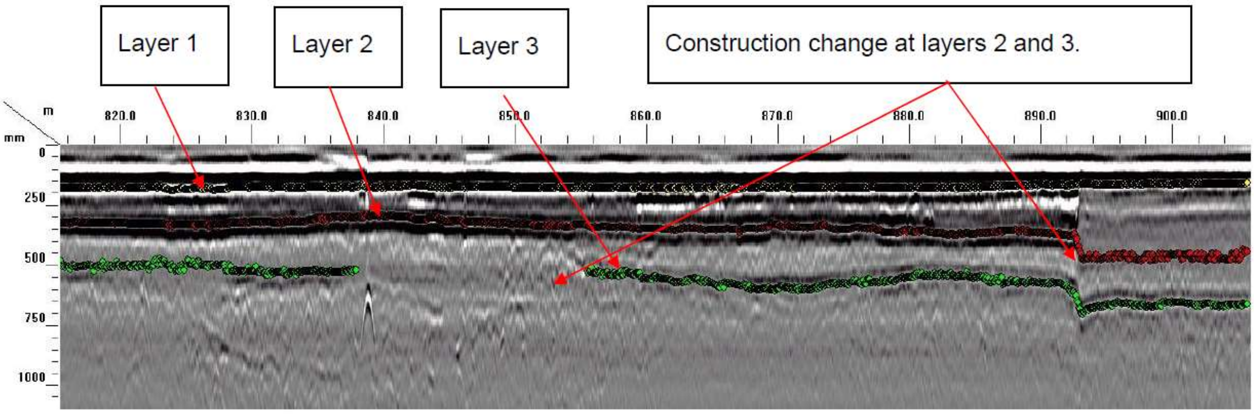



Figure 4.4 shows the interface between the layers, which can be seen clearly at three different areas from chainage 2,000 m to 2,080 m. The contrast in dielectric constant of the materials is evident. This location seems an ideal location for targeting boreholes/cores to identify the true layers and calibrate the dielectric constant.

**Figure 4.4: Radargram of GPR section (1A3OWP)**

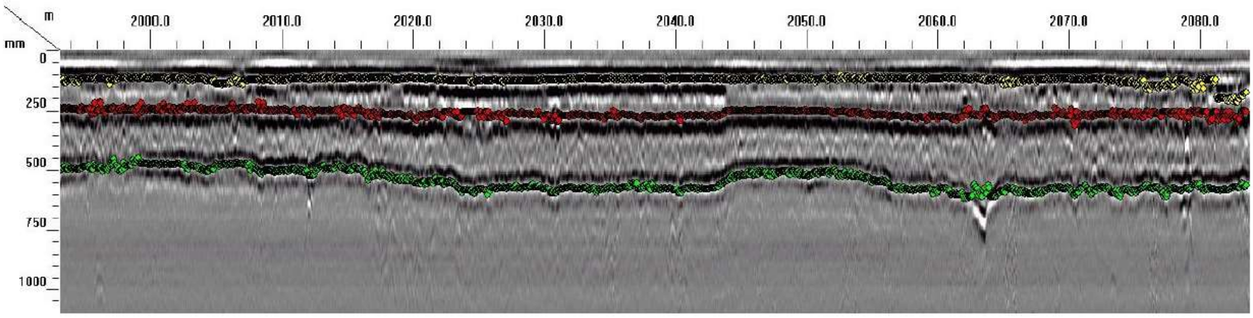



Figure 4.5 shows substantial moisture presence below the interface at around 500 mm in the sublayers.

**Figure 4.5: Radargram GPR section (1A3OWP)**

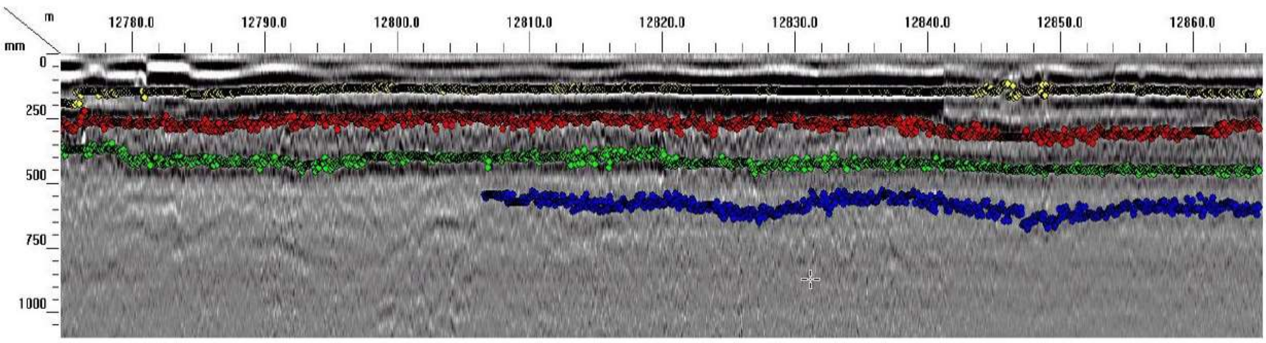



Figure 4.6 to Figure 4.8 show layer thickness throughout the surveyed length for lanes 1, 3 and 5.

**Figure 4.6: Layer thicknesses Lane 1**

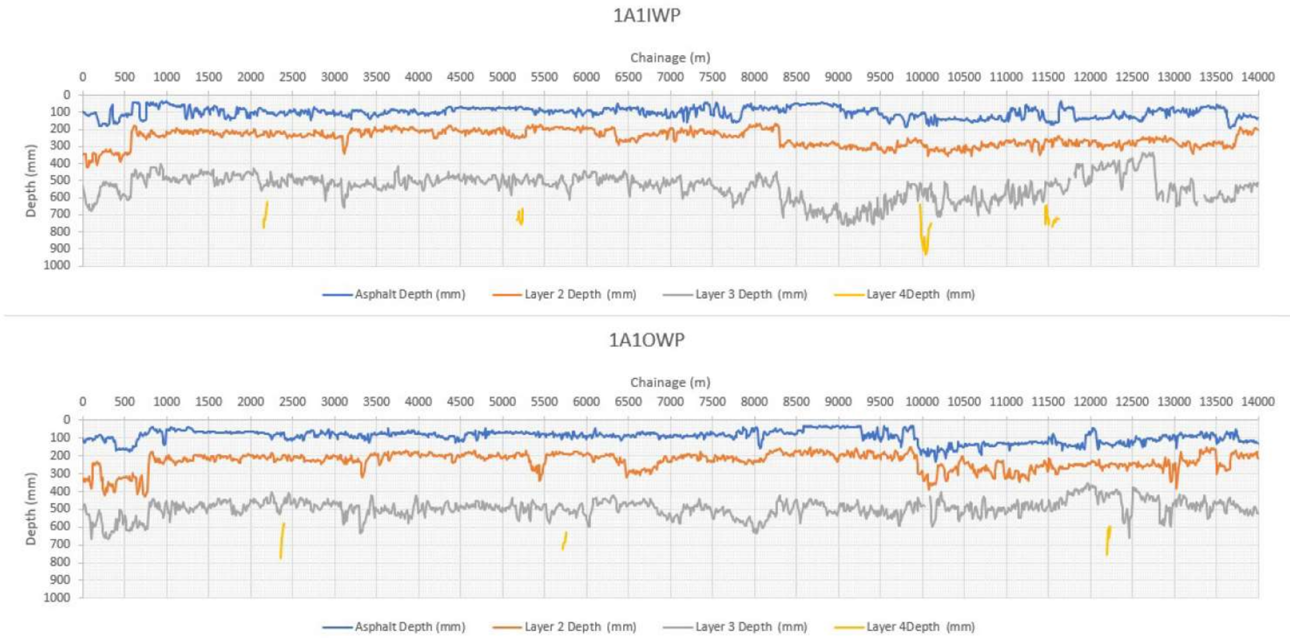



**Figure 4.7 Layer thicknesses Lane 3**

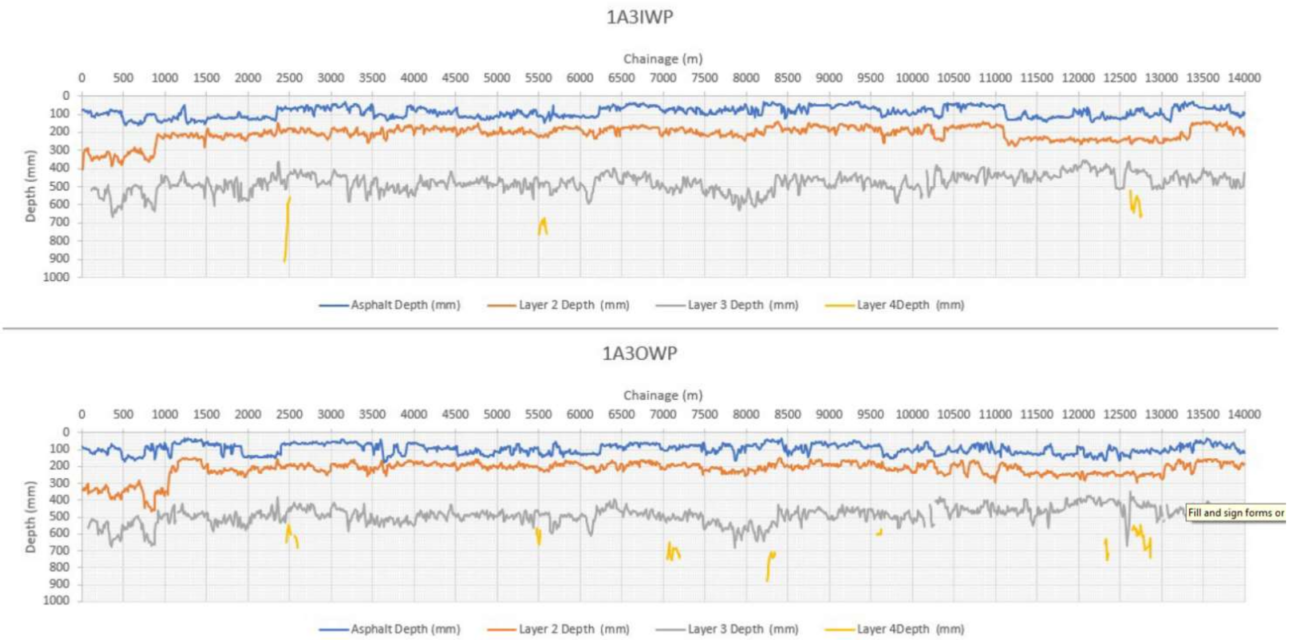
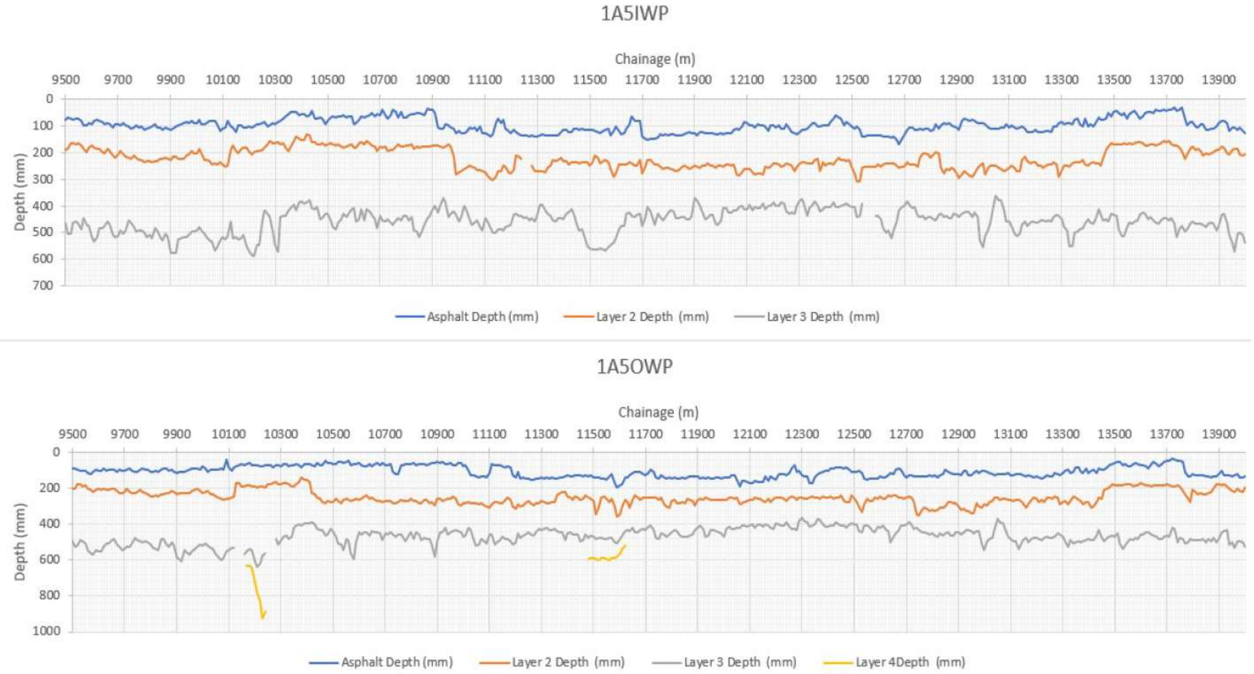


**Figure 4.8: Layer thicknesses Lane 5**




Key findings of Contractor A GPR survey at Mitchell Freeway are as follows:

- Pavement core data was only provided for lanes 1 and 3. The GPR measured thickness was calibrated with these lanes. Due to a lack of core data, the thickness for lane 5 was estimated based on correlations from lanes 1 and 3.
- Some locations did not show fourth layer in the data; therefore, thickness measurement was not possible at these locations.
- The pavement profiles remained homogeneous with no major construction changes for most of the survey lines.
- The changes in depth could be seen between the wheelpaths on all three runs, possibly due to recent widenings or overlays.
- The thickness of the first layer at some locations varied between 30 mm and 201 mm. The asphalt thickness changed at chainage 10,500 m in the outer wheelpath.
- The thickness of the second layer from 0 to 1,000 m was approximately 200 mm greater than the rest of the 14 km section.
- Changes in depths could be seen in the third layer around a chainage of 11,300 m on the inner wheelpath, but it could be fourth layer or an area of potential voids.
- There was a change in the second layer at a chainage of approximately 10,400 m in the outer wheelpath. This could potentially due to a base construction in pavement profile.
- The outer wheel path showed signs of more irregularities in the second layer due to the rise and falls in the data. This could be signs of a granular base with larger aggregate but this could not be confirmed without physical evidence.
- The pavement looked generally homogeneous across all three layers from chainage 2,500 m to 8,500 m.
- At the bridge section, the thickness of asphalt in all four lanes was approximately 170 mm. The thickness of the bottom layer was estimated to be about 320 mm which could be the bottom of the concrete structure. The pavement on the bridge was surveyed but the data was hard to interpret accurately. There is a high chance that reinforcement in the bridge absorbed the GPR energy.

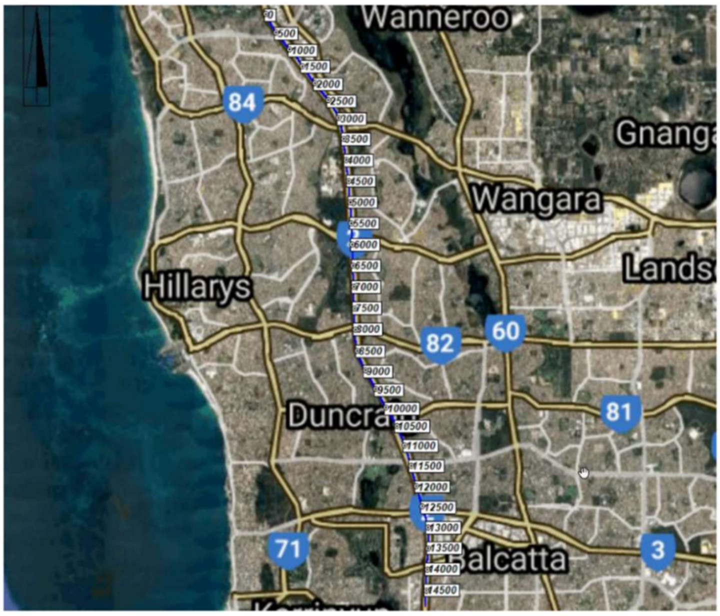
### 4.3.2 Contractor B GPR Data Evaluation

#### GPR survey details

Contractor B Australia carried out GPR survey of approximately 39 km of lanes for the nominated sections on the southbound carriageway of the Mitchell Freeway. The purpose of the survey was to identify and report subsurface layers and any potential anomalies. The RD Camlink system and advanced 2 x GSSI 2 GHz air-horn antennae were used for the survey. The collected data was processed and analysed using the Road Doctor Software.

The data was collected on 11 September 2021. The road was in a dry condition at the time of the survey. Data in each lane was collected separately. Figure 4.9 shows a satellite map of the survey extent of Mitchell Freeway.

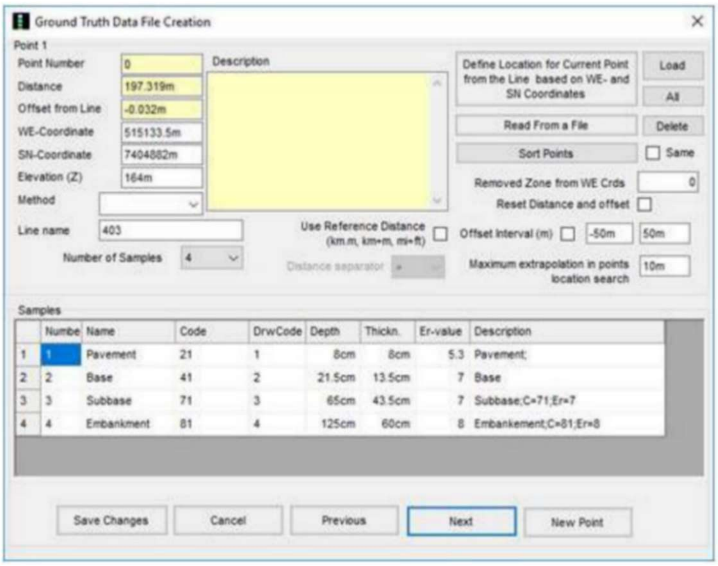
**Figure 4.9: Location map of the survey extent of Mitchell Freeway**




Source: Main Roads/Contractor B Report (GPR survey at Mitchell Freeway).

Data for 74 cores provided by Main Roads was used for calibration in the Road Doctor software using Ground Truth Data option. The software can calculate relevant dielectric constants based on core results. Figure 4.10 shows an example of a Ground Truth Data File.

**Figure 4.10: Ground Truth Data file in Road Doctor**




Source: Main Roads/Contractor B Report (GPR survey at Mitchell Freeway).

### GPR layer thickness tracking

Layer thicknesses were reported at intervals of 1 m, 10 m and 100 m. For this evaluation, the GPR data with 10 m intervals was used. Table 4.4 summarises the measured thicknesses of the pavement layers.

**Table 4.4: Details of thickness of pavement layers measured by Contractor B GPR survey on Mitchell Freeway**

| ID | Layer 1/Asphalt thickness (mm) | | | | | Layer 2 thickness (mm) | | | | | Layer 3 thickness (mm) | | | | | Layer 4 thickness (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) |
| SBFL (LWP) | 42 | 120 | 77 | 14 | 19 | 140 | 307 | 213 | 23 | 11 | 282 | 581 | 428 | 47 | 11 | 399 | 582 | 496 | 48 | 10 |
| SBFL (RWP) | 42 | 121 | 80 | 14 | 18 | 127 | 365 | 233 | 36 | 16 | 290 | 623 | 429 | 45 | 10 | 392 | 599 | 564 | 63 | 11 |
| SBML (LWP) | 33 | 121 | 73 | 19 | 26 | 127 | 283 | 205 | 26 | 13 | 279 | 626 | 434 | 46 | 11 | 404 | 588 | 518 | 48 | 9 |
| SBML (RWP) | 24 | 118 | 75 | 17 | 23 | 126 | 341 | 203 | 26 | 13 | 273 | 597 | 435 | 45 | 10 | 404 | 606 | 512 | 49 | 10 |
| SBSL (LWP) | 29 | 120 | 68 | 18 | 26 | 124 | 284 | 194 | 26 | 14 | 290 | 602 | 432 | 46 | 11 | 435 | 639 | 539 | 50 | 9 |
| SBSL (RWP) | 31 | 123 | 71 | 15 | 21 | 141 | 264 | 195 | 24 | 12 | 276 | 593 | 428 | 44 | 10 | 412 | 636 | 517 | 48 | 9 |

Note: Data collection interval of 10 m.

Key: FL: Fast lane, SL: Slow lane, LWP: Left wheelpath, RWP: Right wheelpath.

Source: Main Roads/Contractor B Report (GPR survey at Mitchell Freeway).

Figure 4.11 and Figure 4.12 show selected radargrams of the Mitchel Freeway southbound section.

**Figure 4.11: Radargram of Mitchell Freeway: southbound slow lane**

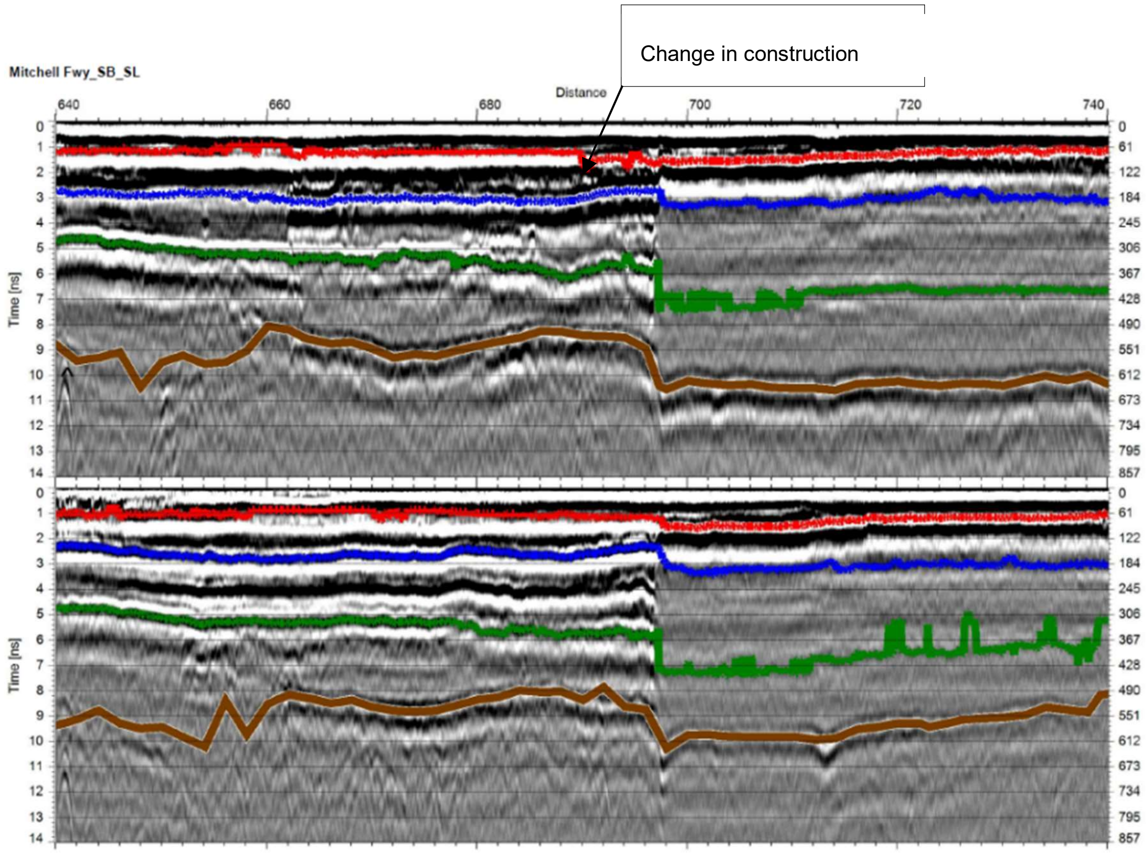



**Figure 4.12: Radargram of Mitchell Freeway: southbound, slow lane**

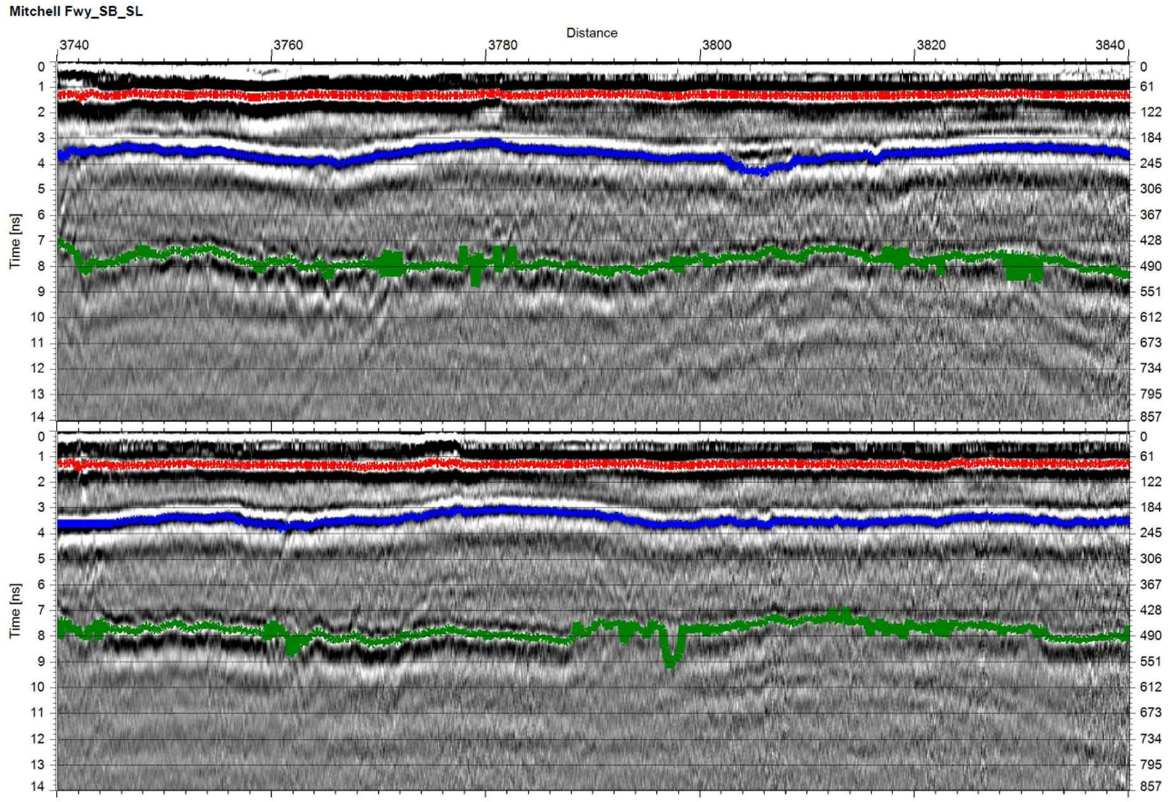


Figure 4.13 and Figure 4.14 show selected radargrams of the Michell Freeway southbound section including voids content.

**Figure 4.13: Radargram of Mitchell Freeway: southbound slow lane with voids content**

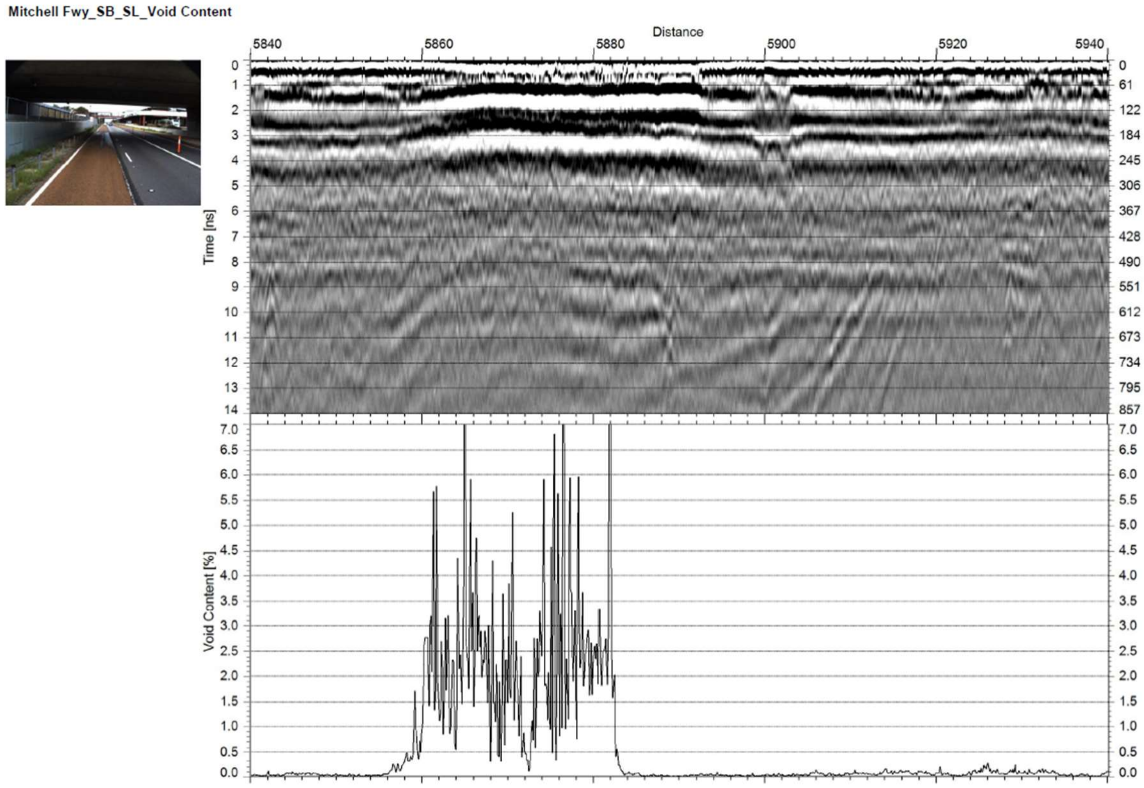
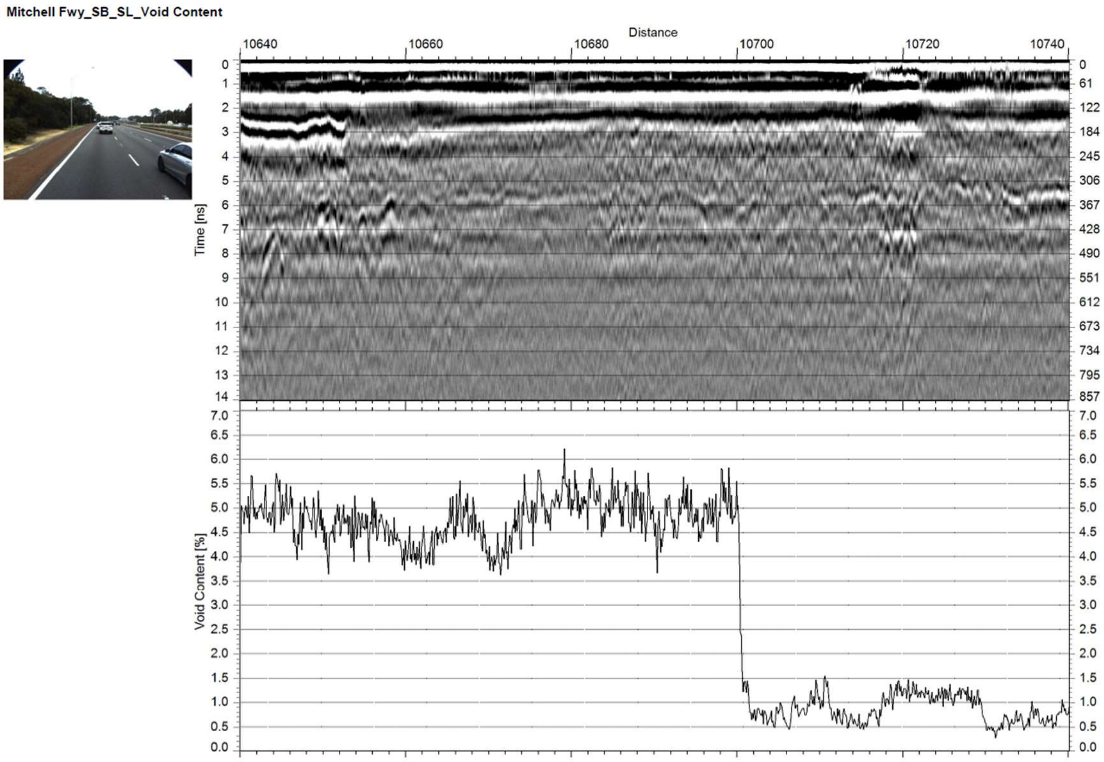



**Figure 4.14: Radargram of Mitchell Freeway: southbound, slow lane with voids content**



## 4.4 Canning Highway GPR Data Evaluation

The Canning Highway GPR survey was carried out by Contractor B Australia.

### GPR survey details

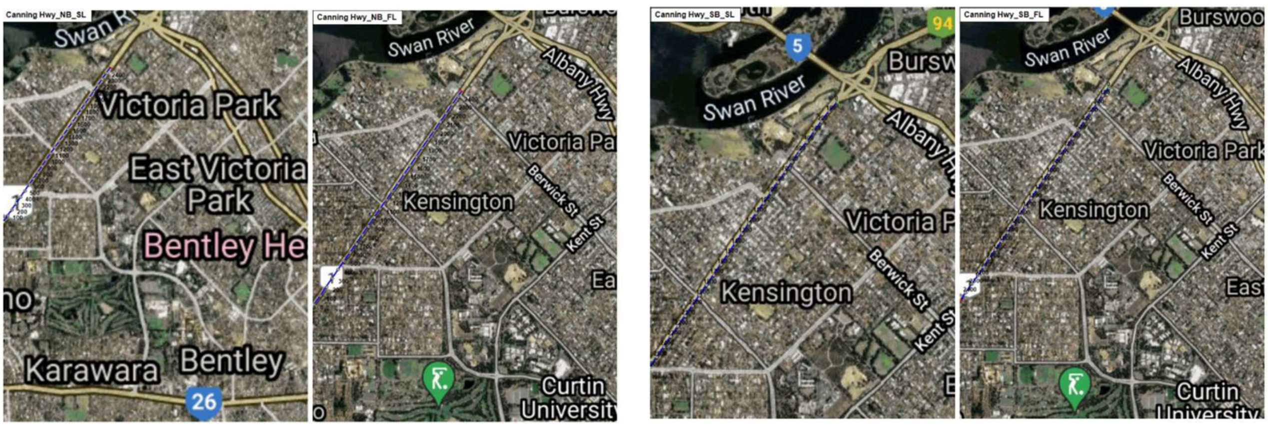
Contractor B Australia was commissioned by Main Roads Metropolitan Region to undertake a GPR survey for approximately 8 lane-km of the Canning Highway (SLK 0.85 to 2.80) between Berwick Street and South Terrace. The Metropolitan Region intended to use the survey results to confirm profiling depths for resurfacing works and to gain a better understanding of whether there was sufficient depth to include a geotextile reinforced seal (GRS) underneath the asphalt.

The survey was conducted using the RD Camlink system using two GSSI SIR30 2 GHz air-horn antennae with GPS and distance measurement instrument (DMI). The collected data was processed using the Road Doctor Software to track pavement subsurface layers. Traffic control was not required as the GPR survey was performed at traffic speed.

GPR surveys were carried out separately on each lane of the northbound and southbound Canning Highway on 11 September 2021. The road surface was in a dry condition at the time of the survey.

Figure 4.15 shows a location map of the survey extent of the Canning Highway.

**Figure 4.15: Satellite map showing survey extent of Canning Highway**




Canning Highway northbound, fast and slow lanes

Canning Highway southbound, fast and Slow Lanes

### GPR layer thickness tracking

Layer thicknesses were measured at intervals of 1 m, 10 m and 100 m. For this evaluation, the GPR data with 10 m intervals was used. Table 4.5 summarises the measured thicknesses of the pavement layers.

There was a good correlation between the GPR survey data and the core data, except at a few locations. For example, the core data at SLK 1.33 at lane 1 suggested a thickness of asphalt of 30 mm whereas the GPR suggested a greater depth at this location. In lane 2, a widening joint is visible from SLK 1.75 to the end of the section. The full extent of the widening is unconfirmed as this was believed to be constructed in the 1960s to 1970s and there is very little documentation.

**Table 4.5: Thicknesses of pavement layers measured by Contractor B GPR at Canning Highway**

| ID | Asphalt thickness (mm) | | | | | Layer 2 thickness (mm) | | | | | Layer 3 thickness (mm) | | | | | Layer 4 thickness (mm) | | | | | Layer 4 thickness (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) | Min. | Max. | Average | Std. Dev. | CV (%) |
| NBFL (LWP) | 47 | 128 | 82 | 16 | 20 | 136 | 310 | 205 | 30 | 15 | 243 | 462 | 338 | 49 | 14 | 426 | 700 | 558 | 54 | 10 | Not found | | | | |
| NBFL (RWP) | 45 | 125 | 80 | 15 | 19 | 134 | 281 | 199 | 30 | 15 | Not found | | | | | Not found | | | | | Not found | | | | |
| NBSL (LWP) | 43 | 136 | 75 | 18 | 23 | 139 | 291 | 201 | 36 | 18 | 234 | 407 | 312 | 33 | 11 | 354 | 804 | 560 | 95 | 17 | Not found | | | | |
| NBSL (RWP) | 48 | 116 | 82 | 16 | 19 | 129 | 274 | 199 | 29 | 14 | Not found | | | | | Not found | | | | | Not found | | | | |
| SBFL (LWP) | 45 | 109 | 75 | 13 | 18 | 138 | 313 | 204 | 38 | 19 | 257 | 498 | 342 | 45 | 13 | 382 | 924 | 14 | 75 | 552 | 705 | 1306 | 996 | 189 | 19 |
| SBFL (RWP) | 53 | 120 | 78 | 15 | 19 | 132 | 318 | 193 | 32 | 16 | Not found | | | | | Not found | | | | | Not found | | | | |
| SBSL (LWP) | 43 | 134 | 73 | 16 | 22 | 146 | 289 | 213 | 28 | 13 | 257 | 445 | 366 | 42 | 11 | 354 | 754 | 513 | 75 | 15 | 656 | 1115 | 860 | 117 | 14 |
| SBSL (RWP) | 38 | 120 | 79 | 18 | 23 | 135 | 332 | 213 | 31 | 15 | Not found | | | | | Not found | | | | | Not found | | | | |

Note: Data collection interval of 10 m.

Key: FL: Fast lane, SL: Slow lane, LWP: Left wheelpath, RWP: Right wheelpath.

Source: Main Roads/Contractor B (GPR survey at Canning Highway).

Figure 4.16 and Figure 4.17 show selected radargrams of the Canning Highway section.

**Figure 4.16: Radargram of Canning Highway: northbound, fast lane**

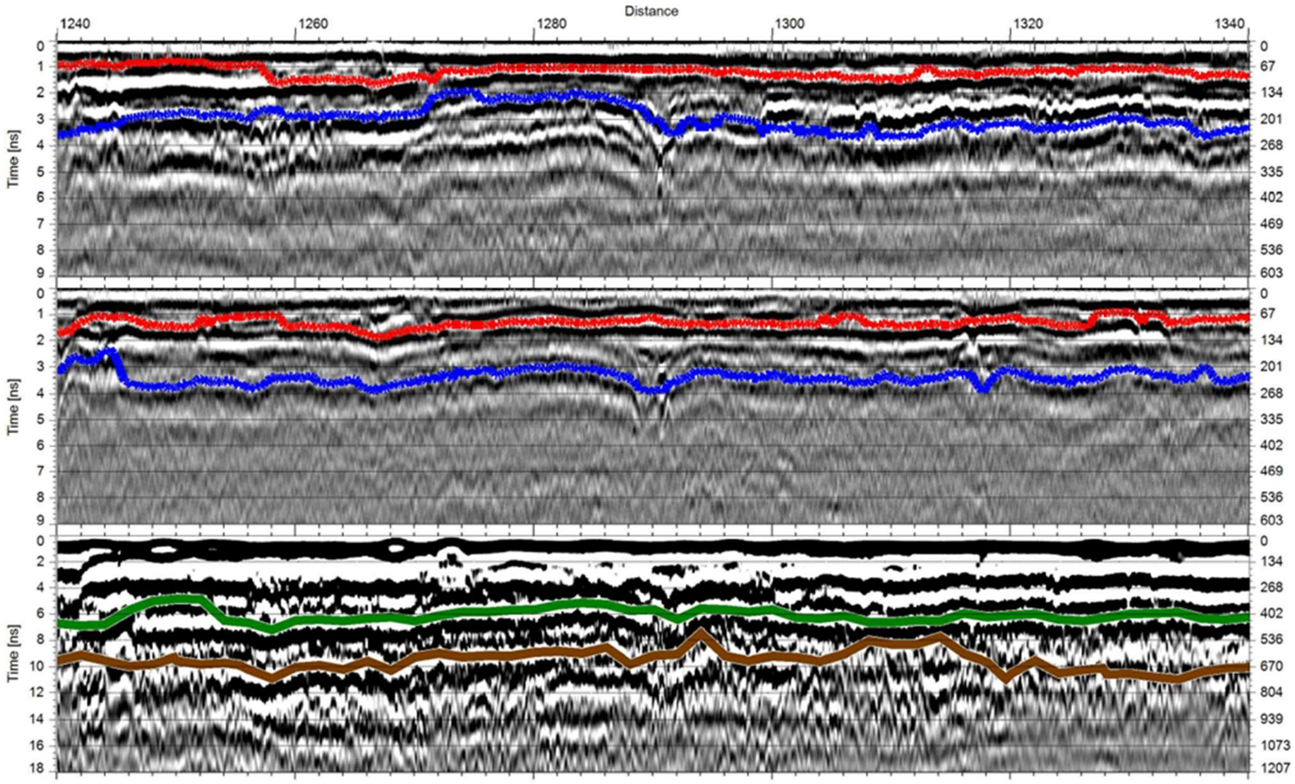



**Figure 4.17: Radargram of Canning Highway: southbound, slow lane**

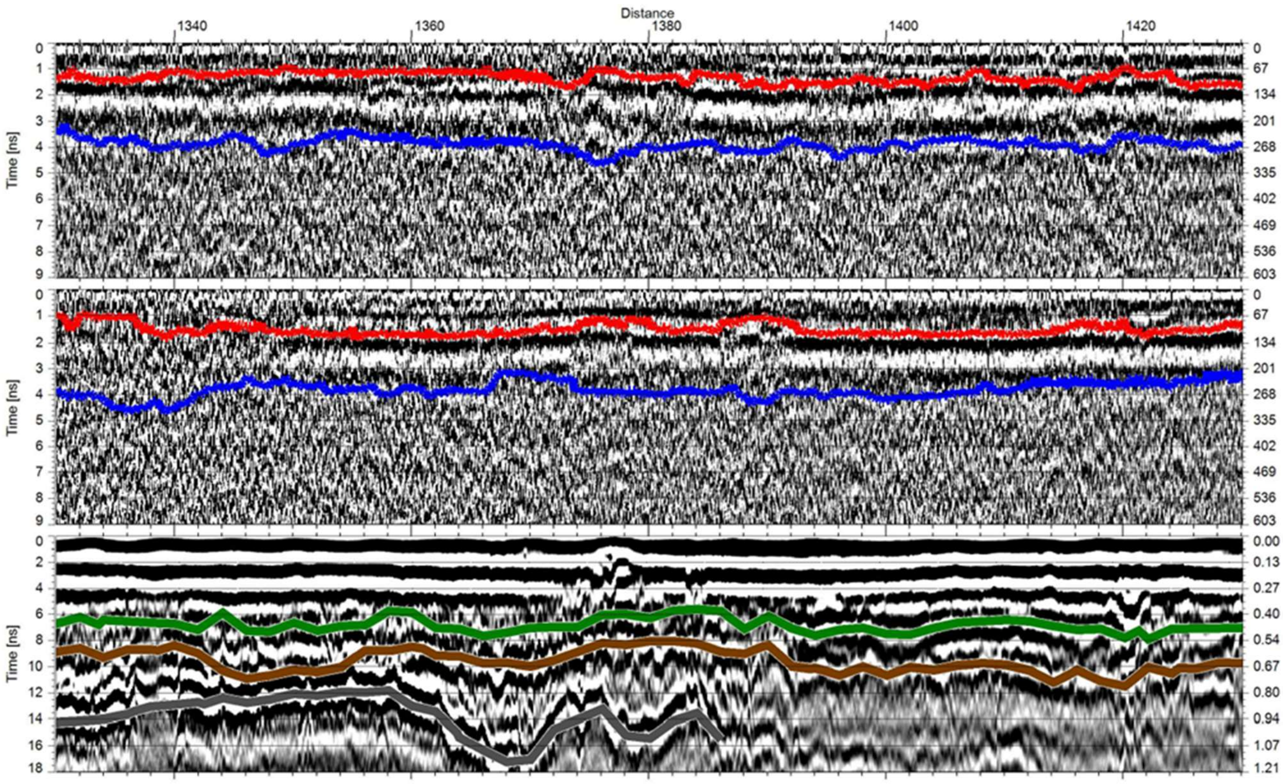



Figure 4.18 and Figure 4.19 show radargrams and void contents at selected sections along the Canning Highway.

**Figure 4.18: Radargram of Canning Highway: northbound, fast lane with voids content**

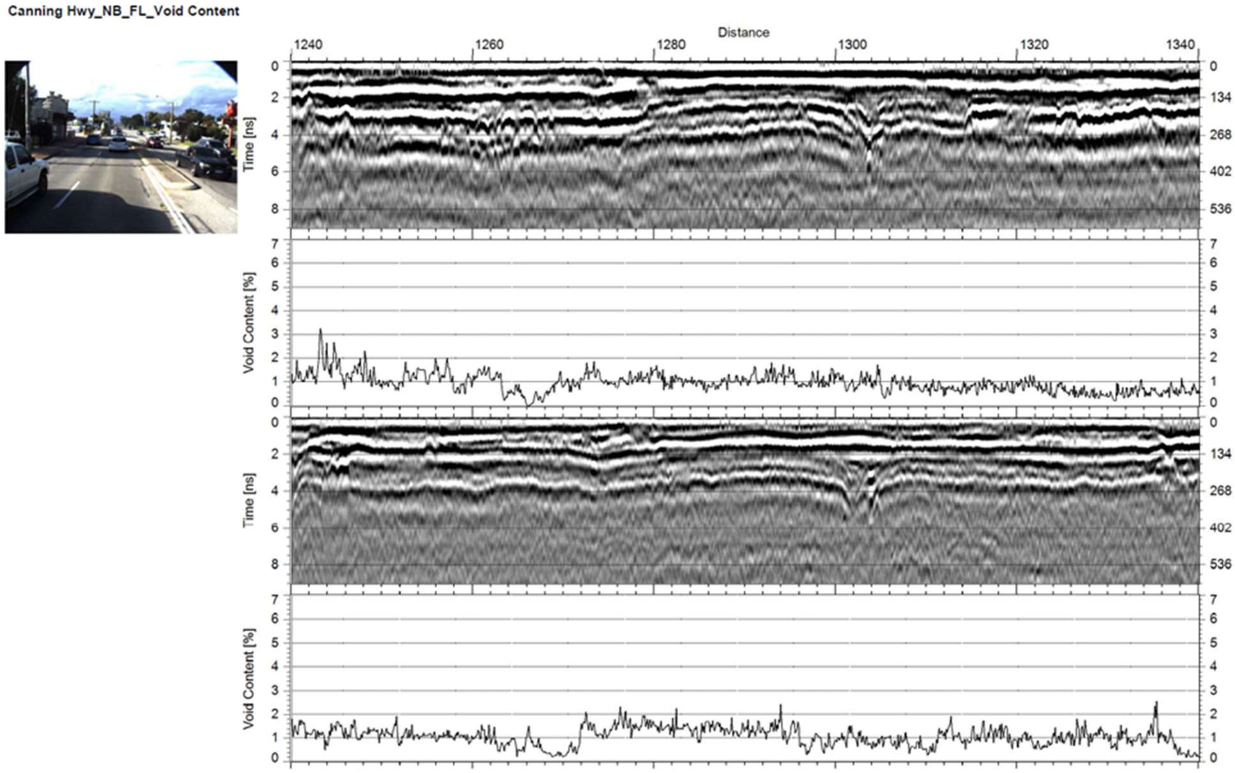
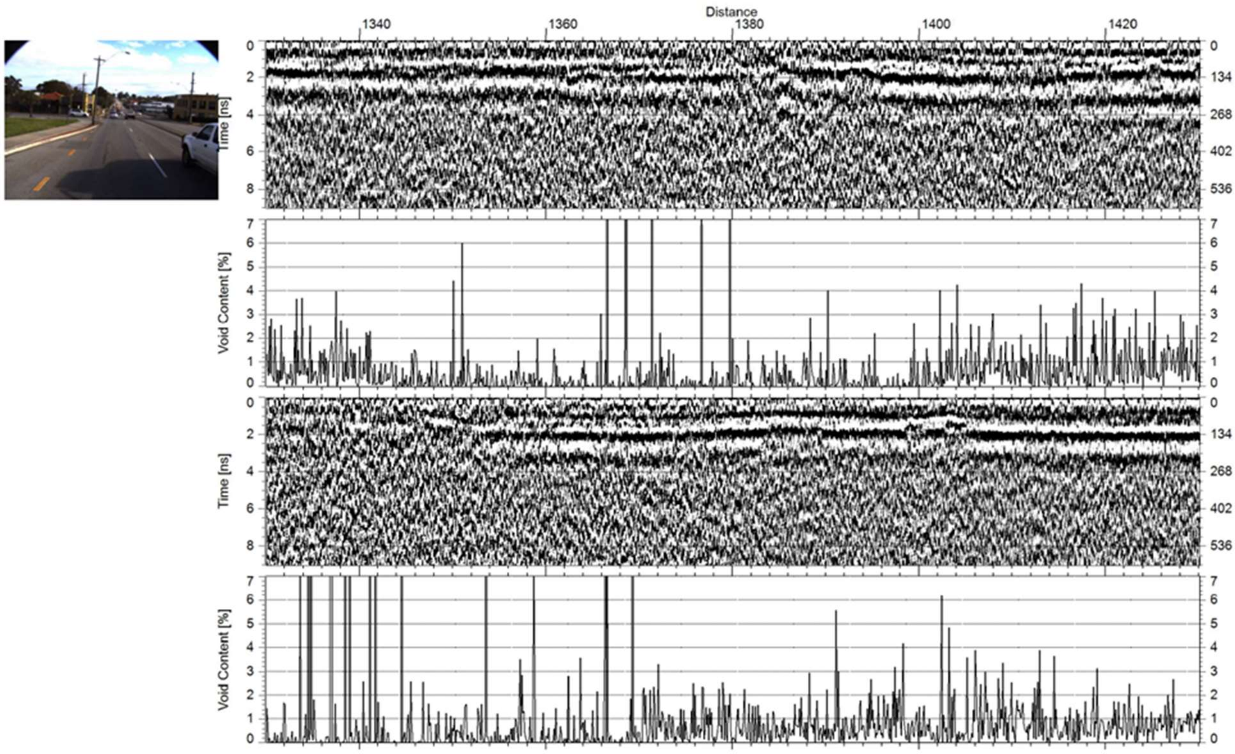



**Figure 4.19: Radargram of Canning Highway: southbound, slow lane with voids content**




The layer thicknesses are shown in Figure 4.20 to Figure 4.22.

**Figure 4.20: Layer thickness – Canning Highway: northbound, fast lane (LWP & RWP)**

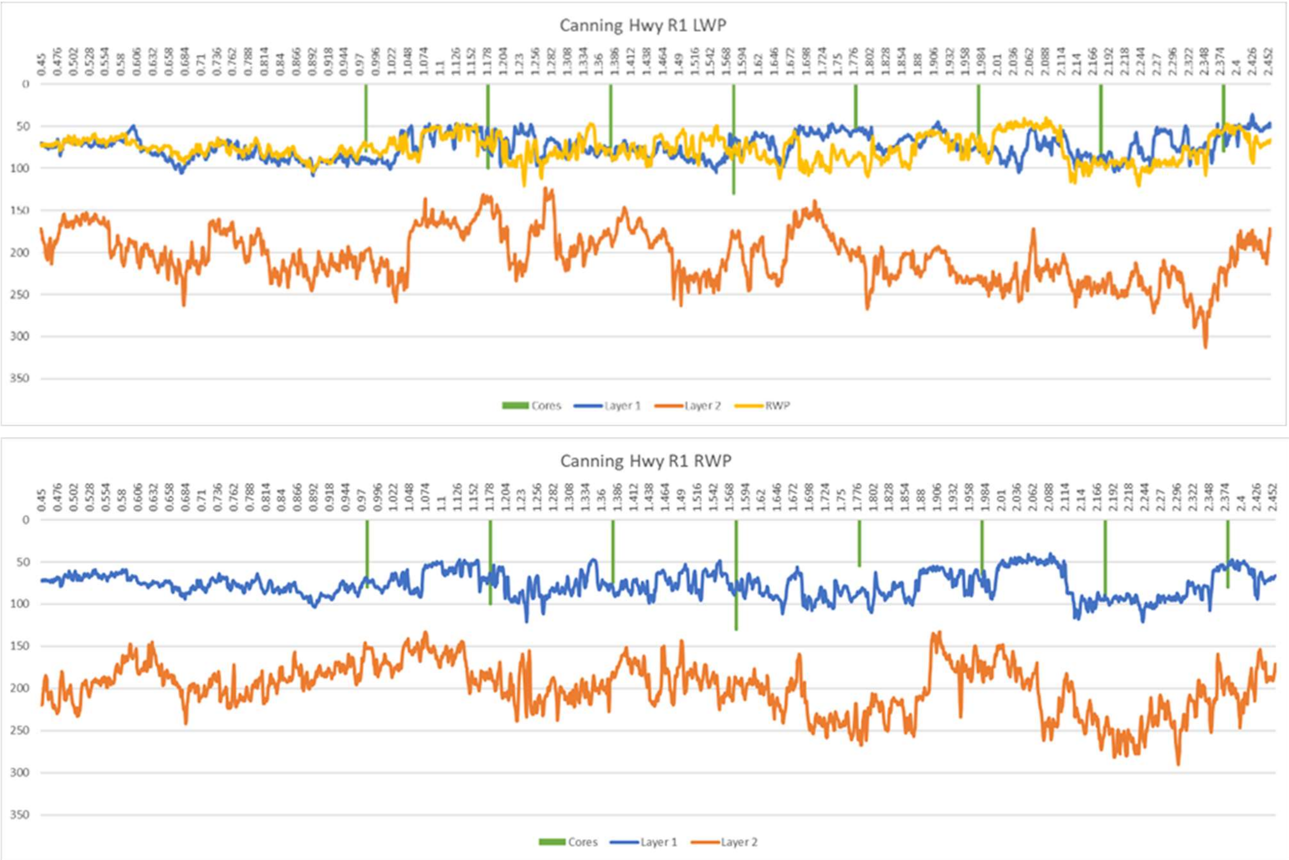



**Figure 4.21: Layer thickness – Canning Highway: northbound, slow lane (LWP & RWP)**

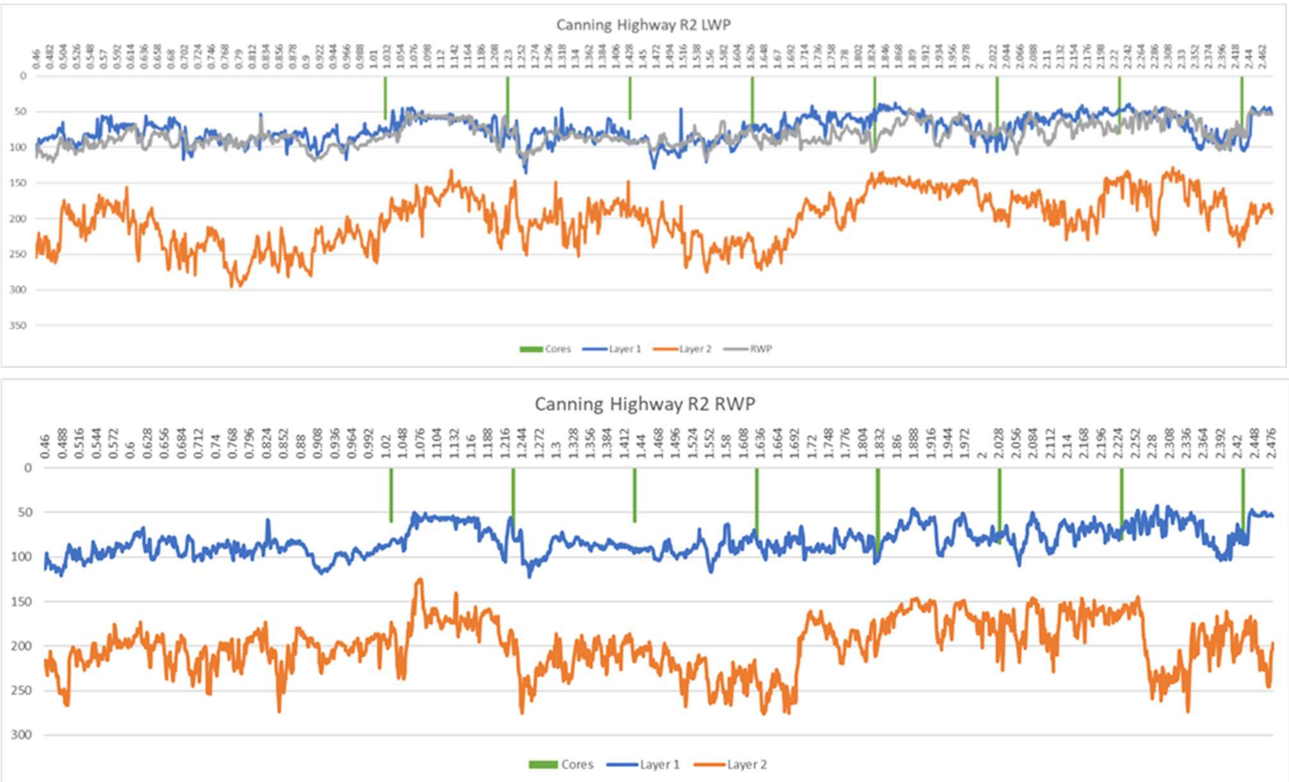
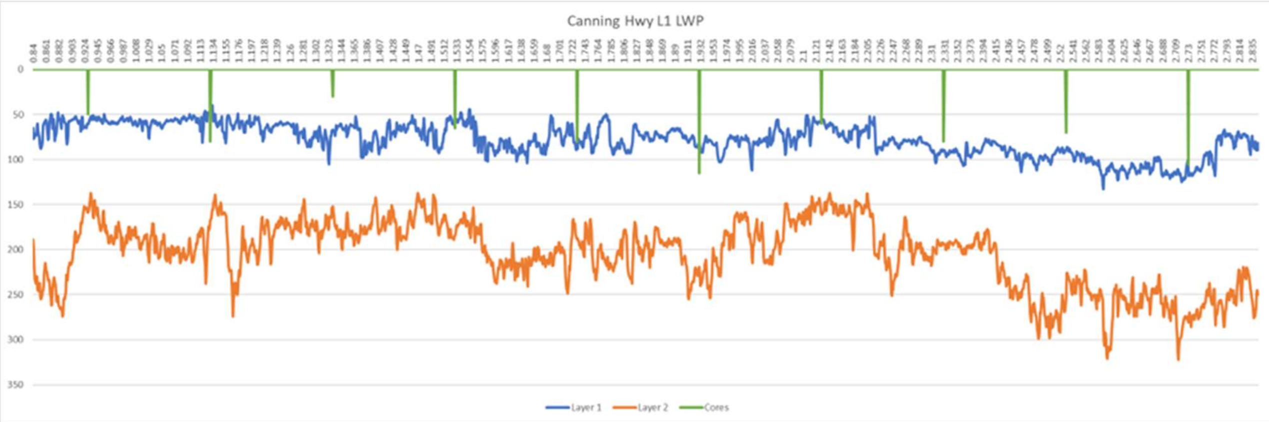
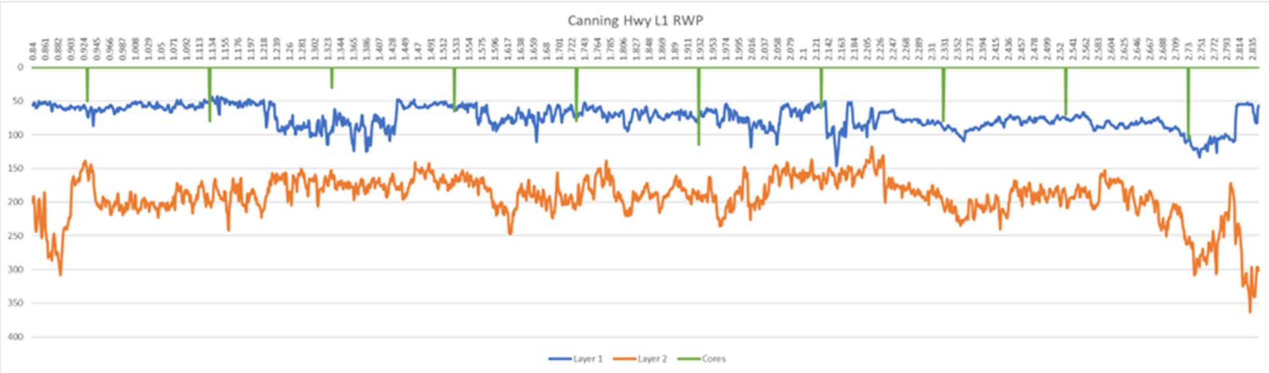


Figure 4.22: Layer thickness – Canning Highway: southbound, fast lane (LWP & RWP)




## 4.5 Comparison of Mitchell Freeway GPR Surveys

### 4.5.1 Comparison of Contractor A and Contractor B Interpretations

Table 4.6 summarises the findings of the Contractor A and Contractor B GPR surveys along a section of the Mitchell Freeway.

Table 4.6: Comparison of Contractor A and Contractor B GPR surveys

| Factors | Contractor A | Contractor B |
|---|---|---|
| Purpose of the survey | To determine pavement layer thickness | To determine pavement layer thicknesses |
| Survey date | 3 July 2021 | 11 September 2021 |
| Survey location | Mitchel Freeway southbound (SLK 13 to 26) | same section as surveyed by Contractor A with extended length |
| Section length | 33.5 km | 39 km |
| coverage | Both wheelpaths (i.e. IWP/RWP & OWP/LWP) | Both wheelpaths (RWP/IWP & LWP/OWP) |
| Core data (previously drilled) | 74 cores | 74 cores |
| Survey method | Each lane was collected separately | Each lane was collected separately |
| Road condition at the time of survey | Dry condition (night work) | Dry condition |
| Speed of survey vehicle | Normal traffic speed | Normal traffic speed |
| Data collection interval | 10 scans/m | 10 m |
| Distance measuring device | Wheel mounted encoder, Xnav IMU GPS | GPS, DMI |
| GPR equipment used | GSSI SIR30 system, 1 GHz (horn antenna), 900 MHz & 1.5 GHz (ground-coupled antennae) | RD Camlink system GSSI SIR30, 2 GHz (air-horn) |
| Software used for interpretation | Not provided | Road Doctor |
| Layers located | 3 (4 at places) | 3 (4 at places) |

The comparison of the Contractor A and Contractor B surveys for the Mitchell Freeway can be summarised as follows:

- The Contractor A survey showed overall uniform thickness between the lanes and no significant evidence of significant thickness changes due to widening. Lanes 1 and 3 behaved the same way and had similar pavement profiles with signs of thickness changes throughout.
- Three layers were generally identified by the Contractor A survey, with the occasional fourth layer. There is a possibility that the thickness of the surface layer in lane 1 was lower between chainages 9,000 m and 10,500 m. The thickness of the surface layer varied between 30 mm and 200 mm.
- Contractor A also surveyed the pavement on the bridge. The concrete reinforcement in the bridges possibly absorbed the GPR signals, making it harder to interpret the data accurately. Contractor B did not provide any interpretation related to the bridge section.
- Contractor B provided layer thickness data in Excel spreadsheets and radargrams throughout the project length. However, the report did not provide any data analysis and interpretation.
- Contractor A used three antennae frequencies: a horn antenna of 1 GHz and ground-coupled antennae of 900 MHz and 1.5 GHz which are consistent with the findings of the literature review in terms of GPR implementation on pavements. The higher the frequency, the higher the resolution (i.e. better presentation of depth). Moreover, ground-coupled antennae are generally believed to be more effective because subsurface reflections are enhanced, leading to greater penetration depth.
- The reported penetration depth of the GPR signals of 1 m for the Contractor A survey and the high correlation with the core data supports the appropriateness of the frequency used for the pavement layer thickness tracking. Contractor B used only the horn antenna with 2 GHz frequency.
- Lane convention – Contractor A used R1, R2 and R3 and Contractor B used FL, ML and SL for different lanes respectively. R3 in Contractor A GPR data indicates the third lane wherever present. Contractor B, on the other hand, used SL the entire time so their ML and SL overlapped where there were two lanes present. This could have been due to closure of lanes for road maintenance and/or rehabilitation works. Contractor A and Contractor B undertook the GPR surveys at different times and the lane configuration would have been slightly different due to changing road works on the freeway.

### 4.5.2 Correlation of GPR Results with Cores

Main Roads provided core data that represents the in situ thickness of the asphalt layer for correlation with GPR survey results for the Mitchell Freeway. The core data did not specify the core locations with reference to wheelpaths. However, considering common practice in core drilling on pavements and following discussions with Main Roads, it is understood that the cores were not drilled exactly on the wheelpaths due to safety considerations. However, they were drilled on the same lanes where the GPR survey was carried out and close to the LWP and RWP targeting cracked areas (if any).

Due to the uncertainty in the core locations and the variable layer thicknesses recorded in the GPR surveys on both wheelpaths, it was not possible to conduct a direct thickness correlation.

Note that the cores were drilled a year before the GPR survey was performed and the intent of the core drilling was to establish asphalt milling depth; therefore, only asphalt layers were cored. The thicknesses of the lower pavement layers (i.e. basecourse and subbase) were not confirmed by coring; therefore, no data was available for correlation with the GPR layer thickness measurements for the lower pavement layers.

Table 4.7 shows the correlation of the Contractor A and Contractor B layer thickness measurements through GPR survey with cores on the slow and fast lanes.

**Table 4.7: Correlation of Contractor A and Contractor B layer thickness measurements with core data**

| Contractor A asphalt layer thickness – Fast lane (R1) | | | | Contractor B asphalt layer thickness – Fast lane | | Contractor A asphalt layer thickness – Slow lane (R2) | | | | Contractor B asphalt layer thickness – Slow lane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SLK | Core (mm) | IWP (mm) | OWP (mm) | RWP (mm) | LWP (mm) | SLK | Core (mm) | IWP (mm) | OWP (mm) | RWP (mm) | LWP (mm) |
| 26 | 70 | 93 | 103 | 52 | 50 | 26 | 60 | 81 | 79 | 43 | 35 |
| 25.6 | 70 | 48 | 169 | 56 | 55 | 25.9 | 70 | 82 | 117 | 44 | 38 |
| 25.3 | 55 | 52 | 79 | 59 | 56 | 25.8 | 55 | 106 | 95 | 45 | 39 |
| 25.1 | 40 | 55 | 61 | 59 | 57 | 25.7 | 60 | 86 | 132 | 46 | 40 |
| 25 | 50 | 57 | 54 | 60 | 57 | 25.6 | 60 | 84 | 93 | 47 | 40 |
| 24.7 | 60 | 63 | 49 | 61 | 58 | 25.5 | 60 | 141 | 155 | 47 | 40 |
| 24.5 | 50 | 65 | 64 | 62 | 59 | 25 | 60 | 131 | 58 | 50 | 42 |
| 24.3 | 60 | 68 | 66 | 63 | 60 | 24.6 | 50 | 135 | 47 | 52 | 43 |
| 24.2 | 65 | 69 | 71 | 63 | 60 | 24.4 | 50 | 119 | 81 | 53 | 44 |
| 24 | 55 | 71 | 65 | 64 | 61 | 24.1 | 55 | 92 | 77 | 55 | 46 |
| 23.8 | 60 | 72 | 76 | 64 | 62 | 23.9 | 60 | 127 | 138 | 55 | 48 |
| 23.6 | 60 | 73 | 75 | 65 | 62 | 23.7 | 60 | 127 | 141 | 56 | 50 |
| 23.3 | 70 | 75 | 70 | 66 | 63 | 23.4 | 70 | 67 | 65 | 57 | 52 |
| 23.1 | 60 | 75 | 71 | 67 | 64 | 23.2 | 60 | 96 | 59 | 58 | 53 |
| 22.7 | 55 | 77 | 81 | 69 | 65 | 22.9 | 60 | 61 | 59 | 59 | 54 |
| 22.5 | 60 | 77 | 79 | 69 | 65 | 22.8 | 60 | 73 | 61 | 59 | 55 |
| 22.3 | 50 | 79 | 68 | 70 | 66 | 22.4 | 60 | 101 | 43 | 61 | 57 |
| 22 | 65 | 80 | 66 | 71 | 67 | 22.2 | 60 | 117 | 65 | 61 | 57 |
| 21.8 | 65 | 82 | 79 | 72 | 67 | 21.9 | 70 | 65 | 77 | 62 | 58 |
| 21.6 | 50 | 83 | 90 | 73 | 68 | 21.7 | 65 | 90 | 89 | 63 | 59 |
| 21.4 | 65 | 84 | 71 | 74 | 68 | 21.5 | 65 | 67 | 78 | 63 | 60 |
| 21.1 | 60 | 86 | 73 | 75 | 69 | 21.3 | 60 | 121 | 127 | 64 | 61 |
| 20.8 | 55 | 87 | 70 | 76 | 70 | 21.2 | 60 | 124 | 126 | 65 | 61 |
| 20.6 | 55 | 88 | 83 | 76 | 71 | 20.8 | 65 | 84 | 94 | 66 | 63 |
| 20.4 | 55 | 89 | 66 | 77 | 71 | 20.7 | 65 | 97 | 100 | 66 | 63 |
| 19.9 | 60 | 93 | 43 | 78 | 73 | 20.5 | 65 | 109 | 122 | 66 | 64 |
| 19.7 | 50 | 94 | 97 | 78 | 74 | 20.3 | 75 | 103 | 55 | 67 | 64 |

| Contractor A asphalt layer thickness – Fast lane (R1) | | | | Contractor B asphalt layer thickness – Fast lane | | Contractor A asphalt layer thickness – Slow lane (R2) | | | | Contractor B asphalt layer thickness – Slow lane | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.4 | 60 | 96 | 73 | 79 | 75 | 20 | 85 | 120 | 128 | 68 | 65 |
| 19.2 | 75 | 97 | 73 | 80 | 76 | 19.6 | 45 | 52 | 70 | 69 | 66 |
| 19 | 60 | 98 | 83 | 80 | 77 | 19.5 | 40 | 71 | 83 | 69 | 66 |
| 18.8 | 65 | 100 | 87 | 81 | 78 | 19.3 | 55 | 55 | 76 | 70 | 67 |
| 18.6 | 65 | 101 | 108 | 81 | 78 | 19.1 | 70 | 58 | 72 | 70 | 67 |
| 18.4 | 65 | 102 | 79 | 82 | 79 | 18.7 | 65 | 70 | 85 | 71 | 68 |
| 18.2 | 65 | 103 | 64 | 82 | 80 | 18.5 | 75 | 105 | 102 | 72 | 69 |
| 18 | 60 | 105 | 65 | 82 | 80 | 18.3 | 60 | 95 | 86 | 73 | 70 |
| | | | | | | 18 | 60 | 54 | 75 | 73 | 71 |
| | | | | | | 17.9 | 60 | 111 | 63 | 74 | 71 |

Notes:

- Cores were drilled close to the LWP on R2 and RWP on R1 targeting cracked areas (if any).
- Contractor B did not provide calibrated data, the core data correlated in Table 3.2 indicates the nearest location within ±0.005 SLK.

Key: IWP: Inner wheelpath, OWP: Outer wheelpath, LWP: Left wheelpath, RWP: Right wheelpath, SLK: Straight line kilometres.

Figure 4.23 and Figure 4.24 show the correlation of Contractor A measured asphalt layer thicknesses through GPR survey with cores in the fast lane and slow lane respectively on both the inner and outer wheelpaths.

**Figure 4.23: Contractor A GPR survey correlation with cores – fast lane (R1 IWP & OWP)**

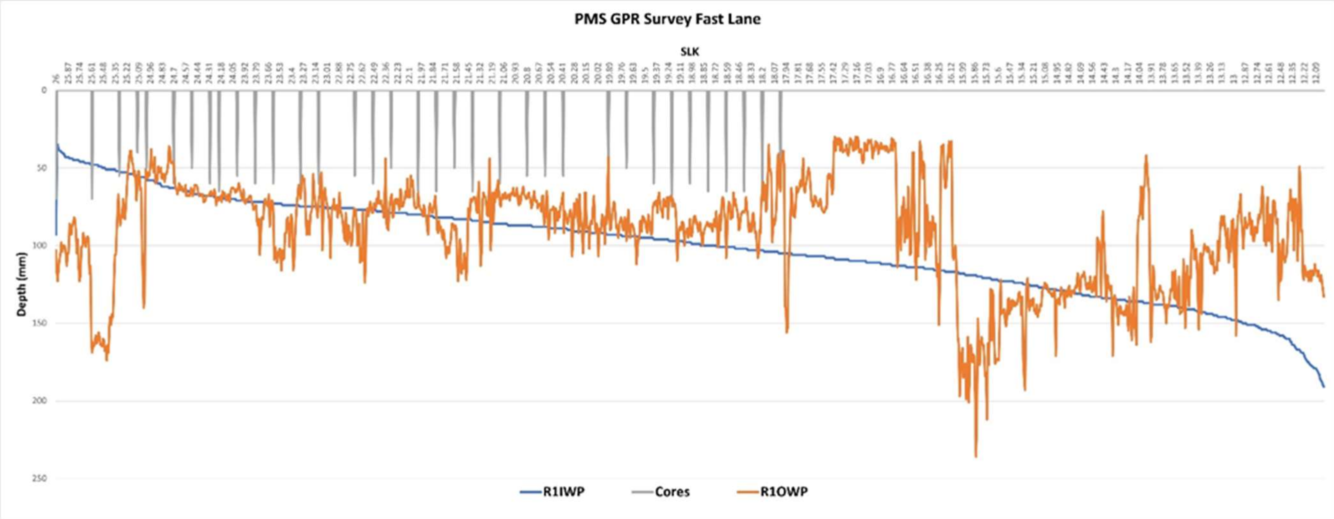



**Figure 4.24 Contractor A GPR survey correlation with cores – slow lane (R2 IWP & OWP)**

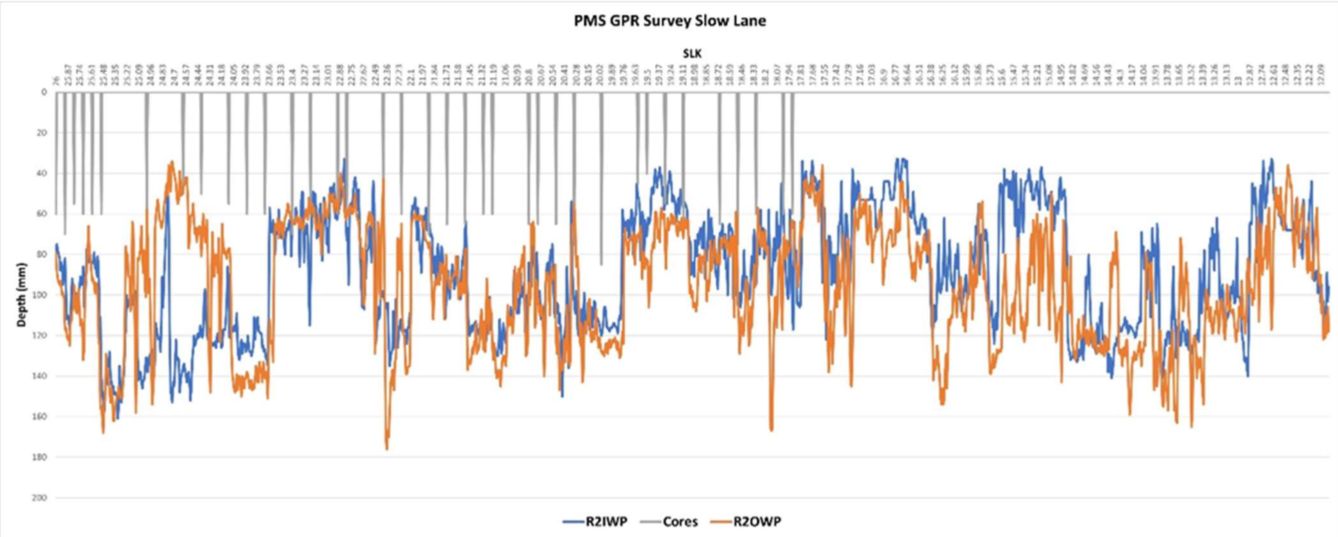



Figure 4.25 and Figure 4.26 show the correlation of Contractor B measured asphalt layer thicknesses through GPR survey with cores in the fast lane and slow lane respectively on both the inner and outer wheelpaths.

**Figure 4.25: Contractor B GPR survey correlation with cores – fast lane (R1 IWP & OWP)**

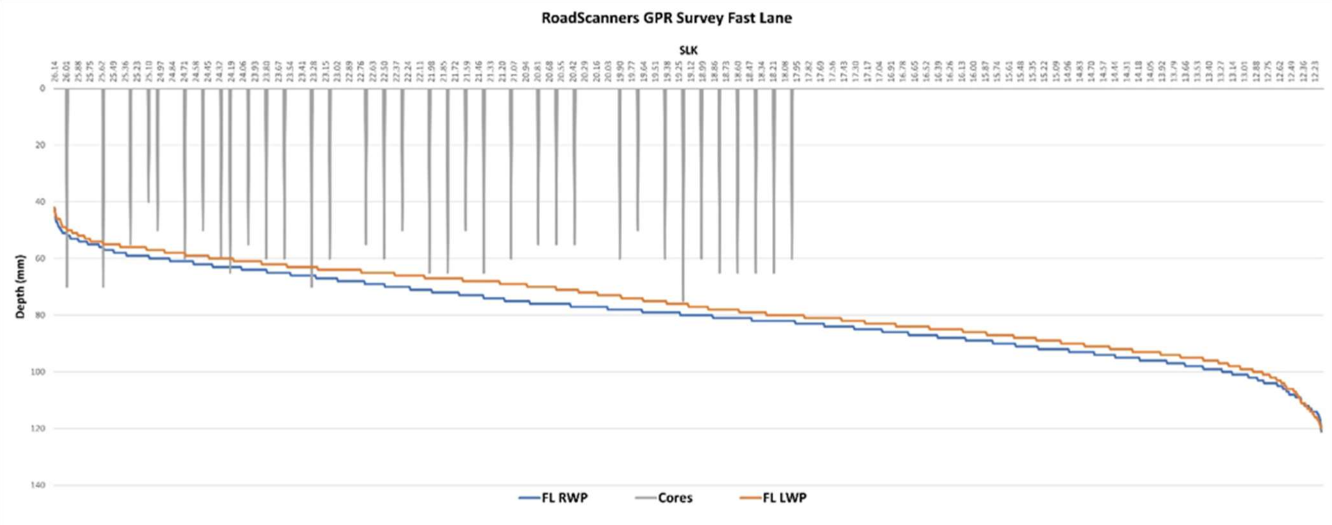
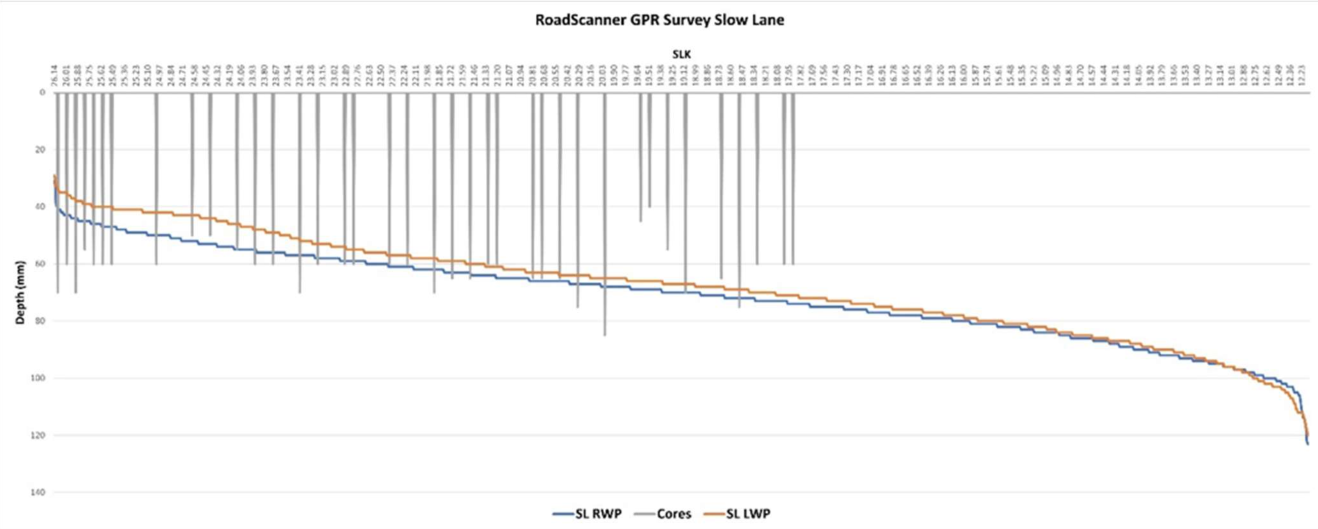



**Figure 4.26: Contractor B GPR survey correlation with cores – slow lane (R2 IWP & OWP)**




Generally, there was a good correlation between the GPR-measured layer thicknesses and the cores thicknesses. Overall, the Contractor B GPR results showed a better correlation with the core data compared to the Contractor A GPR results.

As the GPR survey was only intended to establish asphalt milling depth, only layer thicknesses were tracked. The GPR survey did not provide any information related to high moisture areas, voids and pavement distress, whilst Contractor B also provided voids content data. The GPR capability for conducting pavement investigations could not be evaluated without data related to these attributes.

## 4.6 Key Findings

Key findings of the evaluation of the GPR survey results provided by Main Roads can be summarised as follows:

- The evaluation of the data provides insights into the capability and limitations of GPR. The outcome of this evaluation will provide Main Roads with the opportunity to better plan and optimise the potential GPR field trials in the next stage of the project.
- The location data (GPR coordinates, SLK and chainages) have accuracy issues such as the different SLK values used by different contractors. Moreover, the selection of the locations of the cores in the fast and slow lanes was based on localised pavement conditions (i.e. occurrence of cracking and to keep the operator away from the live traffic). This led to location discrepancy and uncertainty related to the exact core location, making correlation difficult or invalid.

- The coring was carried out prior to the GPR survey. It would be preferable if the GPR survey was carried out prior to coring at target locations to acquire in situ layer thickness information at critical locations. For instance, the GPR data showed layer thickness changes at certain locations (e.g. Contractor A survey for Mitchell Freeway – first layer at 10,500 m in outer wheelpath). These specific locations could be cored to confirm the thickness change and reduce the costs of the geotechnical investigation.
- The GPR radargrams of the Mitchell Freeway provided by both contractors showed pavement layer interfaces and change in construction with a reasonable degree of accuracy.
- For the assessment of GPR capability for pavement investigation, the layer thickness, high moisture areas, voids, pavement distress (e.g. asphalt layer delamination, stripping) should be measured and compared with laboratory testing and in situ testing at critical locations.
- Bridge inspections should be conducted at lower speeds (generally between 30 to 40 km/h) to better interpret pavement thickness profiles.
- Lessons learned from the GPR data evaluation are as follows:
  - GPR surveys and coring for the correlation and validation of results must be planned as a single project. The location information of the core samples and the GPR readings must be in the same location system preferably measured with high-accuracy GPR.
  - Ideally, coring should be undertaken in the same wheelpaths where the GPR survey is carried out.
  - GPR data interpretation should be carried out by a qualified professional – ideally a professional pavement engineer or practitioner.

# 5 Conclusions

Ground penetrating radar (GPR) surveys have the potential to provide a continuous imagery of the subsurface, including pavement layer thickness, air voids, variability in the pavement configuration across the section length and the location of high moisture contents, etc. The major benefit associated with GPR investigations is that it is a non-destructive test that generates a continuous subsurface profile which can be compared with the discontinuous snapshots of the subsurface profiles obtained from destructive geotechnical investigations such as coring and trenching.

Current GPR technology supports the data collection at traffic speeds of 80–100 km/h. The introduction of this technology on the Western Australian road network will provide an opportunity for Main Roads to incur lower costs compared with destructive pavement investigations, reduced traffic disruptions, and an improved quality of work through the adoption of more efficient pavement rehabilitation treatment designs.

It was found that the major benefit of implementing GPR for pavement investigations is the acquisition of continuous images of the subsurface at traffic speeds using non-destructive testing. Dipole antennae are appropriate for project-level studies as they remain in contact with the ground and can be operated at a speed of 40–60 km/h. On the other hand, the horn antennae are vehicle-mounted and can generally be operated at a speed of 80–120 km/h. The selection of antennae frequency controls the penetration depth and the resolution of the subsurface image or radargram. As a wide range of antennae frequencies are available (generally between 10 MHz and 6 GHz), it is critical to consider the project's objectives and deliverables when selecting the appropriate antennae frequency so that the GPR survey meets the specific requirements of the project.

The ability of GPR to perform surveys and interpret the acquired data is dependent on a large number of factors, including material properties, the type of GPR equipment (antennae frequency, processing unit and software), and the skills of the interpreter. Pavement layer thickness, voids and distress in asphalt pavements (i.e. stripping, delamination and cracking) can often be detected with a high level of confidence if the appropriate equipment is used and the contrast in the dielectric constants of the materials is favourable. Major challenges, in terms of delineating different layers, include contamination of materials at the layer interfaces (e.g. basecourse and subbase) and moisture detection in the case of fine-grained clays. Generally, moisture is easily detectable in dry and saturated materials, but it can be difficult to detect in the middle conditions. Experienced GPR contractors have reported that moisture detection can be improved if low-frequency antennae are used and testing is conducted at low to moderate testing speed (e.g. 400 MHz frequency at 50 km/h).

Table 5.1 summarises the suggested antenna frequencies for pavement investigation based on the literature review, market survey and analysis of the Main Roads GPR data.

**Table 5.1: Suggested antenna frequencies for pavement investigation**

| Pavement investigation | Suggested frequency |
|---|---|
| Geological investigation underneath the road embankment | 100–250 MHz |
| Road embankment and subgrade investigation | 450 MHz–2.0 GHz |
| Pavement profile (layer delineation) | 450 MHz–1.0 GHz |
| Asphalt layer delineation | 1.2–2.3 GHz |
| Top asphalt layer thickness determination | 1.0–2.3 GHz |
| Moisture detection | 400 MHz–2.3 GHz |

Notes:

- A range of frequencies are suggested as there is no single frequency which is considered appropriate for GPR investigation.
- Most of the GPR surveys for pavements are carried out using multiple antennae frequencies.

Although the accuracy of GPR depends on several factors, it can be improved by correlating with geotechnical data. The literature review suggested that the error of around 5% without correlation can be reduced to as low as 2% with correlation (noting that various other factors also affect accuracy).

GPR data can be used by pavement engineers and practitioners to make more informed decisions and to optimise geotechnical investigations. The use of GPR is quite limited across all Australian state transport agencies, including Main Roads. However, some US road agencies have integrated GPR surveys into their pavement management systems to enhance project- and network-level decision making. Main Roads could consider integrating GPR data with TSD data to enhance project- and network-level decision making.

The limitation of GPR include high survey and interpretation costs depending on the nature of the project (i.e. difficulty of interpretation, presence of unfavourable materials (e.g. moisture detection in fine clay, attenuation of signals in aggregates having high iron content)). For network level surveys, it can be challenging, and costly, to manage and integrate large datasets as interpretations may require a large number of manhours. The interpretation of GPR data also requires a knowledge of pavement engineering. Currently it cannot be considered as a replacement for traditional testing methods in Australia due to these limitations.

For the best value-for-money outcome, Main Roads needs to have a clear understanding of the project objectives, desired accuracy levels and deliverables from the project inception stage. Potential challenges for Main Roads in GPR implementation are the availability of contractors and equipment, the inherent limitations of GPR technology (e.g. frequency, performance in wet weather, speed of testing, accuracy, errors in interpretations, calibration issues and cost), and the lack of skilled personnel to interpret the data.

Lessons learned from this project are:

- The project's objectives and deliverables must be clearly communicated with the GPR contractor at the project inception stage to ensure that the most appropriate equipment is selected to best meet the intended project outcomes.
- GPR survey and coring must be carried out as an integrated project so that the data can be correlated and the results validated. The location information related to core samples and GPR readings must be in the same referencing system and preferably measured with high-accuracy GPR.
- GPR data interpretation should be carried out by a qualified professional with experience in pavement engineering.

# 6 Recommendations

It is recommended that Stage 2 of the project – to conduct field trials to further assess the capability of GPR – proceed by undertaking the following:

- Compare different antennae frequencies and processing software for GPR output.
- Investigate the capability of the GPR and the accuracy of the interpretations to achieve desired results (outcome-focused surveys).
- Compare the conduct of GPR surveys and geotechnical investigations (destructive testing) in terms of costs and the accuracy of the results.

The GPR contractor must be selected based on their previous experience with similar projects. Although GPR technology is not new, not all contractors have experience in interpreting GPR data related to pavements and road infrastructure generally. The contractor should have access to skilled personnel and a range of antennae frequencies and equipment. Project objectives and deliverables must be documented and communicated with the contractor at the project inception stage.

The following checklist is proposed to be included as part of the contract documentation to ensure project objectives are clearly communicated:

- Site selection criteria for the field trials and details related to the trial sites (i.e. location, pavement configuration/structure, construction-related information, pavement condition data and maintenance and rehabilitation history) should be developed.
- A detailed scope of work and guidelines for field trials should be prepared based on project-specific requirements. They should be handed over to the contractor for the selection of appropriate equipment and survey methodology for the best survey outcome. This document must include a list of intended project outcomes and deliverables such as:
  - layer thickness tracking, voids, crack detection, high moisture areas, change of construction details, pavement layer delamination and stripping
  - location details (high-accuracy GPS or using the same referencing system as Main Roads), lane and wheelpath details
  - pavement surface distress observations or any change in pavement along the project length
  - required accuracy level for the outputs
  - speed of testing.
- Main Roads needs to evaluate technical skills of the potential contractor prior to engagement. They should request details of the contractor's GPR equipment, including antennae frequencies, processing units, software for interpretation and interpreter skills and previous experience with GPR interpretations for pavements.
- GPR calibration procedure.
- Coring procedure, including location details and integration of coring data with the GPR data for correlation and enhancing interpretations. Ideally, coring should be carried out after the GPR survey to assist in the selection of core locations to enhance correlation.
- Deliverables such as interpretation report, GPR data (radargrams, Excel files, plots of layer thickness and moisture data) and videos of the survey.
- Main Roads need to consider developing a draft technical specification for the conduct of GPR surveys based on field trials as part of next stage of the project.

Consideration should be given to using ARRB's TSD vehicle fitted with GPR. It would provide an opportunity to investigate the possibility of integrating GPR data with other TSD and pavement condition datasets as a part of a pavement management system for network-level decision making.

Main Roads need to train its staff in GPR surveying and interpretation to assist them to manage GPR projects and utilise results in project- and network-level decision making to ensure value-for-money.

There is a need to develop more user-friendly software which converts GPR data into information which is meaningful to pavement engineers. Main Roads should consider funding an initiative to achieve innovation in GPR technology and improve efficiency in pavement investigations. This could be a national project funded by national road related organisation in collaboration with Australian transport and road agencies.

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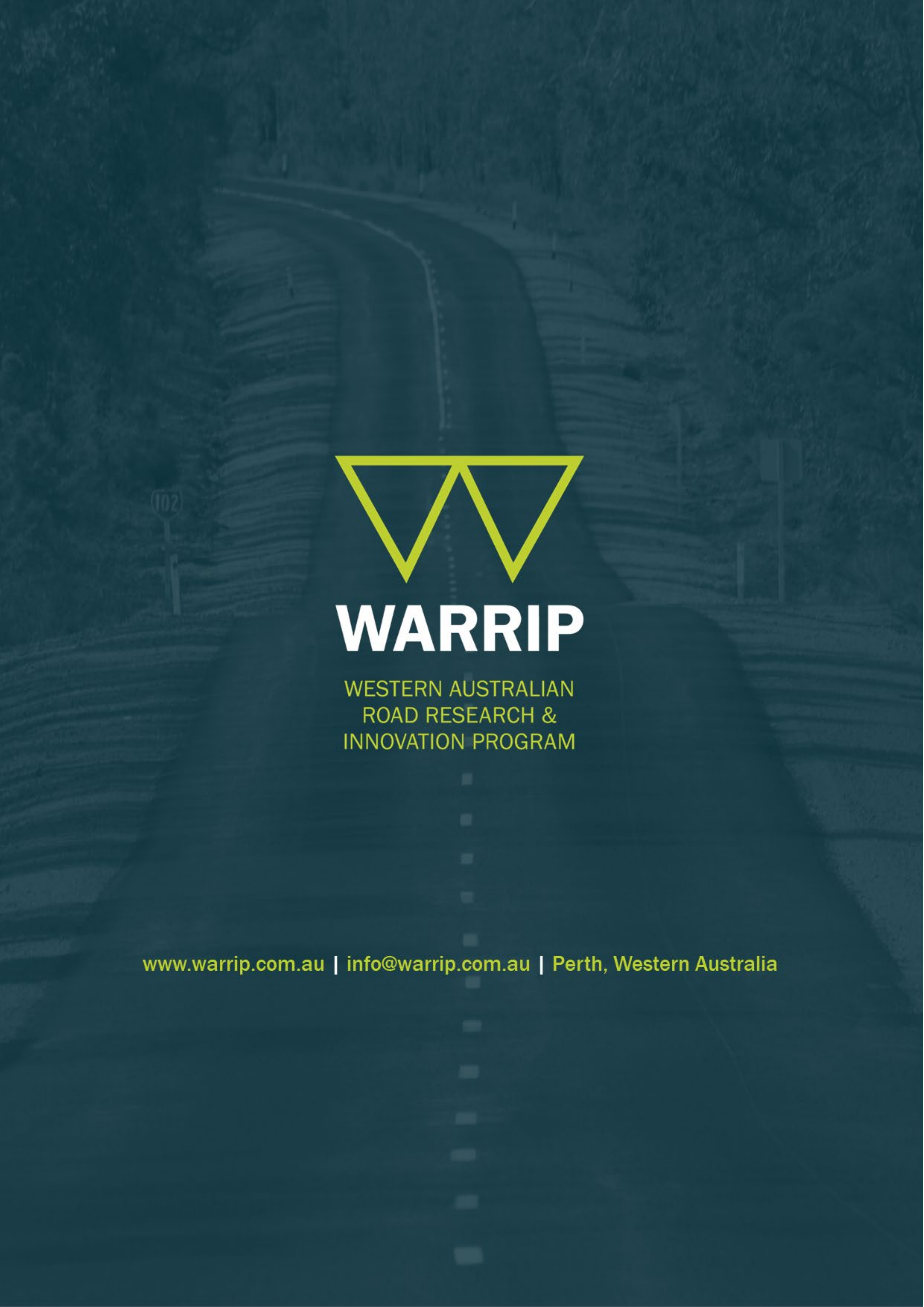

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