NACOE
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ANNUAL SUMMARY REPORT

P105: Implementation of Intelligent Compaction in Queensland – Year 4 (2021–2022)

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Summary

As compaction is critical for the performance of pavement layers, intelligent compaction (IC) is a solution to the rapidly growing need in the road construction industry for faster, more efficient and reliable ways of collecting compaction data, assessing the work during earthworks and pavement construction and giving immediate feedback and indicative information to the roller operator, supervisors, project managers and road engineers to make informed decisions.

This NACOE project commenced in the 2018–19 financial year to facilitate the implementation of IC technology in Queensland. A comprehensive literature review was undertaken during the first year to evaluate the potential benefits of such technology for the Queensland Department of Transport and Main Roads (TMR) and the wider road construction industry.

Year 2 (2019–20 FY) focused on the development of a pilot project-specific technical specification which was successfully trialled on the Ipswich Motorway Upgrade project where the IC technology was trialled on different materials. The study showed that the compaction meter value (CMV) has varying degrees of correlation against the in situ stiffness measured by light weight deflectometer (LWD) and conventional density results (measured by a nuclear density gauge). It was also noted that the CMV is sensitive to in situ moisture conditions during construction. The project funded the Veta program to support the latest GDA2020 system, which became the main cadastral grid to be used across different jurisdictions in Australia.

In year 3 (2020–21 FY), the priority was to disseminate the knowledge and local experience on IC technology and promote its benefits. While monitoring the demonstration field trials, different levels of training were developed to share the knowledge and practical findings. To better illustrate the benefits of IC technology, a benefit-cost analysis was undertaken to cover the impact/difference of using IC.

In the current financial year, the focus of the project was to trial the use of IC technology for asphalt layers. After gaining some experience on a few small projects, an asphalt rehabilitation project was chosen to be delivered as an intelligent compaction project. Pre-mapping was also practiced as it is seen as one of the major benefits of using IC technology for asphalt projects (in identifying weak support areas prior to the paving of the hot mix asphalt overlay). The work provided the opportunity to understand the requirements and details of how the road agencies can monitor, oversee, quality control and accept an asphalt project and what are the required area of work in terms of specifications, technical standards and contracts. Results also showed that for the asphalt layer, the intelligent compaction meter value (ICMV) is dependent

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on the temperature of the asphalt materials. Along with the other major findings, the IC demonstrations have provided a wealth of information and knowledge to share with the industry in order to accelerate the implementation of IC technology. Thus, information sessions and webinars were held and a training session of 2 half-days was organised to share the experience and knowledge.

This report is the summary of the activities undertaken during year 4 (2021–22 FY) of the project, particularly describing the TMR IC demonstration for hot mix asphalt materials in Queensland.

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1 Introduction

1.1 Background

Adequate compaction is critical for ensuring the long-term performance of pavement layers and earthworks. Current density measurement methods are costly and, more importantly, can be time consuming and the cause of delay for projects. As these current methods have their own constraints and limited number of test points can only be done on each project, they might not be a true representation of the work for which they are measuring. Pavement cores and sand replacement samples used for density testing are intrusive and time-consuming methods that provide limited coverage, whereas nuclear density gauge testing has associated health and safety risks.

Intelligent compaction (IC) is an equipment-based technology used to improve the quality control of compaction. IC vibratory rollers are equipped with a high-precision global positioning system (GPS), infrared temperature sensors, an accelerometer-based measurement system and an onboard colour-coded display. IC is used to improve compaction control for various pavement materials including granular and clayey soils, subbase materials and asphalt materials. The accelerometer-based measurement system is a core IC technology that was invented in the early 80s and is still evolving today (Federal Highway Administration (FHWA) (2017c) Technical Brief – *Intelligent Compaction Measurement Values* (*ICMV): A Road Map*).

IC rollers facilitate real-time compaction monitoring and timely adjustments to the compaction process by integrating measurement, documentation and control systems. These rollers also maintain a continuous record of the number of roller passes and material stiffness measurements that are conveniently displayed on colour-coded maps of the project site. Over the last decade, this technology has gained popularity around the world and has been shown to improve construction quality and productivity (https://www.intelligentconstruction.com).

IC can provide important and immediate roller operating parameters to the operator (in the form of a visual map) to ensure that pavement layers and earthworks are compacted uniformly and in accordance with appropriate standards. IC data can also be uploaded and stored online for archiving and remote-monitoring purposes. in last years, this technology reached the level of acceptance that can be confidently used for the benefit of road users, road agents and other industry partners. Figure 1.1 shows the recent use of IC rollers for an asphalt project.

Figure 1.1: Intelligent compaction rollers – asphalt work

IC technology is a game changer that significantly increases the level of detail on the pavement layer while it is compacted. This important information on compaction is used for different purposes such as work monitoring, quality control onsite and quality assurance for work conformance and acceptance by providing on-the-fly feedback and details on compaction which helps to:

- improve construction efficiency (by having real-time data collection)
- increase the quality of pavement construction by achieving consistency and compaction uniformity of the final work
- avoid under-compaction (leading to less respective defects and longer lasting pavement layers)
- avoid over-compaction for asphalt layers (increasing the productivity and achieving better performance by preventing unnecessary works and excessive efforts after completion of compaction
- prevent reworks after getting the test results
- make savings for contractors by avoiding penalties (as the work output is determined during construction)
- overcome issues with limited amount of testing (and increase the reliability of the information)
- provide accurate and unlimited construction records for a wide range of measurements.

1.2 Project History

The National Asset Centre of Excellence (NACOE) is working on implementing the use of intelligent compaction technology as an innovative way for monitoring purposes to improve the quality and quality assurance of compaction works. The project also helps establishing the technology, localising the experience and disseminating the knowledge within the industry which improves construction consistency and quality, increases productivity and reliability of work for the benefit of road users, road agents and other industry partners.

NACOE project P105, *Implementation of Intelligent Compaction (IC) in Queensland* has been investigating the hardware and software requirements for implementing IC in Queensland, as well as transferring international knowledge and experience to the local industry. A new pilot specification for the use of IC in road pavement construction has been developed as part of the project. In addition, the project is also identifying and quantifying the costs and direct and indirect benefits of this innovative technology, as well as developing technical specifications and training materials to facilitate future rollouts.

Since the beginning of the P105 project (in January 2019), Australia has significantly increased its awareness of IC technology and the associated benefits when adopted in transport infrastructure projects. A comprehensive literature review was undertaken during the first year (Fatahi et al. 2019; Zargar & Lee 2019) to evaluate the potential benefits of such technology for the Queensland Department of Transport and Main Roads (TMR) and the wider road construction industry. A summary of existing IC specifications adopted in Europe and the USA was presented, which may serve as references for the development of Australian specifications on the use of IC. Additionally, an Intelligent Compaction Data Management workshop was undertaken with a recognised international expert in IC technology in year one.

Year 2 (2019–20 FY) focused on the development of a pilot project-specific technical specification for use in demonstration trials (PSTS116 for demonstration trial). The specification was successfully trialled on the Ipswich Motorway Upgrade Stage 1 (Rocklea to Darra, R2D) project where the IC technology was used on different materials compacted as part of the project including embankment fill, subgrade, cement modified base and unbound granular base. It was found that IC technology can readily identify soft areas in a pavement or embankment and can also be used to improve the uniformity of the compacted layers.

The study showed that the compaction meter value (CMV) has varying degrees of correlation against the in situ stiffness (measured by a light weight deflectometer (LWD)) and conventional density results (measured by a nuclear density gauge). It was also noted that the CMV is sensitive to in situ moisture conditions during construction. The team delivered an online webinar to disseminate the results and findings from the demonstration trial. The Australian flexible Pavement Association (AfPA, AAPA at the time) also delivered a virtual masterclass, providing additional training on the use of the latest IC data management software, Veta (version 6.0 at the time), and the project has funded the Veta package to support the latest GDA2020 system, which became the main cadastral grid to be used across different jurisdictions in Australia.

In Year 3 (2020–21 FY), the priority was to disseminate the knowledge and local experience on IC technology and promote its benefits. While monitoring the demonstration field trials and planning for more trials with different materials, different levels of training were developed to share the knowledge and practical findings from field trials. To better illustrate the benefits of IC technology, a benefit-cost analysis was undertaken to understand the impact/difference of using IC.

1.3 Scope of Project

Year 4 of the project (2021–22 FY) focused on trialling the use of IC technology on asphalt layers.

After gaining some experience on a few small projects, a 12-shift rehabilitation work was selected to be treated and delivered as a full-scale intelligent construction project for the purpose of having first-hand experience of all the challenges while assessing the advantages, requirements and costs. Pre-mapping was identified and practiced as one of the major benefits of using IC technology for asphalt projects. The trial provided the opportunity to understand the requirements for utilising IC, demonstrated how the road agencies can monitor, oversee, quality control and accept an asphalt project in which IC technology is used. It also provided a guidance to develop/update the specifications, technical standards and contracts where IC technology is used. It will help to provide an opportunity to develop a checklist for asphalt IC projects.

After applying IC on different pavement materials, to help implement the technology and demonstrate its benefits, the concept of using IC, results of analysis, details of experience and lesson learned were shared in 2 webinars ('Introduction to intelligent compaction', in March 2022 and May 2022) and published as an annual report. Additionally, a training session on more details of the IC concept, data analysis and the use of the Veta software package (with hands-on experience) was held on 23 and 24 June 2022.

1.4 Report Structure

Section 1 of the report is followed by a discussion in Section 2 of the requirements for preparing and implementing an IC project, including checks and practical and operational procedures. Section 3 explains the details of the field demonstration trial and the works carried out onsite. The trial statistics and work analysis results are presented, and outputs of the Veta package are explained and outlined in Section 4 with the findings from the operation (including improvements due to the use of IC technology). In Section 5, the activities and the work undertaken for knowledge transfer are listed, and Section 6 presents the conclusions, lesson learned and recommendations.

2 Preparation and Requirements

The trial undertaken in Year 4 of P105 was treated as if it was an IC project to be delivered to TMR. The aim of the trial was to experience the impact of IC technology, increase confidence in its use and encourage more trials while producing a close-to-reality estimation of the cost and benefits and moving towards the next stages of implementation including drafting technical notes, specifications and improvements and customising the requirements etc. for Queensland.

The project team identified a few grey areas for the use of IC technology, particularly for asphalt works and, therefore, decided to start looking at these areas as part of pre-trial projects to get familiar before carrying out to the main trial project. This includes the processes, knowledge about equipment used and implementation of IC, etc. In doing so, a couple of smaller projects were selected to obtain more knowledge and experience in a practical and operational environment, particularly in the areas where there were some lack of knowledge or there was no certain process to carry out the task. These earlier works as pre-trial project were also great opportunities to get certainty around different sides of requirements and get ready for the trial. With that approach, the trial could be a full-scale work, not just part of a project.

The projects selected for the preparation purpose were:

- Pine Mountain Road, North Ipswich
- Main Road, Wellington Point.

The project team reviewed the whole project to look at all aspects from different angles (as much as possible). To manage the preparation phase, the basic requirements for carrying out an IC project are listed and explained in the rest of this section.

In the following sections of this chapter, the requirements for an IC project (requirements to carry out the intelligent compaction on a road project) are listed and described.

2.1 Required Hardware

The minimum requirements defined for IC practices dictates the machinery, technology and devices required to guarantee the adequacy and required accuracy and consistency (compatibility) of the data. These requirements are presented in Table 2.1.

Table 2.1: Required instrumented roller equipment for IC practices

Specification	Description	Instrumented rollers	GNSS *	Accelerometer	Temp. sensor	Modem or Wi-Fi	Onboard documentation system
Embankment & reclamation	Self-propelled, vibratory: Smooth, single-drum steel Smooth, double-drum steel Pad (sheep's) foot	Required	Required	Required	None	Required	Required
Embankment & reclamation	Self-propelled, pneumatic roller			None	None		
Asphalt pavement	Self-propelled, vibratory: Smooth, double-drum steel			Required	Required		
Asphalt pavement	Self-propelled, pneumatic roller			None			

* GNSS: Global Navigation Satellite System

Source: AASHTO PP 81-18:2020 – Table 2.

The required hardware for an IC project is listed below. Depending on the required level of the project, different combinations might be utilised.

2.1.1 IC Instruments on Roller

Two Dynapac tandem asphalt rollers CC2200 were used during the trial.

The system level these 2 rollers have is the Dynapac Compaction Meter plus the Dyn@lyzer with GNSS (Global Navigation Satellite System) which registers all the compaction meter data and continuously displays the compaction results to the operator on the computer screen. The data is, at the same time, recorded and saved allowing full traceability and quality assurance. The GNSS receiver (such as GPS, GLONASS, Galileo, etc.) provides the precise position of the roller on the job site at all times. The level of accuracy depends on site requirements.

The rollers have a drum width of 1.5 m (as per product brochure), an operating mass (including roll over protecting structure, ROPS) of 7,600 kg (each front and rear module, 3,800 kg) and an operating speed range of up to 12 km/h. The other details and characteristics of the machine are described in Figure 2.1.

Figure 2.1: Details of the used rollers

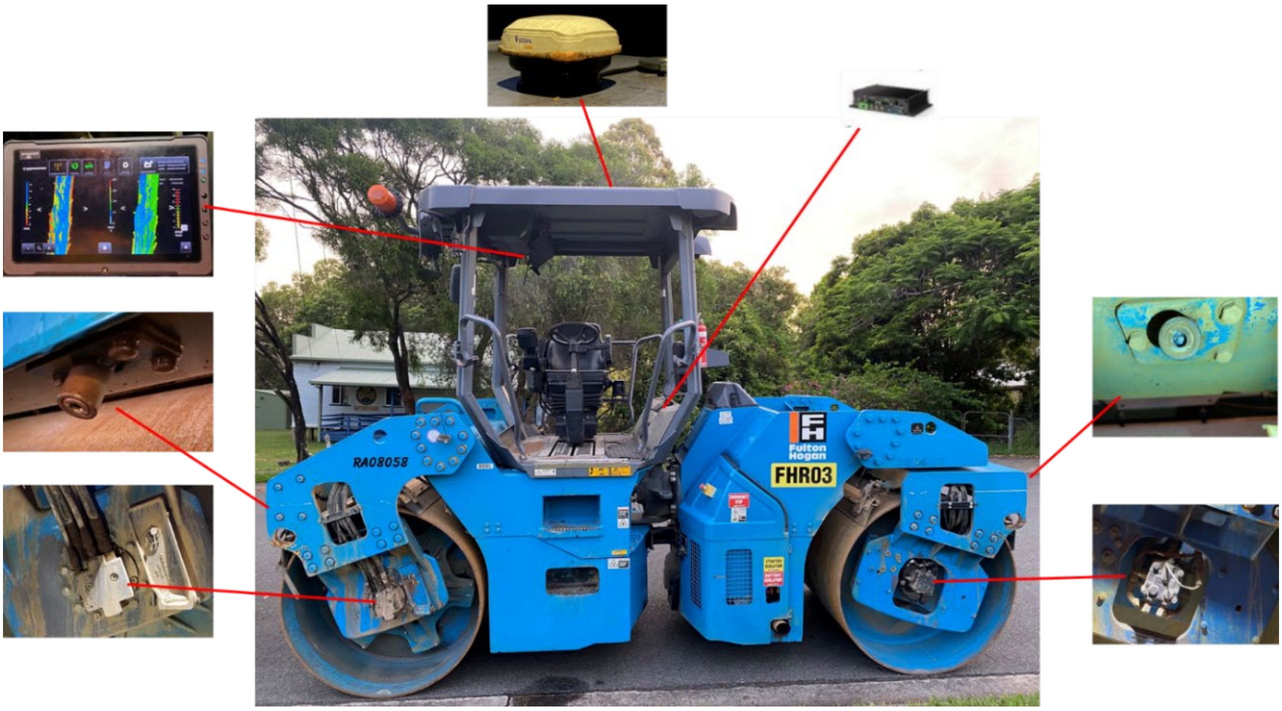
Traction	
Vertical oscillation	±7°
Theor. gradeability	42 %

Compaction	
Centrifugal force (high/low amplitude)	78 kN/67 kN
Nominal amplitude (high/low)	0.7 mm/0.3 mm
Static linear load (front/rear)	25.3/25.3 kg/cm
Vibration frequency (high/low amplitude)	48 Hz/67 Hz
Water tank volume	750 l

Source: CC2200 Dynapac roller operator's manual

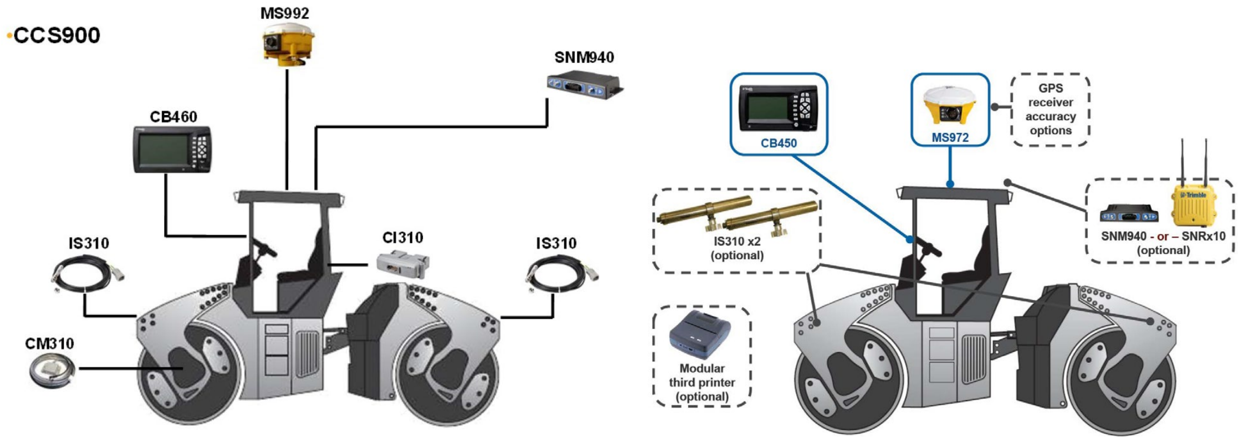
A typical IC system includes a roller, an accelerometer mounted on the drum, an integrated roller measurement system, a GPS receiver and temperature sensors (for asphalt). The required/basic IC components of the instrumented roller are as shown in Figure 2.2 below and are described further below.

Figure 2.2: IC components on an IC roller (example of original equipment manufacturer, OEM roller)



As demonstrated in Figure 2.3, the IC components can also be retrofitted onto an existing roller by installing IC kits.

Figure 2.3: Examples of IC components on an instrumented (retrofitted) roller



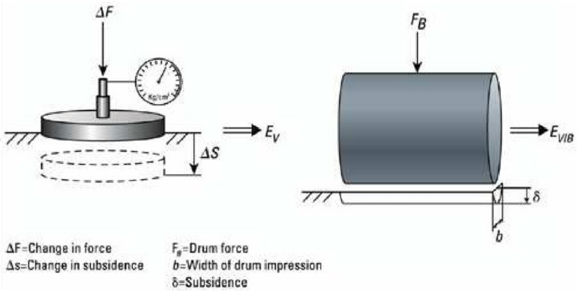
Source: Courtesy of Trimble.

Accelerometer and continuous measurement system

The accelerometer basically measure the IC values which indicate the result of compaction. When the roller exerts compaction force on the compacted materials (through the roller drum), the compacted materials react the force back to the roller drum. The harder the compacted materials, the larger the reactive force. The reacted force is captured by the accelerometer in terms of acceleration and the control system then processes the acceleration signals and computes ICMV in different ways.

The rollers used in the trial can measure both CMV and E_{vib}. It was decided to measure and use the E_{vib} as the ICMV for this project because it involves more advanced technology and calculation. The E_{vib} values correlate well with load bearing capacities from the plate loading tests (see Figure 2.4 for the analogue).

Figure 2.4: The analogue between E_{vib} and load bearing capacities from the plate loading tests



Source: FHWA technical note (2017).

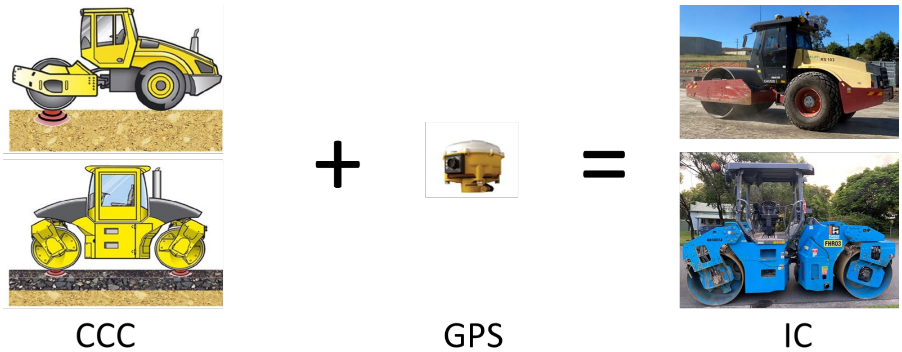
The number of roller passes, the drum acceleration, velocity and amplitude can be recorded continuously with the measurement system. The collected information can then be interpreted as intelligent compaction measurement values (ICMVs) to assess the level of compaction achieved. Based on the modulus (E_{vib}) reported by the measurement system, optimisation of the compaction process can be achieved by the roller operator by ensuring that the ICMVs achieved are equal to or greater than a predetermined threshold value (i.e. target ICMV). This process is recognised as the Continuous Compaction Control system (CCC).

GPS

The Global Positioning System (GPS), originally Navstar GPS, is a satellite-based radionavigation system owned by the US government and operated by the US Space Force. It is one of the global navigation satellite systems (GNSS) that provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to 4 or more GPS satellites. Obstacles such as mountains, buildings and trees can block the relatively weak GPS signals.

Assigning GPS coordinates to each of the measurements from the CCC system gives the capability to locate and relate the IC results and use/analyse them. Figure 2.5 shows the link between CCC and IC.

Figure 2.5: CCC and IC

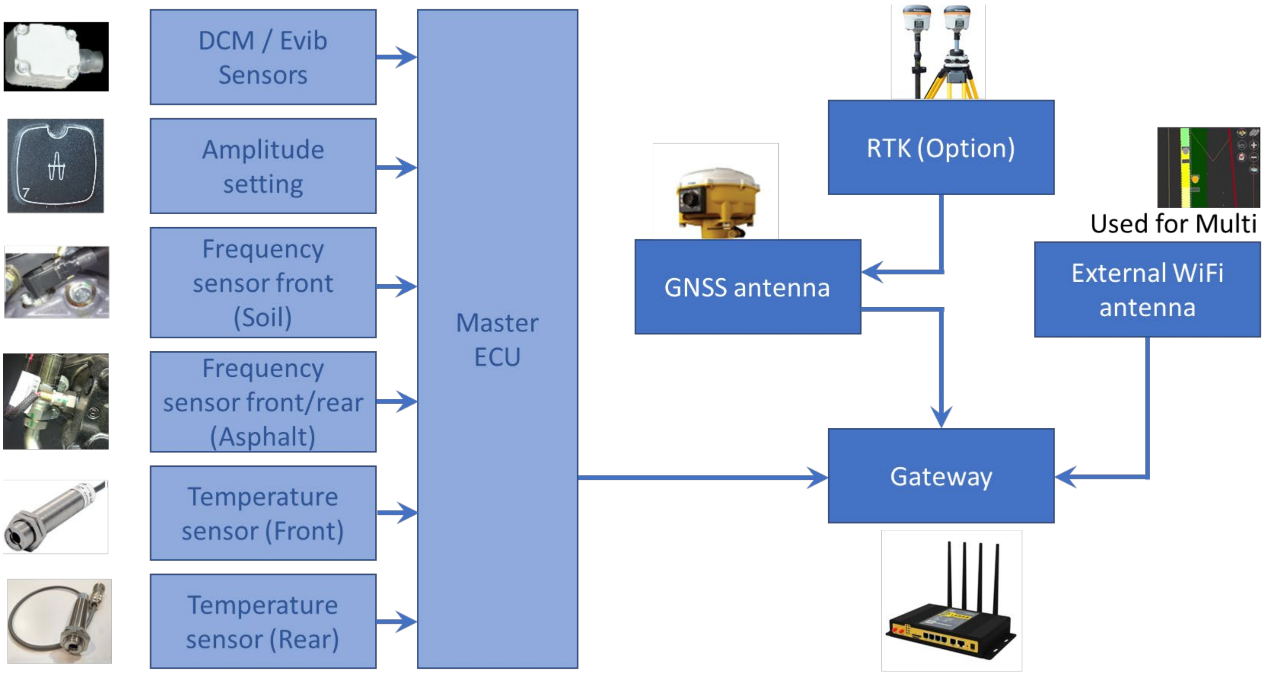


The coordinate system also provides the time stamp needed for IC. As location is a fundamental part of IC, there is a minimum accuracy requirement for GPS used in IC projects and if this accuracy cannot be achieved, other options should be sought and additional solutions should be added to the system.

Gateway

The gateway module is basically the brain of the system and the compiler of all data which gathers all information and details from different IC components and assigns and compiles them, sends the details to the display screen and archive as the IC output (Figure 2.6). The gateway is usually located behind a plastic cover behind the operator’s seat and, in some occasions, it might be the reason for some breakdowns.

Figure 2.6: Data/information flow through the Gateway

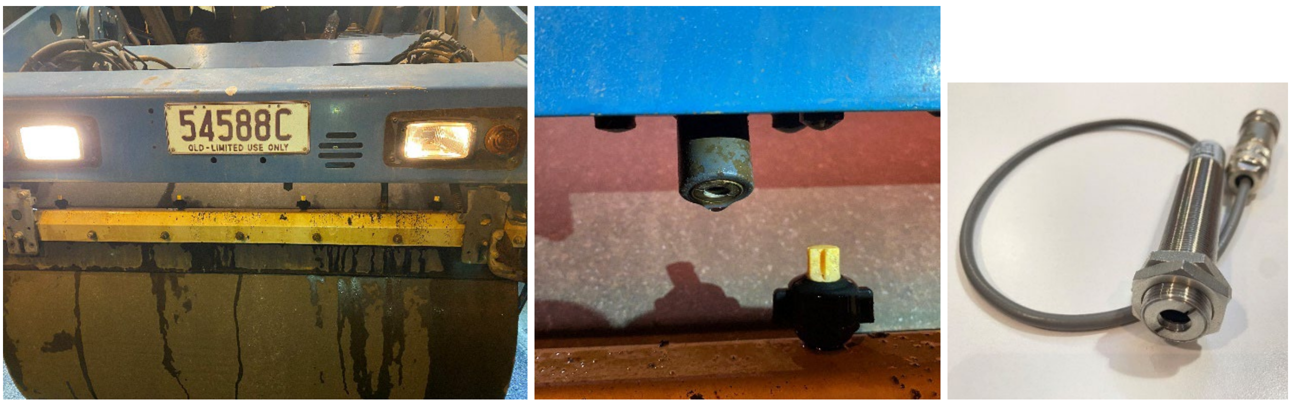


Source: Dynapac brochure.

Temperature sensors

For the asphalt projects, it is vital to monitor the temperature of the rolling layer as it directly impacts compaction. As temperature is one of the attributes for quality assurance, surface temperature is measured and recorded on both sides of the roller (for both forward and reverse rolling). It is important not to forget that this is surface temperature, not the mid-matt temperature (commonly known as asphalt temperature). The calibration of these temperature sensors is important, and they should always function within an acceptable tolerance (error range). Figure 2.7 shows the temperature sensor and its location on the roller.

Figure 2.7: Temperature sensor (for asphalt)



Onboard report system

All IC rollers display the measured attributes on the standard dashboard screen in real time (while compacting). Figure 2.8 shows the basic display feature that shows only a single (or couple of) value/s for a particular point the roller is working on.

Figure 2.8: Display showing basic IC measured attributes

By activating a module and adding a screen or a special tablet programmed and paired for that purpose, all the measured IC attributes can be displayed in real time in the form of a coloured map (with location), in front of the operator. Figure 2.9 is an example of a display which helps the operator to monitor the progress of the work and understand what the required works are.

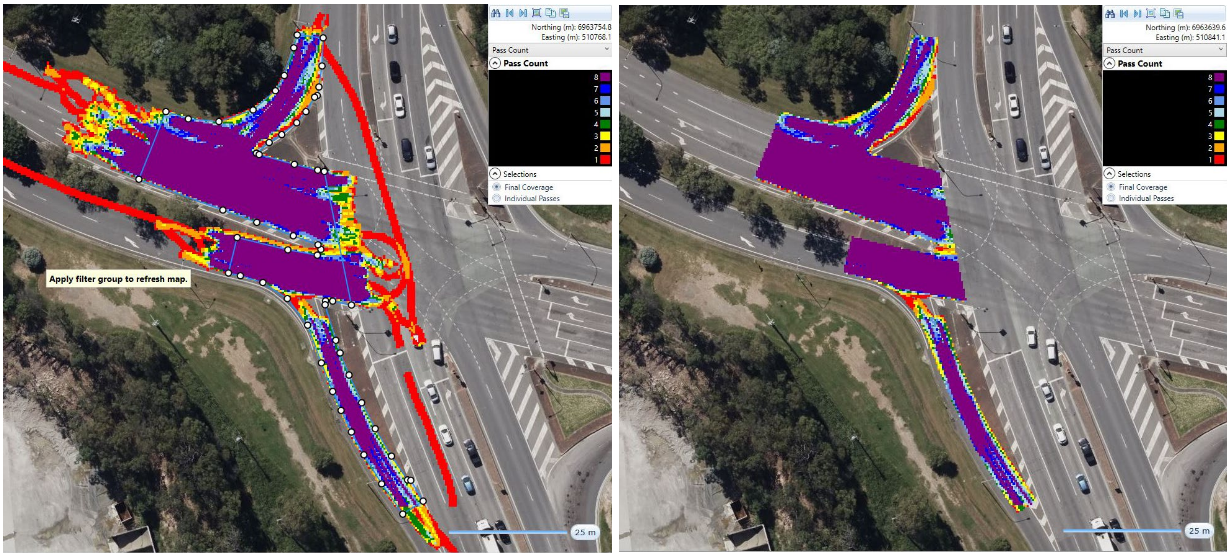
Figure 2.9: IC display screen with colour-coded map

2.1.2 Rover

For different reasons which are briefly explained below, it is required to have accurate coordinates. This should be defined or located by a handheld rover which is accurate enough:

- Boundary of work (at the end of each lot or shift):
  The boundary of work should be defined within the analysis software package to accurately calculate the level of coverage, as one of the main criterions for work delivery for an IC project. Any different assumed boundary points change this coverage percentage. It also impact the test results which will be correlated and calibrated. It changes the averaging for the work representatives which can impact the acceptance of the work. Figure 2.10 demonstrates how important it is to have the coordination of the boundary points. The figure on the left shows all the moves (even unnecessary ones or for the transport purposes, etc.), while the figure on the right demonstrates the work area which is the base for the aseesssment and acceptance.
  If there is no defined boundary in the system, the software then considers the pass 1 as the reference/base for measuring and calculating the coverage percentage, which is very likely not to be accurate enough.

Figure 2.10: Boundary points to be used to define the required work area and filter the exclusions



- Accurate coordinates of test spots:
  As the correlation process on the first lot (correlation lot) is an important output of the IC (for the granular pavement layers and earthworks), it is important to have the right coordinates for test points to be entered in the system, otherwise the correlation work might be affected.
- Reference to a point:
  In different scenarios it is required to spot a point (e.g. a soft spot based on the map IC provides, off the range temperature or chasing details of an area or a point) which can be easily done by using a rover.

2.1.3 GPS Base Station

When GPS accuracy on the roller working on a road project is not enough, the use of a GPS base station is an option. A GPS base station is a GPS receiver at an accurately known fixed location that is used to derive correction information for nearby portable GPS receivers. This correction data allows propagation and other effects to be corrected out of the position data obtained by the portable GPS receivers, which provides increased location precision and accuracy over the results obtained by uncorrected GPS receivers. This system consists of an antenna, radio, radio antenna, and power source. The radio and environment/physical conditions control the distance that the correction signal travels. The typical range of the correction signal is about 3.2 km (2 mi) in radius without repeaters, and a repeater may extend the distance an additional 3.2 km (2 mi) (AASHTO PP 81-18).

2.2 Required Checks and Verifications

To be able to accurately work with every equipment and tool, it is essential to verify them. The following verification processes should be carried out prior to IC work to ensure all equipment and tools function with the right level of accuracy.

2.2.1 Rover Verification

The accuracy of rover readings can be easily checked by the service provider or by comparing it with the coordinates from surveying. To check the accuracy and repeatability of coordinates from rover, random readings can be read and analysed with the following steps:

- Identify a point.
- Read the coordinates of the point using the rover.
- The rover should be moved from the location and brought back again on the point location.
- Re-read the coordinates of the point.
- Repeat the steps several times (at least 10 times in this verification).
- The maximum distance between any 2 readings demonstrates the error for repeatability of the rover.
- The reading error will be determined by comparing the readings with the coordinates from surveying.

To review and check the readings from the rover, the below exercise was carried out during the trial.

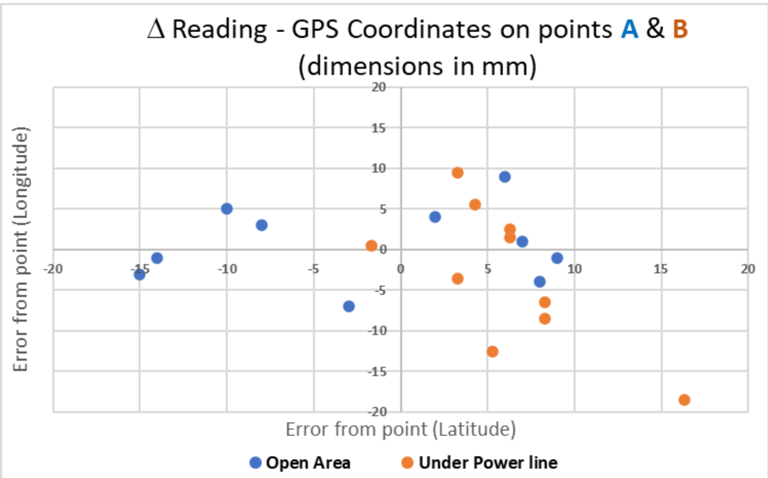
To show different situations, Three points along the trial area were chosen and marked for testing the rover's accuracy; one in an open area, one under a tree and another one under a power line. The coordinates on each point were then recorded 10 times, independently, with the rover, according to the procedure above. The readings were compared with the accurate coordinates from surveying and the results of the average and variations were as shown in Table 2.2.

Table 2.2: Verifying the rover accuracy

					523696.533	6959283.358				
	Point ID	Easting (m)	Northing (m)	Height (m)	Δ Easting (m)	Δ Northing (m)	Δ Easting (mm)	Δ Northing (mm)	Error (mm)	
Open Area	RANDOM 1	523696.530	6959283.351	16.149	-0.003	-0.007	-3.0	-7.0	7.6	9.7 mm
	RANDOM 2	523696.525	6959283.361	16.165	-0.008	0.003	-8.0	3.0	8.5	
	RANDOM 3	523696.518	6959283.355	16.141	-0.015	-0.003	-15.0	-3.0	15.3	
	RANDOM 4	523696.523	6959283.363	16.144	-0.010	0.005	-10.0	5.0	11.2	
	RANDOM 5	523696.519	6959283.357	16.141	-0.014	-0.001	-14.0	-1.0	14.0	
	RANDOM 6	523696.541	6959283.354	16.150	0.008	-0.004	8.0	-4.0	8.9	
	RANDOM 7	523696.535	6959283.362	16.153	0.002	0.004	2.0	4.0	4.5	
	RANDOM 8	523696.539	6959283.367	16.148	0.006	0.009	6.0	9.0	10.8	
	RANDOM 9	523696.540	6959283.359	16.152	0.007	0.001	7.0	1.0	7.1	
	RANDOM 10	523696.542	6959283.357	16.134	0.009	-0.001	9.0	-1.0	9.1	

The maximum error (difference between the readings by the rover and the surveyed coordinates) was 15.3 mm, with the average error/deviation of 9.7 mm for readings in open area. Details of individual surveys are shown in Figure 2.11.

Figure 2.11: Distribution of reading of rover for Point A (open area) and B (under power line)



This figure shows a maximum error of 24.7 mm (worst case) and an average of 9.8 mm under the power line and, surprisingly, around 1.3 m for readings under the tree. That means for the areas with obstacles like trees and similar, a base station or another solution is needed to achieve the acceptable level of accuracy.

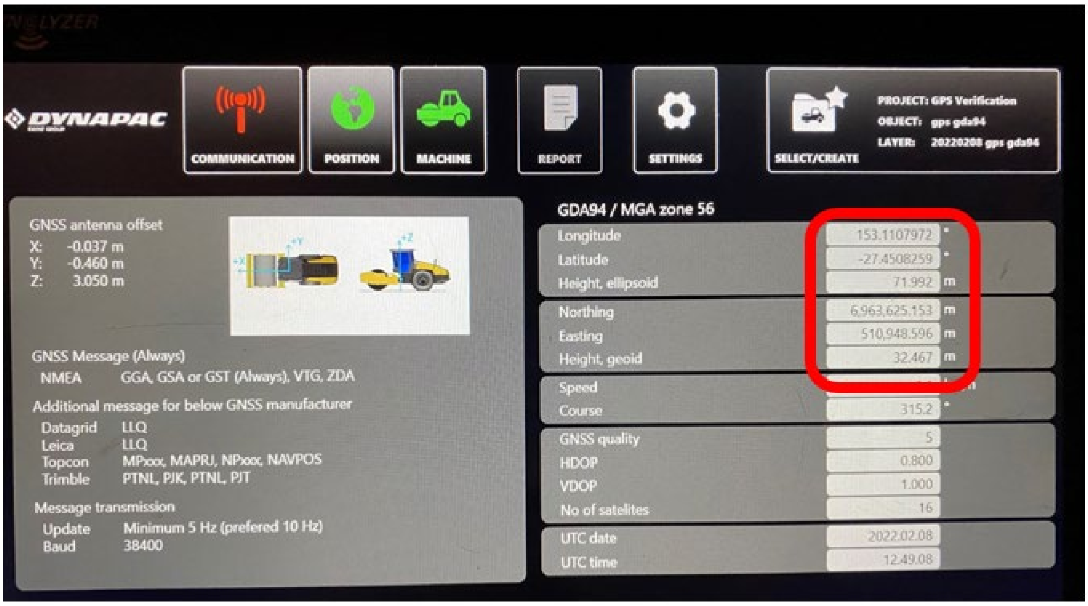
2.2.2 GPS Verification

Once the accuracy of the rover is verified, it can be used to check the accuracy of the GPS on the roller.

To identify the accuracy level of the GPS, the below steps should be followed:

- Move the roller forward until the GNSS header computation is initialised. That is when the measurements (including the readings for coordinates) and movements are shown on the screen.
- Move the IC roller and park it at an appropriate and safe location. As these steps may take several minutes, it is necessary to make it at a safe location (e.g. not in the way of other movement in the workshop).
  Record the GPS measurements from the display screen on the IC roller. Figure 2.12 shows where the coordinates are displayed which might be just the coordinates for the position of the GNSS antenna (reading set #1).

Figure 2.12: GPS coordinates on display screen – no offset applied

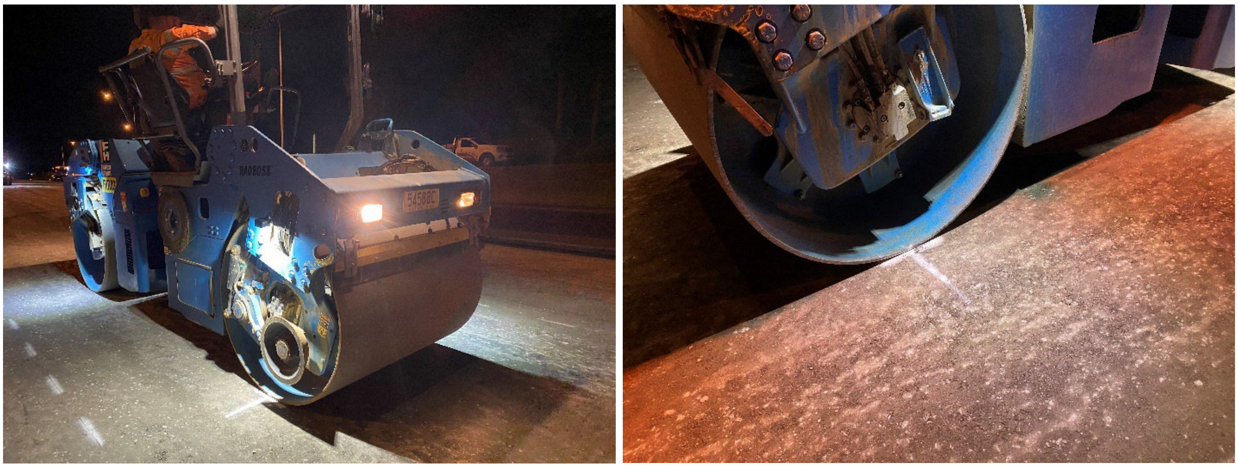


- Locate the rover on the GPS and read the coordinates (reading set #2). Figure 2.13 shows how to accurately locate the rover on the GPS.

Figure 2.13: GPS verification – how the coordinates of the current GPS location should be read and recorded

- While the roller is parked, mark both sides of the roller drum (i.e. left and right edges of the **front** drum contact patch). As shown in Figure 2.14, it is important to accurately mark the middle points.

Figure 2.14: GPS verification – marking the drum edges



- Stop the IC recording on the roller and close the file.
- Move the roller from the parked location to be able to record the coordinates.
- As demonstrated in Figure 2.15, the rover should be used to measure the coordinates of the drum edges (reading set #3 for left and #4 for right).

Figure 2.15: GPS verification – coordinates of drum edges

- Average the rover GPS measurements, in case the roller GPS measurement is at the centre of the front drum (reading set #5).
- By comparing the readings and coordinates and calculating the difference between the different 'reading sets', the following details can be determined:
  - Which coordinates are displayed on the display screen, as sometimes the location of the GPS antenna is displayed, while other times it is the location of the drum (after applying the offsets for the drum).
  - Which coordinate system is used by the roller
    Usually, the coordinate system used by the rover and/or roller can be easily checked by going through the menu's setting options, but on some occasions (including for one of the rollers in this trial), it is not clear.
- The accuracy of the roller can be calculated.
  As per AASHTO PP 81-18, the error should be within ± 6 inches (approximately 150 mm) in both the northing and easting directions.
  One of the reasons for having a 6 inch (approximately 150 mm) error is the fact that the typical size for IC the grid in IC systems is between 340 mm*340 mm and 400 mm*400 mm and the error should not be more than half of the dimension of the IC grid cell, otherwise the measured attributes would be assigned to incorrect locations.
- Open the IC file and read the coordinates of the last point/s (depending on what is checked).
  The text file can be opened in MS-Excel or Veta, and the data can be sorted based on time, etc. (reading set #6).
- By comparing the reading set #6 with the coordinates recorded by rover, the application of the offsets (for the drum) can be checked.

To calculate the accuracy of the GPS on the roller in the trial, the above procedure was carried out and the results were as in Table 2.3 below.

Table 2.3: GPS verification – checking the accuracy

Setting (rover)	Location of Rover	Coordinates (Rover)				Coordinates on screen (Roller)		Difference with Roller (Screen)		
		Easting	Northing	Ave. Easting	Ave. Northing	Easting	Northing	Δ Easting	Δ Northing	Distance (m)
GDA94	Roller Drum (Left)	510,947.198	6,963,625.100							
		510,947.203	6,963,625.099	510,947.201	6,963,625.098	510,948.596	6,963,625.153	1.395	0.055	1.396
		510,947.203	6,963,625.095							
	Roller Drum (Right)	510,948.588	6,963,625.594							
		510,948.590	6,963,625.591	510,948.589	6,963,625.593	510,948.596	6,963,625.153	0.007	-0.440	0.440
		510,948.589	6,963,625.593							
	On Existing Antenna	510,948.055	6,963,623.825							
		510,948.056	6,963,623.821	510,948.056	6,963,623.824	510,948.596	6,963,625.153	0.540	1.329	1.435
		510,948.056	6,963,623.825							
	On Default Antenna	510,948.051	6,963,623.597							
		510,948.054	6,963,623.599	510,948.053	6,963,623.598	510,948.596	6,963,625.153	0.543	1.555	1.647
		510,948.053	6,963,623.599							
GDA2020	Roller Drum (Left)	510,947.775	6,963,626.482							
		510,947.774	6,963,626.485	510,947.774	6,963,626.485	510,948.596	6,963,625.153	0.822	-1.332	1.566
		510,947.773	6,963,626.489							
	Roller Drum (Right)	510,949.187	6,963,626.976							
		510,949.186	6,963,626.977	510,949.186	6,963,626.977	510,948.596	6,963,625.153	-0.590	-1.824	1.917
		510,949.186	6,963,626.979							
	On Existing Antenna	510,948.647	6,963,625.222							
		510,948.652	6,963,625.220	510,948.650	6,963,625.220	510,948.596	6,963,625.153	-0.054	-0.067	0.087
		510,948.652	6,963,625.219							
	On Default Antenna	510,948.644	6,963,624.979							
		510,948.643	6,963,624.979	510,948.644	6,963,624.980	510,948.596	6,963,625.153	-0.048	0.173	0.180
		510,948.644	6,963,624.981							

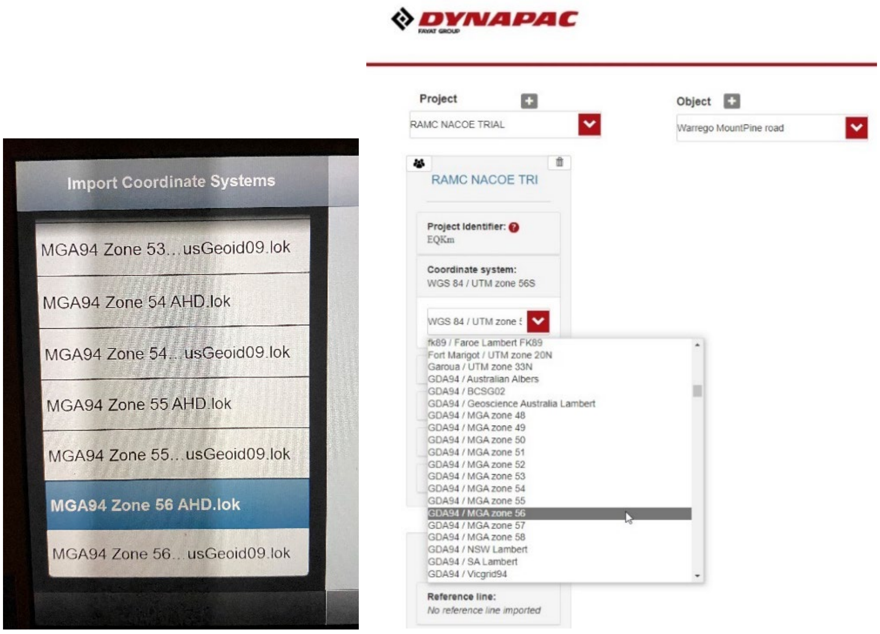
Based on this exercise, it was confirmed that the roller for the trial was using the GDA2020 coordinate system (although the display screen in front of the operator was showing the WGS84 as coordinate system, but the transformation code which was used to recalculate the northing & easting was converting the data to the GDA2020 equivalent).

It was also demonstrated that the GPS error of 87 mm was within the acceptable range without using the base station. The GPS was still accurate enough even when adding the error of the rover, 15.3 mm, to this.

2.2.3 Aligning the Readings of Roller GPS and Rover

To eliminate the risk of losing data which will cause re-work, before starting the project and recording measurements all the measurements from the different devices should be checked and set so that they are consistent along the project. As an example, it is necessary for all the IC rollers and the rovers to measure based on the same coordinate systems, as it is required to cross-check and use data from different sources. Thus, it is essential to know which coordinate system is to be used (e.g. WGS84, MG-GDA94 or MG-GDA2020). These settings and details should be part of the job description and work plan, because if the data is not matched or aligned, there will be some extra work to convert these, or work needs to be re-done. Figure 2.16 shows that the coordinate systems on both roller and rover were compared and checked.

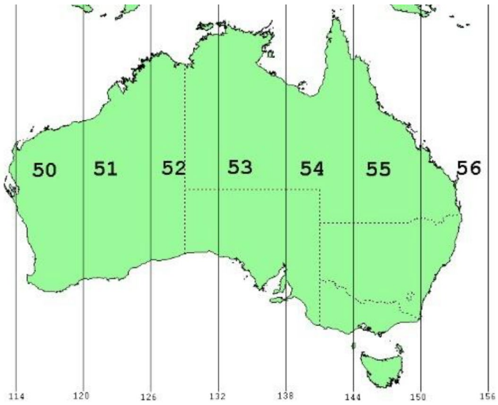
Figure 2.16: Same coordinate systems on the roller (right) and rover (left) + compatible with other project files



Setting – coordinate system to be used

At the beginning, for setting up the project and create a work file in the system, defining the work area (which is technically called universal transverse mercator zone, UTM zone) for the system is required So the system knows which coordinate system and area should be used for the recording and reporting.
Figure 2.17 illustrates the UTM zones for Australia which is needed for the work setting.

Figure 2.17: UTM zones for Australia



2.2.4 Aligning the Readings of the Roller GPS and Recorded Data in the IC File

The operation system gathers the information and assigns location to the data. Depending on the design of the system and where the actual GNSS antenna is located, the system should shift the measured coordinates to the location of the roller drum (based on the direction of travel and offsets of the antenna compared to the roller drum) to assign the right coordinates to the IC data. This IC data then will be assigned to the grid cells under the contacted rolling area.

To be able to check where the GPS coordinates in the IC files are referring to and to verify if the offsets are correctly applied, the offsets on the roller need to first be understood and checked.

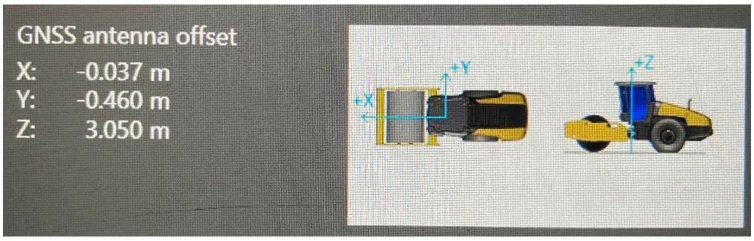
Antenna offset with the measurement tools

The position of the antenna relative to the drum's contact surface with the ground is pre-set in the system. This varies depending on roller model and assumes that the GNSS antenna has been positioned on the factory default location.

There are 2 offsets that should be determined, measured and applied to be able to locate the exact point onsite, from the coordinates in the IC file:

- Offset of actual GPS location from GPS reporting datum. This term is visually explained in Figure 2.18 and is a pre-defined value for the factory default location.

Figure 2.18: GPS offsets (between the location of antenna and articulation point



The antenna offset that is shown in the above figure (taken onsite from the Dyn@Lizer, the operation package) refers to the distance from the antenna location (on the back left corner of the roof, shown in Figure 2.19) to the centre of the articulation joint of the machine (as shown in Figure 2.18). The X and Y dimensions correct the data forward and sideways in a horizontal plane and the Z dimension refers to the distance from the antenna to ground level.

Figure 2.19: Position of the GPS antenna

After applying these offsets and correcting the data, the coordinates will be referring to the ground level in the centre of the machine, the articulation point. This information comes from the machine setting and data loaded into the machine's parameter file; it cannot be changed by the operator to avoid any incorrect calibrations.

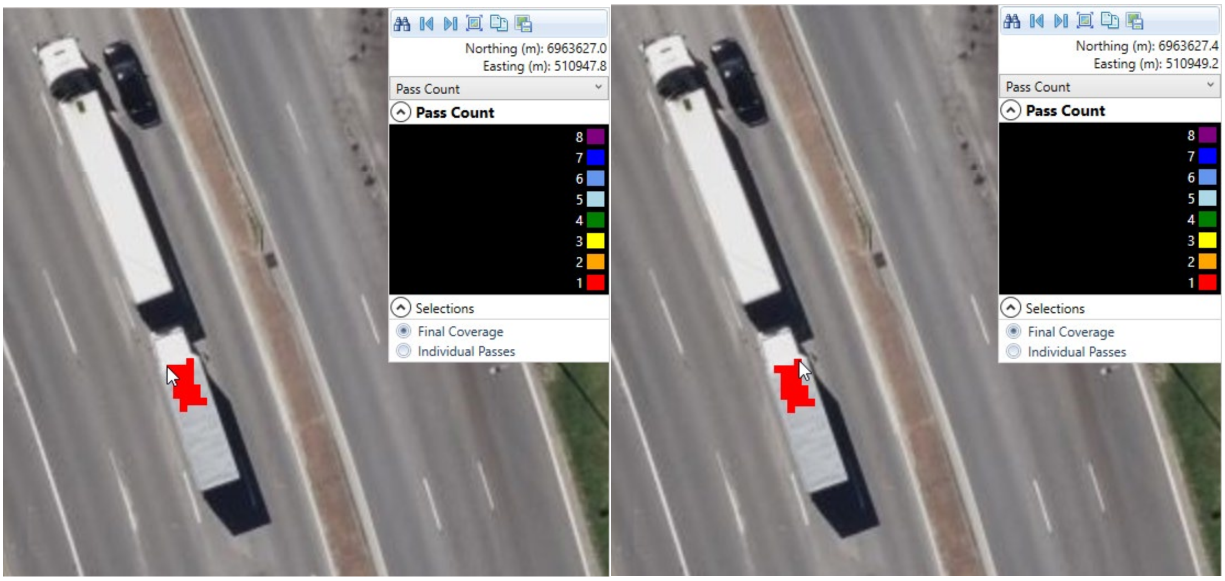
- Offset of each measure (e.g. temperature sensor, compaction measurement, etc.) from the reporting datum (which is now, at ground level on the articulation point) which is shown in Figure 2.20 on both sides of the roller's articulation point.
  That may mean it is required to apply different offsets for different sensors and IC components (temperature, compaction, etc.).

Figure 2.20: Roler's geometry

Based on the information from the manufacturer, within the machine settings and parameters there is a second calculation which refers to the distance between the articulation point and the centre/axis of the drum (which is basically half of the distance between the wheelbases of the machine). The Dynalyzer (or any operation system that is used) has this information and applies it for correcting the data further to do the coordinate shift and assign the exact coordinates to the collected data at the centre of the drum axis.

As per the last 2 steps of GPS verification in Section 2.2.2, the coordinates in the IC file can be reviewed and the application of the offsets can be checked. Figure 2.21 demonstrates how the recorded coordinates, after applying all the offsets, can be read.

Figure 2.21: Recorded GPS coordinates of marked points (in the IC file)



The following is additional information about the coordinates and files:

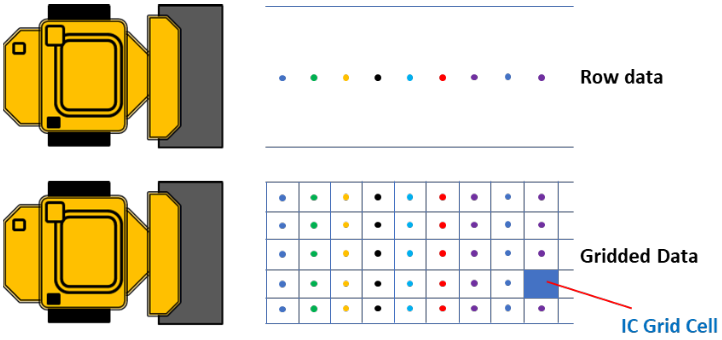
- The coordinate system cannot be changed in an existing project. A new project file must be created if different coordinates are required.
- The GPS position value shown on the POSITION tab on the menu of the tablet (display screen) is the raw data (also called clean data, with no correction; in this case, RAW NMEA0183) that is a direct message from the GNSS receiver.
- The northing/easting shown on the Dynalyzer tablet main work screen (displayed coordinates) is the projected position of the receiver including the calculation/correction for the selected coordinate system, it does not include any of the offsets or adjustment to the drum position.
- The coordinates in the IC data file reflect the shifted coordinates (using offsets).

Assigning measured IC data to the IC grid cells (and creating the IC file)

When the IC system is active and logging the file, it does not just log one GPS position at the centre of the drum. The system uses the GPS position and the offsets/corrections in the software to calculate the position of each drum edge contact point with the ground (compaction surface) for the left and the right. The system will then save the data in all grid cells between these 2 points; this will cover the centre point of the drum. Each grid cell is 400 mm x 400 mm (for the roller used in this trial) and the centre point of the grid cell is the position that is saved and can be checked in the database/analysis files along with the compaction data.

Each IC attribute (e.g. ICMV, temperature, speed, frequency, amplitude, etc.) is measured frequently and is a unique value for the whole width of the roller (on that contact/compaction area) which is assigned to all grid cells passed by the drum on that pass. This area includes all the cells between the left and right drum edges, as shown in Figure 2.22. The dimension of these grids varies from system to system, but it is usually between 340 mm*340 mm to 400 mm*400 mm.

Figure 2.22: Concept of grid cell and how IC raw data is applied to the gridded system



The system will always collect the data from the leading drum, so when traveling in the forward direction, the grid cells are being positioned with the front drum along with the data from the front temperature sensor (temp sensor), etc., and when in reverse, the grid cells are being positioned with the rear drum along with the data from the rear temp sensor, etc. Simply, the front drum left and right edges are used when going forward and the rear drum left and right edges are used when going in reverse.

This IC data is assigned to the grid cells just when the roller has passed 50% of the cells along both dimensions. As illustrated in Figure 2.23 and Figure 2.24, the base-point (trigger) for applying the criteria is the middle of the contact/compaction area (i.e. middle line of the roller drum).

Figure 2.23: Pass count criteria for each grid cell: moving over 50% of both dimensions

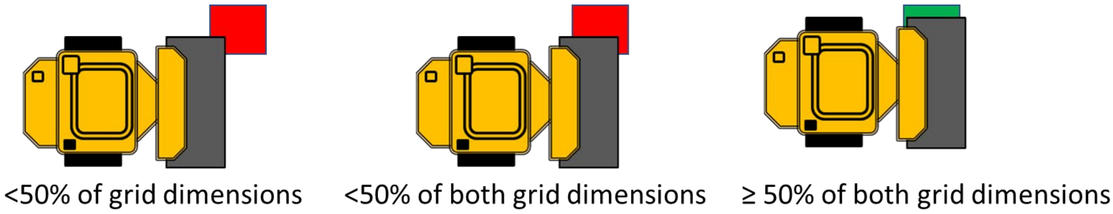
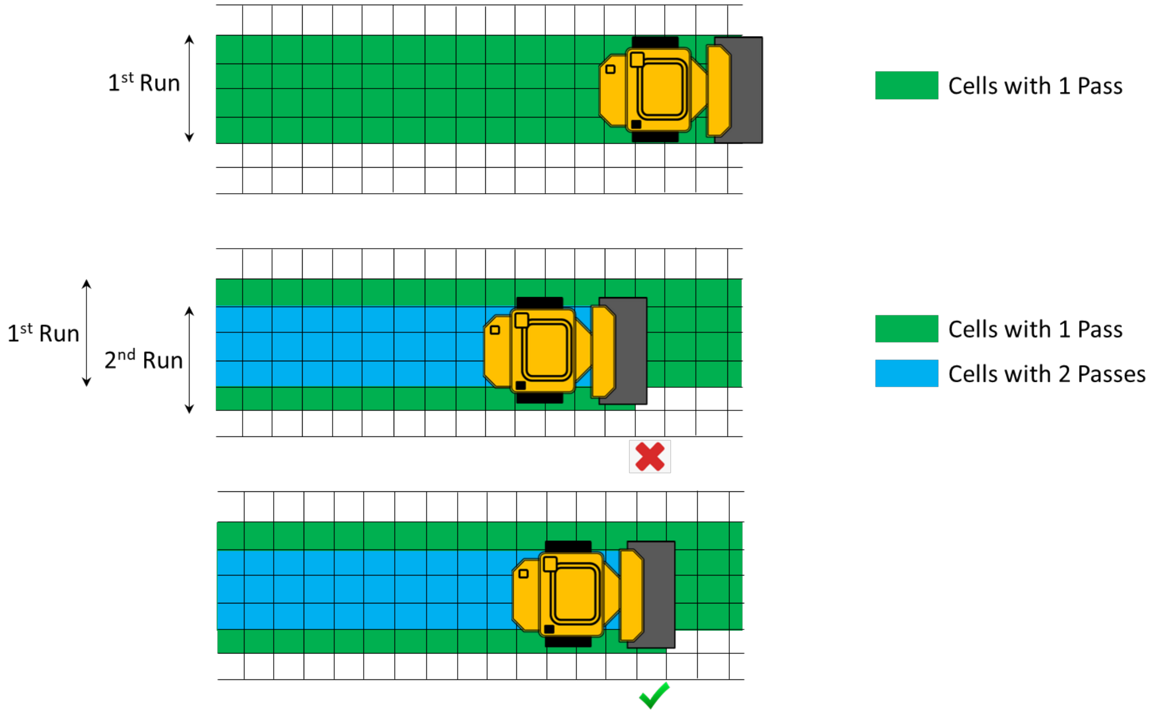


Figure 2.24: Process of counting the passes and pass count criteria on each grid cell



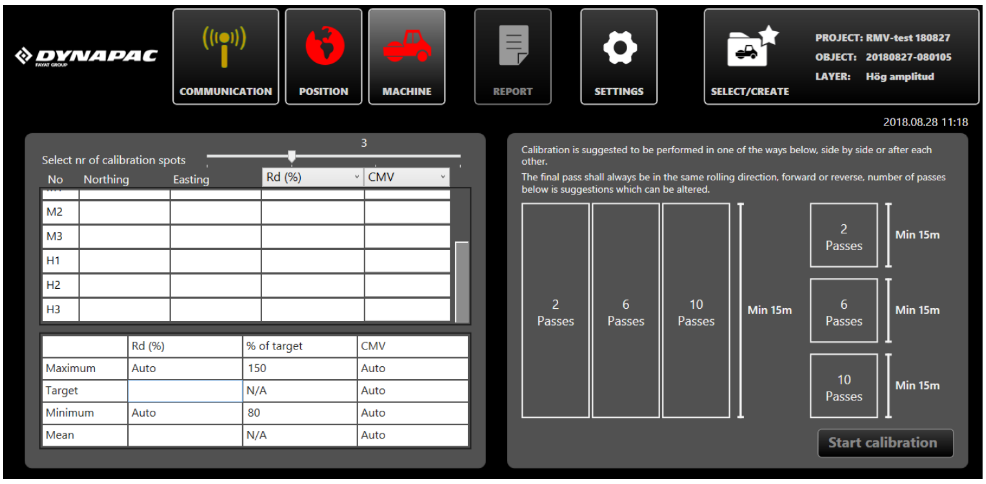
2.2.5 Verification of ICMV

ICMV, as the most indicative IC parameter, requires to be calibrated (repeatable) and comparable among the same equipment model. Calibration of the ICMV (in this case CMV/E_{vib1}/E_{vib2}) against acceptance control values is only possible for soil compaction.

Calibration of compaction meter value in relation to acceptance control values can be performed in the system. In order to be valid, this must be performed under exactly the same conditions that apply to the rest of the surface that is to be compacted. That means material, layer thickness and moisture content must be the same as for the work surface. Machine parameters such as linear load and amplitude must be unchanged, as must direction of travel, driving speed, etc.

Based on the manufacturer's manual (Accessories Manual for Dyn@lyzer), calibration must be performed on 3 surfaces, each at least 15 m in length. The first surface must be compacted with a small number of vibrating passes (e.g. 2), the second surface must be compacted with a medium number of passes (e.g. 6) and the third surface must be compacted with a high number of passes (e.g. 10). The number of passes is a basic recommendation and must be adapted according to applicable compaction requirements for the object.

Figure 2.25: Example of calibration process – start



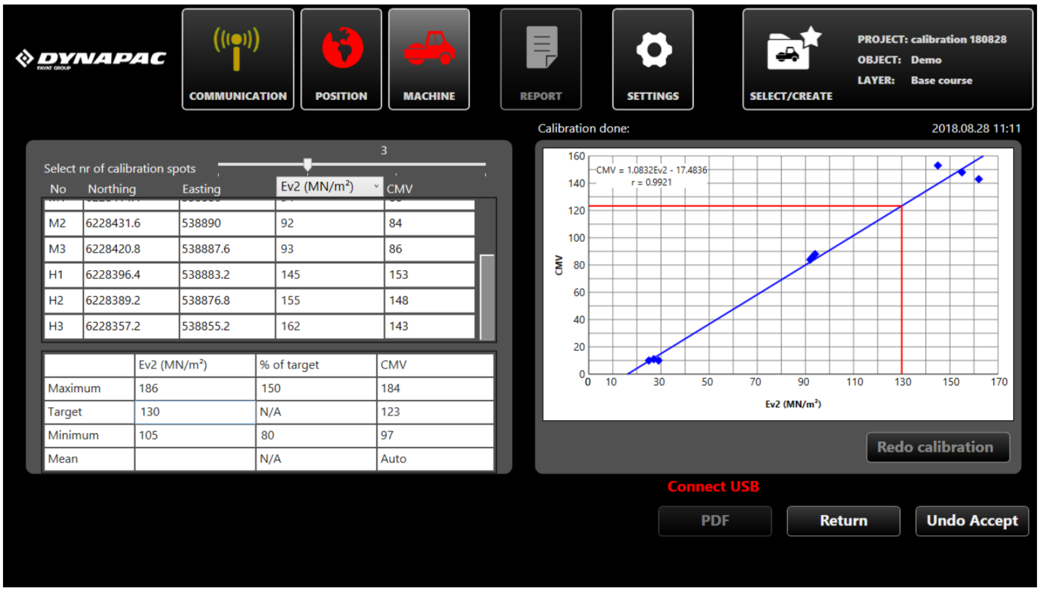
On each surface, a number of measurements are then performed using the acceptance control method that applies to the object. The location of these measurements is given by the system (e.g. in Dyn@lyzer or WorksOS) after completion of the calibration operation. The position is presented together with the measured compaction meter value for each location.

After testing on each location, the measured values are entered into the system as shown in Figure 2.25. The system then automatically calculates the correlation coefficient and the link between compaction meter value and the acceptance inspection value.

The working process for calibration is as follows:

- Create the layers/file.
- Select 'Calibrate' under Acceptance value.
- Select the number of calibration points required per calibration surface, as well as the Acceptance inspection value that applies to the object (this value can also be selected later).
- Drive the machine out to the calibration area and select 'Start calibration'.
- Compact the indicated surfaces with the correct number of passes, and then select 'Finish calibration'.

Figure 2.26: Calibration process – example of results



- The system now calculates which points are to be measured and presents these in table form, with position and measured compaction meter value.
- Carry out acceptance control measurements at the indicated points and then enter the values for each location in the table.
- As demonstrated in Figure 2.26, the system then calculates correlation links and correlation coefficients for calibration and reports these to the user. The specifications normally state the minimum acceptable value for the correlation coefficient.
- Select 'Accept calibration' to approve and use this in the continued compaction work.
- If the correlation is not good enough or if the calibration is defective in some other way, the process can be repeated.

2.2.6 Verification of Temperature Sensors

As one of the most important attributes to be monitored and checked, the asphalt temperature is measured by 2 infrared sensors (both sides for forward and reverse rolling) pointing down to the asphalt surface. Figure 2.27 shows where the temperature sensors are located. The temperature is measured in one single area in front of the drum with a diameter of around half a metre. As with other values, this value is assigned to all grid cells passed by the drum on that pass (all cells between the left and right drum edges). There might be temperature variations along the width of the drum, especially close to the work edges. However, typically, more variation is seen longitudinally because of truck change, segregation, etc.

Figure 2.27: Temperature sensors

Routine maintenance including cleaning is required for these sensors to make sure there is nothing blocking the sensors. Figure 2.28 shows how much these sensors are exposed to dust and water turbulence and as they are very sensitive, it is necessary to inspect and clean them routinely.

Figure 2.28: Maintenance of temperature sensors

The technical details for the temperature sensor are provided in Table 2.4.

Table 2.4: Technical data for paramenters of temperature sensors on the rollers used in the trial

Parameter	Note/Range
Temperature range (°C)	−20 °C ~ 500 °C
Accuracy (digital & voltage)	±1.5% of reading or ±2 °C, whichever is greater
Accuracy (TC)	±1.5% of reading ±2 °C ,or ±4 °C , whichever is greater
Repeatability (digital & voltage)	±0.5% of reading or ±1 °C, whichever is greater
Repeatability (TC)	±0.5% of reading ±1 °C, or ±2 °C, whichever is greater
Response time (95% energy)	150 ms
Temperature resolution	0.1 °C

Source: Raytek-Direct® CM Temperature Sensors – Operational Manual.

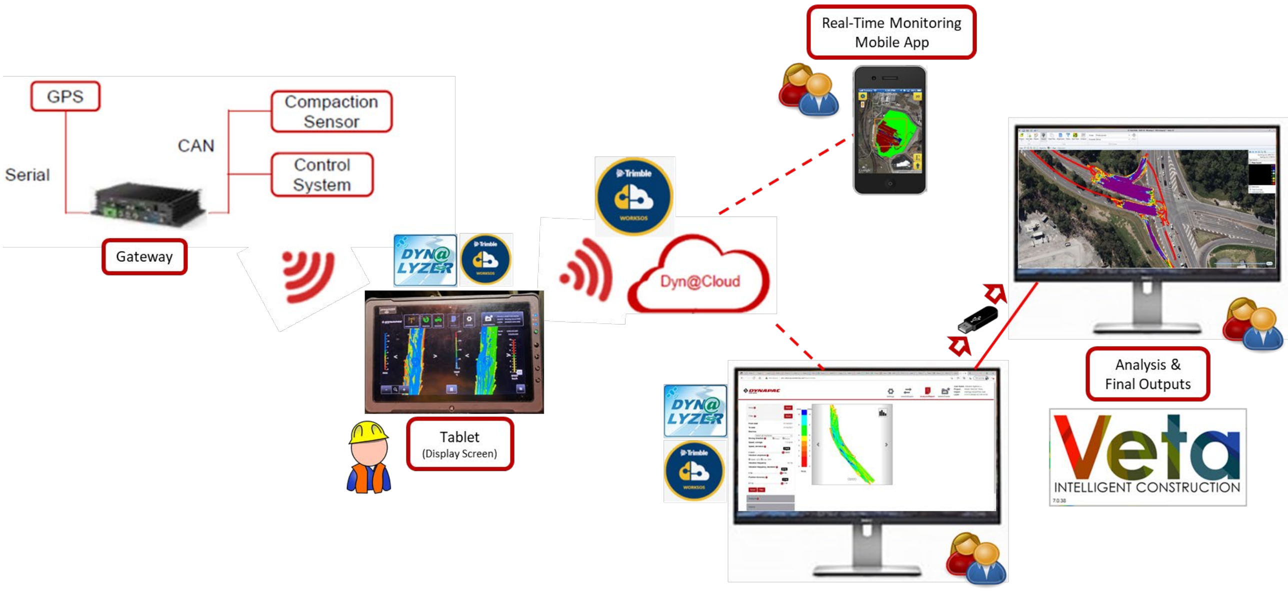
To verify the accuracy of the temperature sensors, as demonstrated in Figure 2.29, the measured temperature should be compared with the manually measured temperature at the same point the mounted sensor is pointing to and based on AASHTO PP 81-18; the difference should be within 5 °F (~3 °C). As it is important to have correct measurement with calibrated equipment, sensors should be regularly checked and cleaned by operator.

Figure 2.29: Verication process of mounted temperature sensors

2.3 Required Software/Packages

How each component of the iC package and the whole system works from setting up a project to analysing a job and report on it is demonstrated in Figure 2.30:

Figure 2.30: Data flow and packages used for IC



2.3.1 Operation (Data Management Module + Field Module)

An operational package that is a data management and also field data collection module should be used to handle the project creation/setting, the data collection during the work, the data check/review after the operation and the data extract at the end. As the rollers used in this trial were Dynapac, the respective system was used. The package, called Dyn@Lizer, accommodates all the works from file/project creation to data extract at the end of the work.

Dyn@Lyser

As the rollers used for this trial were OEM Dynapac, the operation system was Dyn@Lizer, which manages the operation during data collection through the tablet containing software for the Dyn@lyzer continuous compaction control system. This tablet communicates wirelessly with the Gateway via Wi-Fi. The tablet has a power supply in the docking station by the machine's driver's seat and at the end of the shift, the data can be reviewed (though it is not as detailed as Veta), extracted and used.

There are improved modules which can be purchased for more complicated works and/or safer and more efficient operations as described below.

Dyn@Lyser Online

By using this service, project generation and analysis can be done on a cloud server. New projects, as well as updates to existing ones, can be shared directly with the machines in the field without the need to physically visit each machine. The as-built data is continually transferred from the machine to the cloud server as long as there is a functional internet connection. In the event of a missing connection, data will be buffered in the onboard computer and transferred once a connection, cellular or Wi-Fi, is detected.

Dyn@Lyser Multi

Two or more rollers can work together on the same soil or asphalt layer when using Dyn@lyser multi package. They share compaction data over a Wi-Fi connection and all rollers can see the combined result from all participating machines in near real time. If the connection is lost, data is buffered up to 30 minutes. As soon as the connection is restored, the buffered data will be transferred. Data older than 30 minutes will not be sent to the other machines. Once the data from all machines is imported to the office, all data will be merged regardless of any lost connections during production.

When 2 Dyn@lyzer Multi systems are loaded with the same project and are within Wi-Fi range of each other, the Communication icon will turn yellow. This indicates that the machines are connected. This process is automatic and requires no involvement of the operator provided that the same project was loaded in all tablets being used. Once production has started and data is transferred, the icon will turn green and it stays green as long as data is being sent. If the sending machine stops or pauses the data recording, the icon will turn yellow again. The data from the other machine/s will be received in 5 second increments and will appear in the production plot in near real time. If the connection is lost, data will always be saved in each system independently and transmission of data will be resumed once the Wi-Fi connection is re-established.

2.3.2 Data Review and Analysis

To show the results of the IC project and provide the statistical analysis, carry out the correlations, present the IC outputs and analyse the final results, different software packages can be used. Some of these packages are provided by the manufacturer and as they are designed based on a particular brand, machinery and data model, they cannot be used widely.

There are also some comprehensive packages, like Veta, which can be used with a majority of data models and IC brands.

Veta

Veta is a map-based tool used for viewing and analysing geospatial data. Veta can import data from various intelligent compaction (IC) machines, paver-mounted thermal profilers (PMTP), and dielectric profile systems (DPS) to perform viewing, filtering, sub-lotting, spot test imports and analysis. Veta displays compaction information in easy-to-read formats, including graphs and maps.

With Veta, it is possible to view multiple maps and store data from different machine types in the same project.

Veta is a very well-accepted package and is a requirement in the FHWA's generic IC specifications and AASHTO IC specifications for soils and asphalt materials. Veta is also increasingly adopted by US departments of transportation and in the majority of IC projects in Europe (https://www.intelligentconstruction.com).

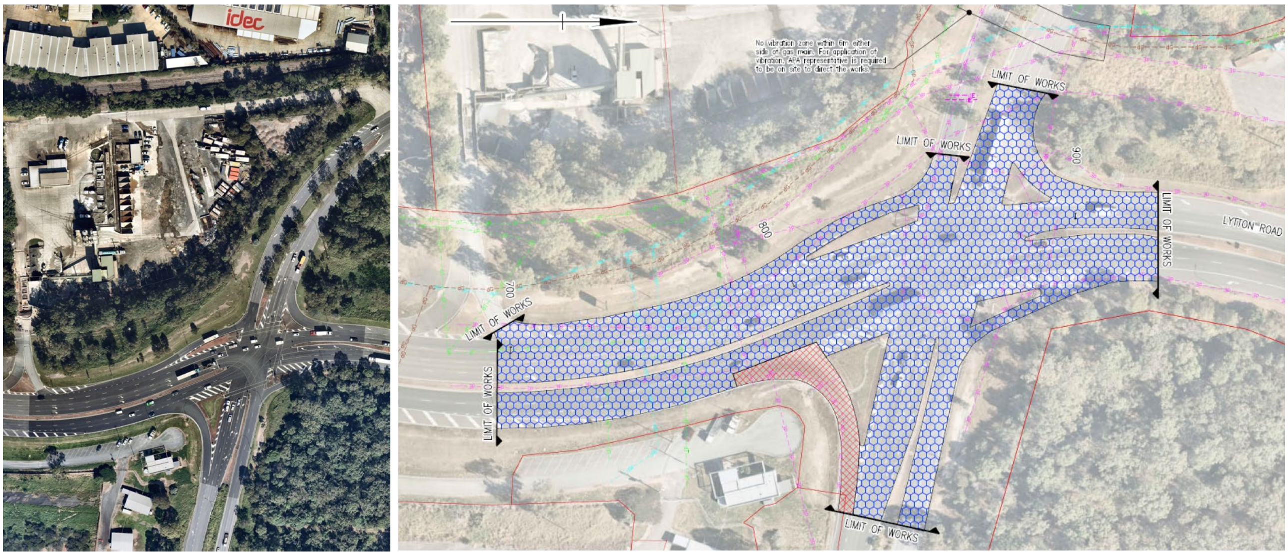
3 Field Demonstration/Trial

To trial the use of IC technology on asphalt layers, one of the TMR asphalt projects was selected to organise and practice the implementation of intelligent compaction.

3.1 Project Details

The selected site for the trial was at Port of Brisbane, at the intersection of Lytton Road and Paringa Road with approximate area of 10,480 m^2 with 2 asphalt layers of EME2 and AC14 (A10E) to be laid in 12 shifts (8 EME2s and 4 wearing courses). An overview of the project and its surroundings is shown in Figure 3.1.

Figure 3.1: Trial site – Port of Brisbane, intersection of Lytton Rd & Paringa Rd



Source: Google Maps

3.1.1 Project Execution Plan

The asphalt trial was planned as per the Project Execution Plan presented in Year 3 of this project.

3.2 On-site Activities

To carry out the IC-related tasks onsite and trial the technology, the works mentioned in Sections 3.2.1 to 3.2.4 were undertaken.

3.2.1 Pre-Mapping

Pre-mapping is defined as measuring the baseline stiffness of existing support materials using an IC roller. The IC measurement value (ICMV) system is used to estimate stiffness based on acceleration signals caused by roller drum rebound. The pre-mapping ICMV and its measurement depths – typically 3 to 5 feet (app. 900 mm to 1,500 mm) – depend on the roller type, weight, drum dimension, vibration frequency and amplitude, speed, direction of travel, and the stiffness of the mapped materials (FHWA 2017b) Technical Brief, *Intelligent Compaction for Pre-mapping*).

The main reason to pre-map an area for existing layers is to assess the support underneath and identify soft spots before constructing the next layer.

Pre-mapping originated as a research activity on the 2008 FHWA and transportation pooled fund (TPF) (TPF) IC project in Minnesota. The project team used a Sakai double-drum IC roller to measure the baseline support condition by mapping subbase materials at low vibration frequency and amplitude prior to the asphalt layer construction at Route 4. Later during paving, construction traffic caused the asphalt layer to fail prematurely. A soft spot had occurred, and the team later realised they could identify the soft spot in the pre-mapping data. Due to this discovery, the industry now recognises the value of pre-mapping; the data collected by pre-mapping can help a construction team identify potential soft spots before pavement failure (FHWA 2017a).

Nowadays, pre-mapping is strongly recommended in the IC specification of several states by their department of transportation (DoT) as well as some European road authorities.

During the trial for P105, as the profiling was exposed to the granular material, there was a chance to carry out pre-mapping on some areas (where the operation, safety and time allowed). The pre-mapping was done with both CMV and E_{vib}.

Some manufacturers have added a feature to their rollers (called Active Bouncing Control) which warns if a double jumping (bouncing) phenomenon happens, or it may even stop the operations when this condition is present. This helps to avoid potential damage to the equipment during the pre-mapping.

Some notes on pre-mapping include:

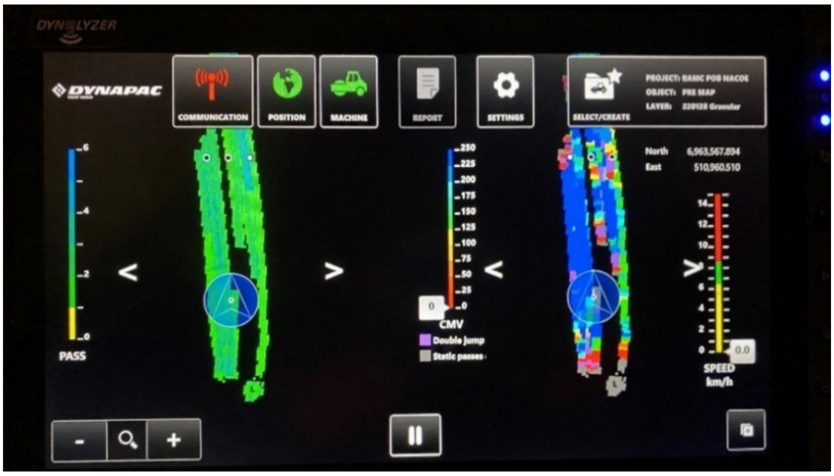
- It is recommended to pre-map the current layer with the same machine/s as the subsequent layer/s.
- To avoid 'double jump' happening during pre-mapping, the IC machine settings such as frequency, amplitude and speed should be carefully selected. When pre-mapping stiffer materials, roller frequency and amplitude need to be lowered to prevent double jumps.
- Pre-mapping is recommended on granular materials only, not on any stiff layer such as asphalt or concrete.

During the trial, pre-mapping was carried out on different areas (where possible) with both CMV and E_{vib} to evaluate the uniformity of the granular layer underneath, to find any soft spot and to seek any correlation between the readings of these 2 different ICMVs. Figure 3.2 is an example of the system display for a pre-mapping rolling work on part of this trial which shows the ICMV and also the spots with double-jump.

Figure 3.2: Pre-mapping before the asphalt placement

Some areas, though were weaker spots compared to the adjacent area, were not soft and did not have issue. Figure 3.3 shows an example of pre-mapping output.

Figure 3.3: Pre-mapping – finding the weak areas and soft spots



Depending on the contractual requirements of a project and/or reference used for assessing the outlier points, different ranges and thresholds can be used to define the outlying points/areas. The following are a couple of reviewed examples:

- The proposed methodology in the European specification (CEN/TS 17006:2016) which works on 10 percentile and 5 percentile outlying range (based on the mean ± 1.28 * st. dev. or mean ± 2 * st. dev.).
- The other way of distinguishing and displaying the differences is with the recommendation from FHWA technical brief, (2017b, *Intelligent Compaction for Pre-mapping*):

> To simplify the display, the chosen colour palettes should include the ranges for the low (soft spot), medium (target) and high values (stiff). As an industry recommendation, 20 percent of the target ICMV and below can be considered 'low'; and 50 percent more than the target ICMV can be considered 'high'. Double jumps can also be identified by a recommended specific value. Another option is to determine the above threshold values based on specifications, such as: mean + std, mean – std, mean – 1.28*std (i.e. 0 percentiles of ICMV), and minimum acceptable ICMV.

3.2.2 Asphalt Rolling

During the placement of both EME2 and wearing course layers (AC14H-A10E), the IC rollers were functioning and recording data. There were also some occasions in which the IC roller got out of operation and data collection and recording stopped, due to technical or operational issues. These can be common issues which should be considered when deciding whether the IC technology should be the source of quality control, quality assurance or/and delivery for a project. The issues encountered during the trial were as follows:

- The IC tablet ran out of charge.
- The roller had to be out due to refilling.
- The breakdown of the roller at the end of a shift.
- System time-out at the beginning of the shift.
- GPS issue (with accuracy) were the coordinates were not accurate enough.
- No recording of E_{vib}. Were the system was restarted and worked again.
- Occasions when the licence and/or subscription was expired.
- At the beginning, due to the size of the first run, a smaller roller (which was not an IC roller) was used to do the transverse joint.

In these cases, it is better to carry out the last round of compaction with one of the IC rollers.

3.2.3 Testing

Core density test

Based on the area for the trial and the number of shifts, coring was undertaken on 29 locations for the EME2 layer and 25 locations for the wearing course. The coring steps and report details are shown in Figure 3.4.

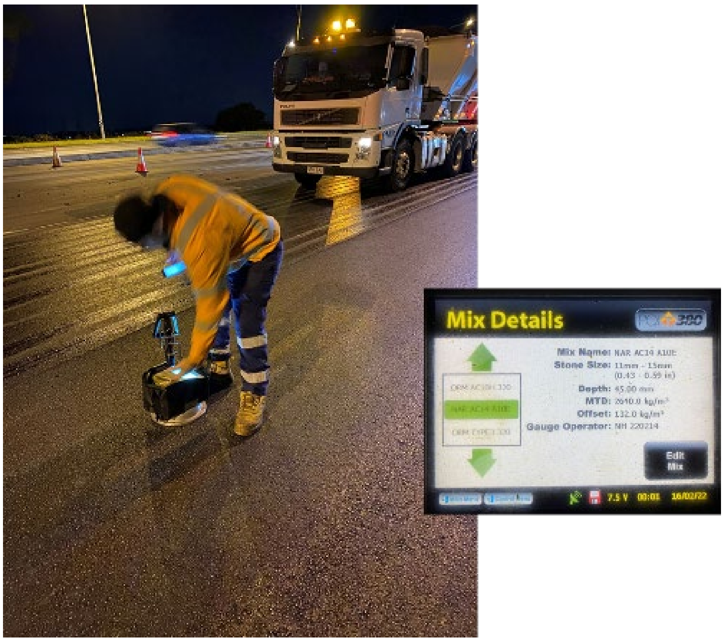
Figure 3.4: Core density test

The results were put into the system to correlate with the IC compaction data and to find out the optimum and required number of passes. The test method for density and moisture that was used was AS/NZS 2891.9.2 and AS/NZS 2891.8 and the number of cores and location of the test points were defined in accordance with Q050 (TMR 2020).

Pavement quality indicator test (PQI)

To be able to have a greater number of test points (for better correlation), another series of tests were carried out with PQI on the wearing course, which is demonstrated in Figure 3.5. The same approach was used to correlate the test results and the IC data.

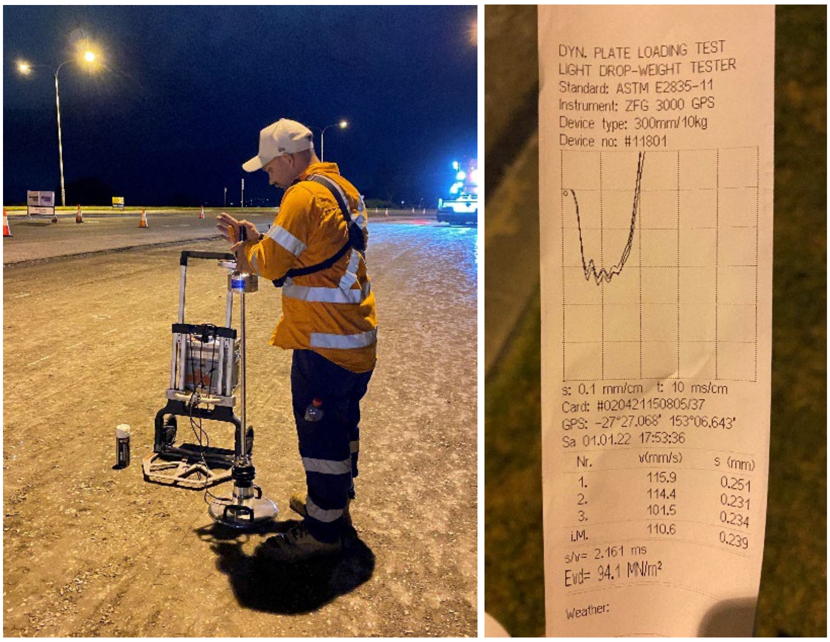
Figure 3.5: PQI test onsite



Light weight deflectometer test (LWD)

LWD testing was part of the original project plan to carry out after each roller pass, but due to the operational constraints during the trial (time and safety), it could not be done, and testing was undertaken on a very limited number of locations. Figure 3.6 shows the LWD testing in process and an example of the test result.

Figure 3.6: LWD test onsite



3.2.4 Recording the Coordinates

As demonstrated in Figure 3.7, to follow the IC procedures, location/coordinates of all the test points and the work boundaries for each shift were recorded by the rover and entered into the system to accurately correlate the test results and IC data sets.

Figure 3.7: Using the rover for recording the coordinates of test spots and boundaries

It is important to have a site-personnel with the right equipment and level of training to accomplish this task. This task should be part of the role for a dedicated site IC personnel who understands the concept and practice.

4 Data Analysis

After extracting the data from the IC system, importing the raw IC data and entering other details and information like test results and work boundaries into the Veta package, the data was reviewed and analysed.

4.1 Veta – Project Monitoring and Statistics

One of the first uses of IC data is to monitor the rolling operation and have statistical analysis on them to improve the quality of work and to assist with making informed decisions.

Statistical analysis can be undertaken on all measured attributes such as E_{vib} (ICMV) for both pre-mapping and compaction processes, passing on each area/point, temperature, rolling speed, amplitude and frequency, etc. and an output can be presented in different forms like coloured spatial map, charts, graphs and tabulated data. The data and analysis results can be easily copied to other applications for more analysis or reporting purposes.

4.1.1 Pre-mapping

The main reason to pre-map an area (on the existing layer) is to assess the support underneath, evaluate the uniformity of the granular layer and identify soft spots (if there are any) before constructing the next layer. The benefits of pre-mapping were confirmed with the analysis of IC data using the pre-mapping approach from the European IC specification. The specification considers any ICMV out of the 'Mean ± 2 * St. Dev.' range as an outlying value. This corresponds to 5 percentile outlying data (ICMV) and can be 'Mean ± 1.28 * St. Dev.' if it needs to correspond with 10 percentile outlying.

The statistics provided in Figure 4.1 are based on the IC data for pre-mapping on the base layer for the trial.

Figure 4.1: Pre-mapping – statistics on ICMV (E_{vib}) for one of the areas: mean = 205.47 & st. dev.= 139.83

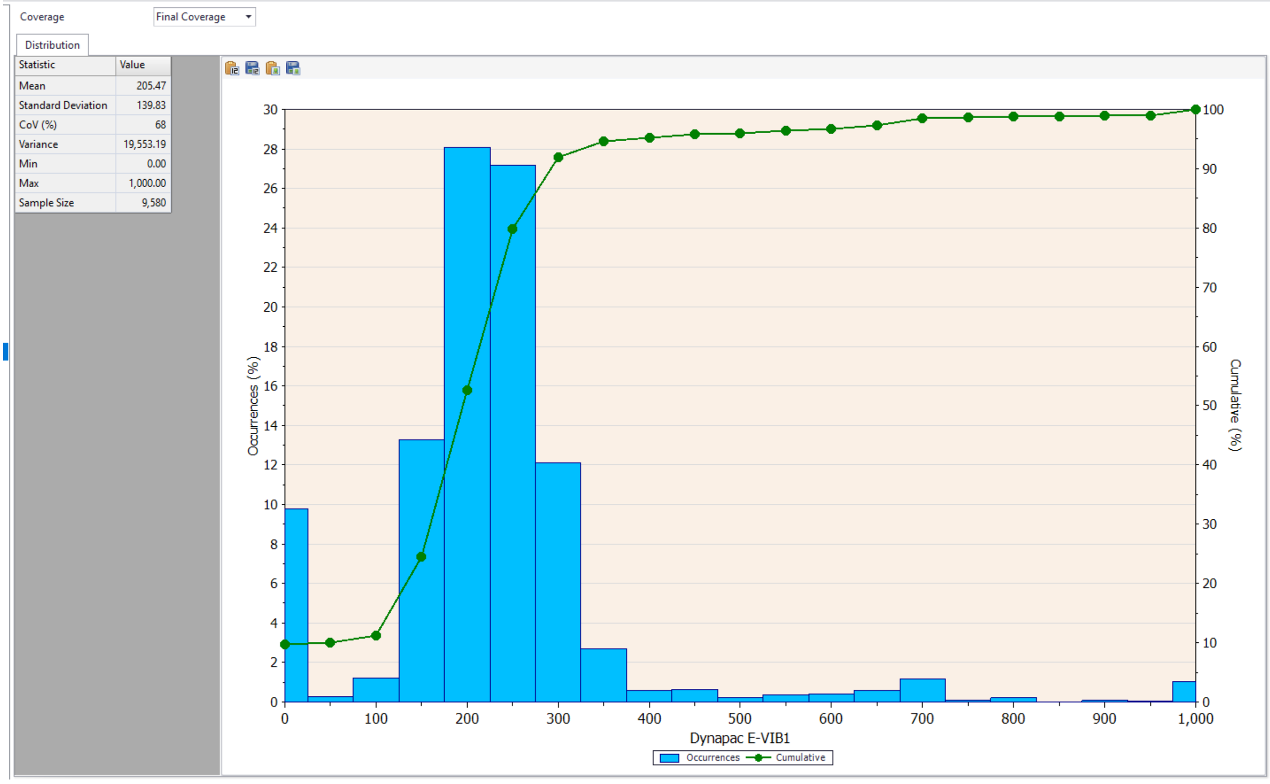
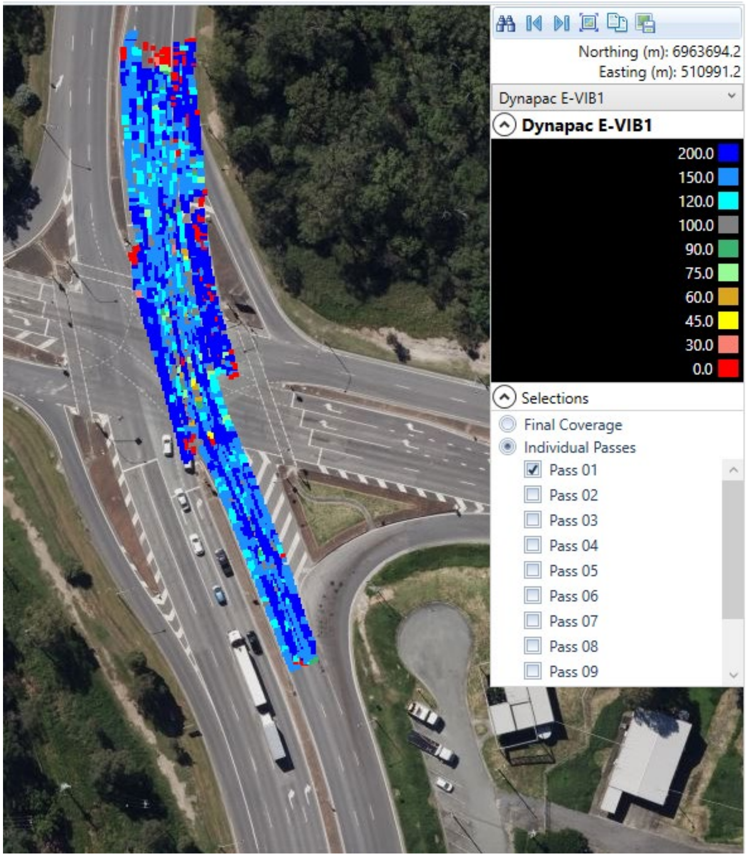
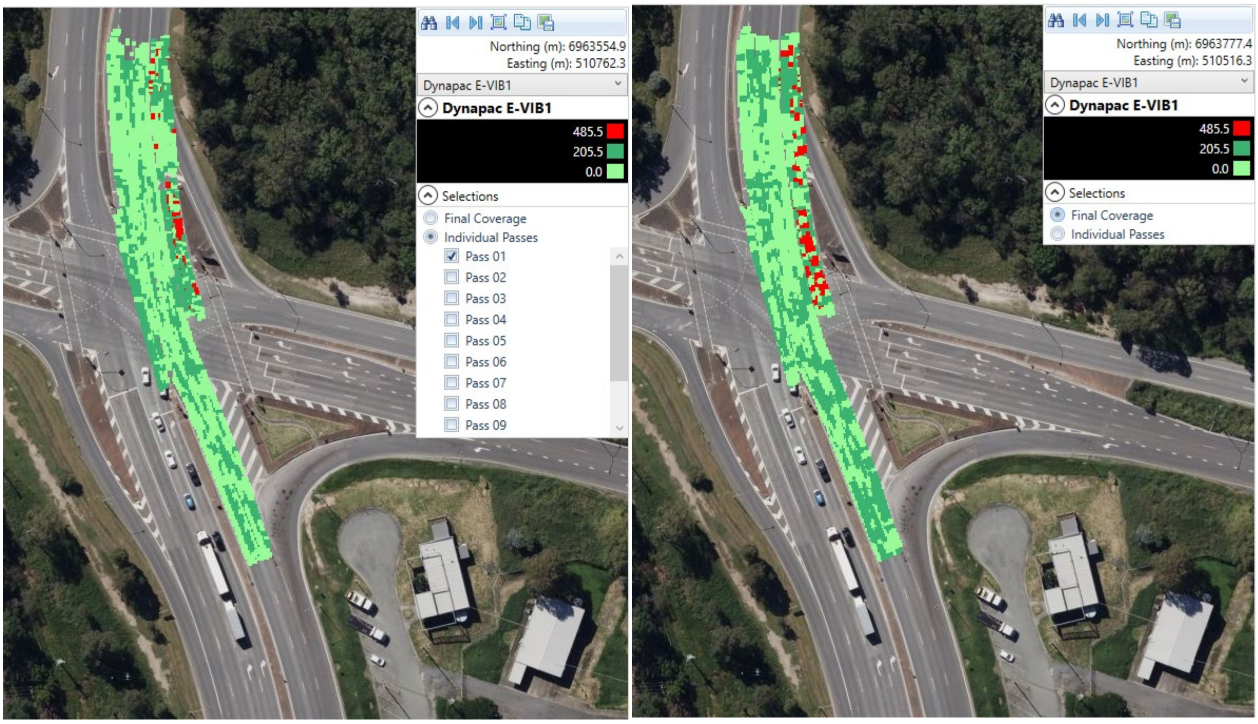


Figure 4.2: Pre-mapping – ICMV (E_{vib}) display for one of the areas



For the collected E_{vib1} for the pre-mapped area shown in Figure 4.2, using the methodology in the European specification (CEN/TS 17006:2016), there were not any soft points (no lower outlying range). To reflect that and to display the acceptable range (particularly for the weak areas), the display can be set in Veta to show these ranges (mean ± 2 * st. dev. which are 205.5 ± 2 * 140). Figure 4.3 demonstrates the ranges for assessing the pre-mapping.

Figure 4.3: Depiction of the pre-mapping results using the accepted ranges from the European IC specification

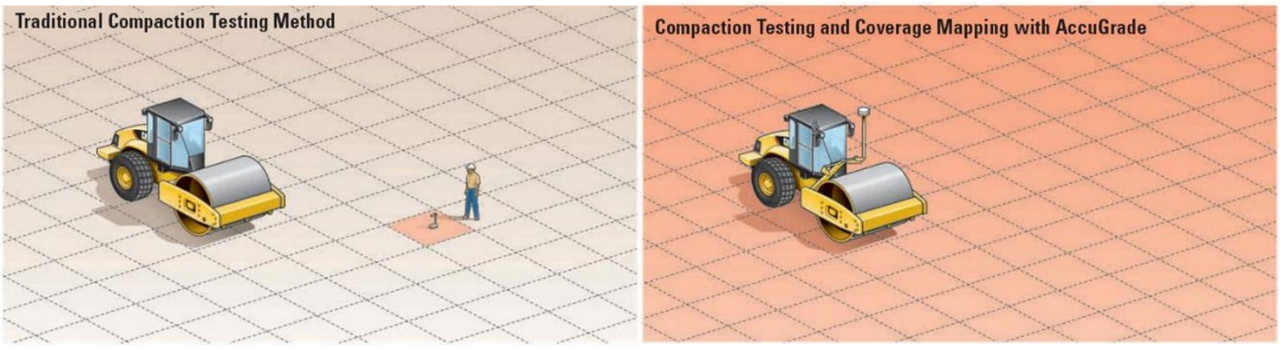


When using the European IC specification, it is important to know that the area of analysis influences the results as the proposed methodology works based on the statistical parameters of the analysed area, and the results may differ a bit when considering different areas for analysis (e.g. a lot/sublot, carriageway or the whole shift or the total job). Practically, each file should be analysed before the next layer is done while there is still time and space to correct the condition underneath (if needed).

4.1.2 Coverage

Coverage is the most important recorded attribute in intelligent compaction and one of the biggest improvements that IC can offer to the road construction project. One of the biggest issues in road construction is the limited testing available for quality control or/and quality assurance. As per Figure 4.4, a traditional compaction testing method can only cover a small portion of the work, while IC reflects the whole area of compaction with more details. To have a tangible comparison between the current method of quality control and the IC methodology, the recent asphalt trial was used to demonstrate the different level of details provided.

Figure 4.4: Differenence of coverage between conventional method of testing compaction vs IC technology



Source: G. Chang (2016)

Quality control

Considering the size of the IC grid cells as 400 mm*400 mm, for the trial area of approximately 11,000 m^2, IC technology provided IC data for 68,750 cells (test points), while the current conventional testing method provides 29 samples for EME2 and 25 samples/data points for the wearing course. This means, that IC has provided over 2,370 times more information for monitoring of the EME2 layer (this value is over 2,750 times for the wearing course).

Work acceptance

Assuming the result of every test point (e.g. core results) can be confidently applied to a radius of 1 m around it (i.e. each core test covers 3.1 m^2), the current methodology can cover only 91 m^2 of the whole rolled area (11,000 m^2) with 25 cores on the wearing course. IC provided acceptance evidence for 9,900 m^2 (even with the worst case scenario where IC coverage is equal to 90%). That means IC provided around 110 times more evidence and reliability for project acceptance.

Considering the work boundaries and the IC data extracted into Veta, Figure 4.5 and Figure 4.6 show the coverage of the rolling work for EME2 and the wearing course asphalt work.

Figure 4.5: Veta output – Port of Brisbane – EME2 – coverage

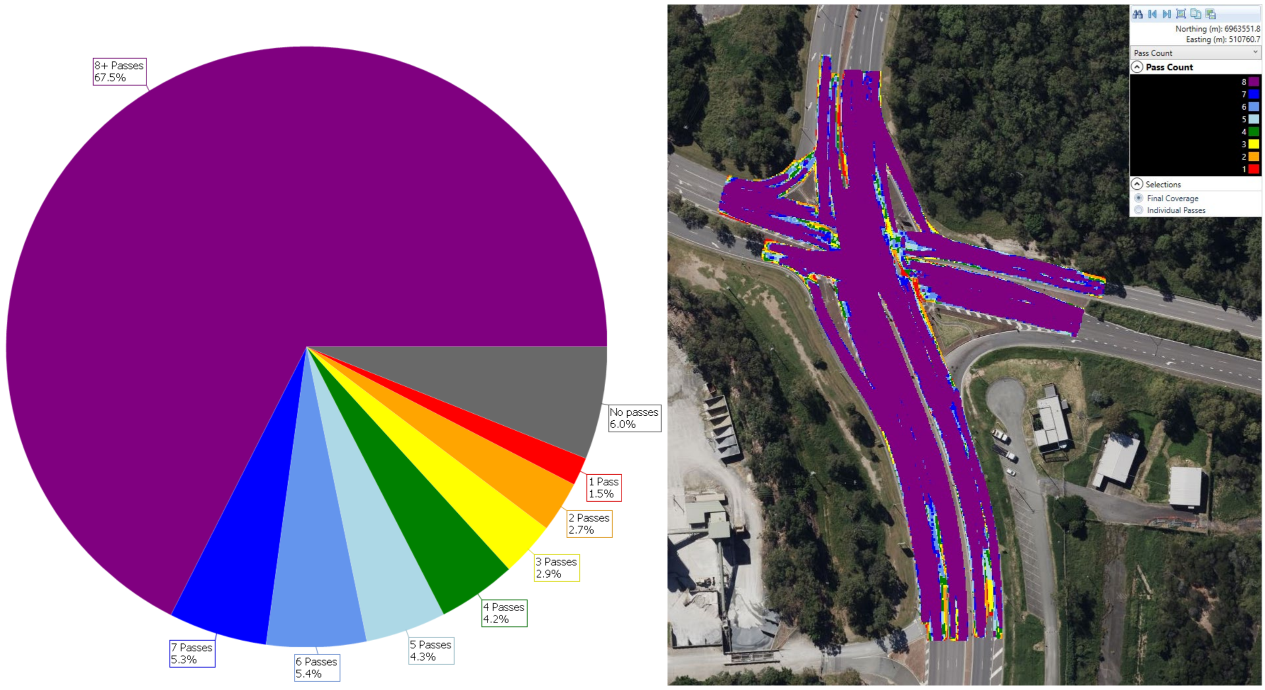
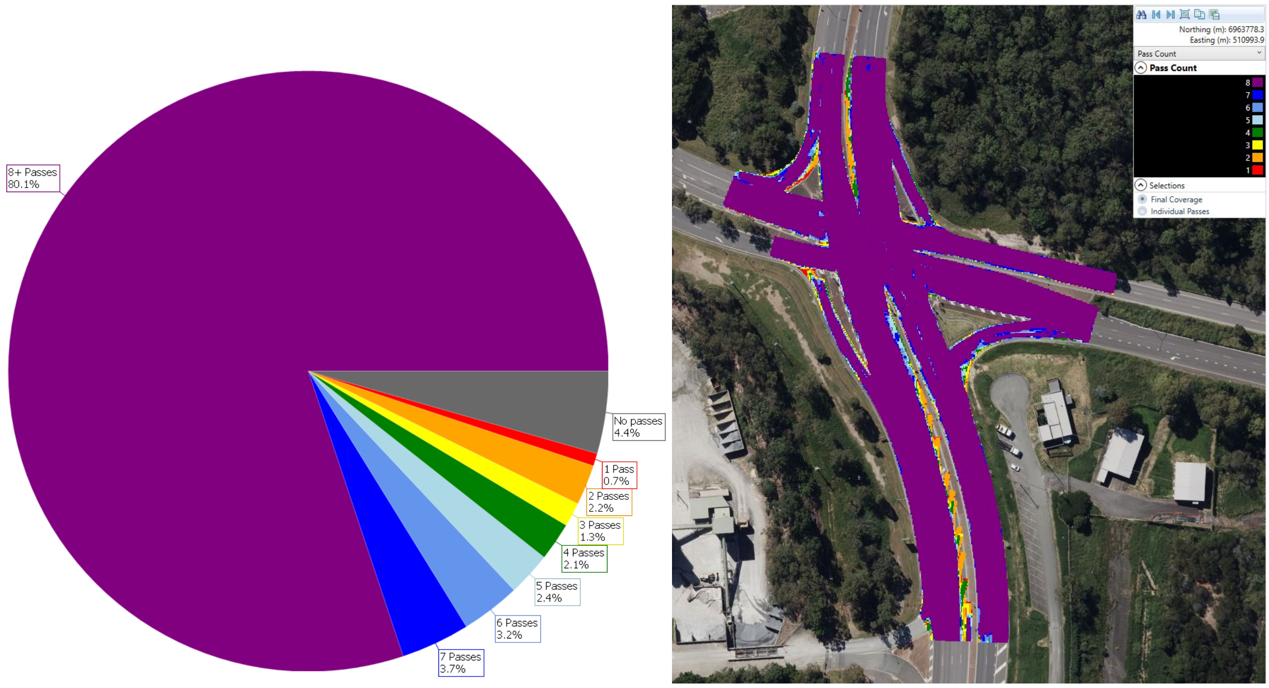
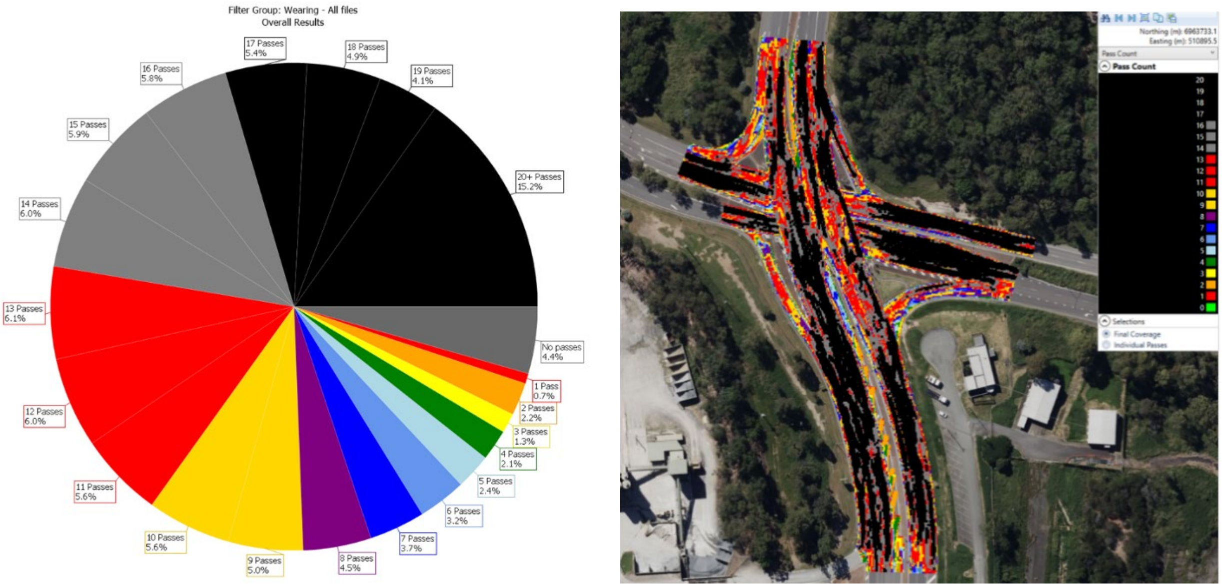


Figure 4.6: Veta Output – Port of Brisbane – wearing course – coverage



The graphs and maps can be easily customised for different data ranges to accommodate the target values or desirable and acceptable/unacceptable ranges. For example, Figure 4.7 was changed and set to spatially present all number of roller passes.

Figure 4.7: Veta output – Port of Brisbane – wearing course – coverage (all passes)



The tabulated data for the IC can also be used for monitoring, reviewing and analysing purposes. One of the uses of the coverage data is to ensure the work is done in an efficient way, as it is possible (and common) to overwork and spend excessive time and energy. This is mainly due to the uncertainty about the work results which comes from not having on-the-fly feedback while compacting. By using IC, the required work (e.g. target number of passes, minimum coverage, etc.) is done with confidence and without the need for extra effort which makes the work an informed practice.

Based on the IC data for the trial, the required work for the project was estimated and compared with the actual work done onsite. For this purpose, the calculated 'Pass-m^{2}' unit was used as the measure for comparison.

Wearing course

As the target number of passes for the AC14H (A10E) was 4 passes, considering the area of 11,057 m^2 for the wearing course, the required work was 44,227 Pass-m^2 (= 4 passes * 11,057 $m^{2\,‡}$).

Note ‡: the term 'pass' in IC means any move on the point (grid-cell). In some parts of Australia in operation sector, the pass means a forward and reverse run together which is recognised equal to 2 passes by IC technology. This should always be confirmed and harmonised in advance. The common practice of the rolling pattern when needs to move laterally, is to shift by half a drum width (till cover the whole width of the work area). So, the first and last roller runs do not get the same number of passes (Figure 4.8) and require extra runs to meet the target number of passes.

Figure 4.8: Rolling pattern during asphalt placement – half-drum width lateral move (overlap)

To include this practical and operational facts in the calculation, the minimum required work was scaled up to accommodate this common practice.

Figure 4.9 and Table 4.1 explain the details of the extra percentage required for rolling. The figures in the Table 4.1 are for different scenarios of placement width and aiming for 4 passes (as target number of passes). Assuming the average run width of 4.5 m, drum width of 1.5 m and additional work around movements and joints, the increased percentage of 25% was applied, which made the required work 55,283 Pass-m^2 for this layer.

Figure 4.9: Rolling pattern and need for extra pass to achieve target number of passes

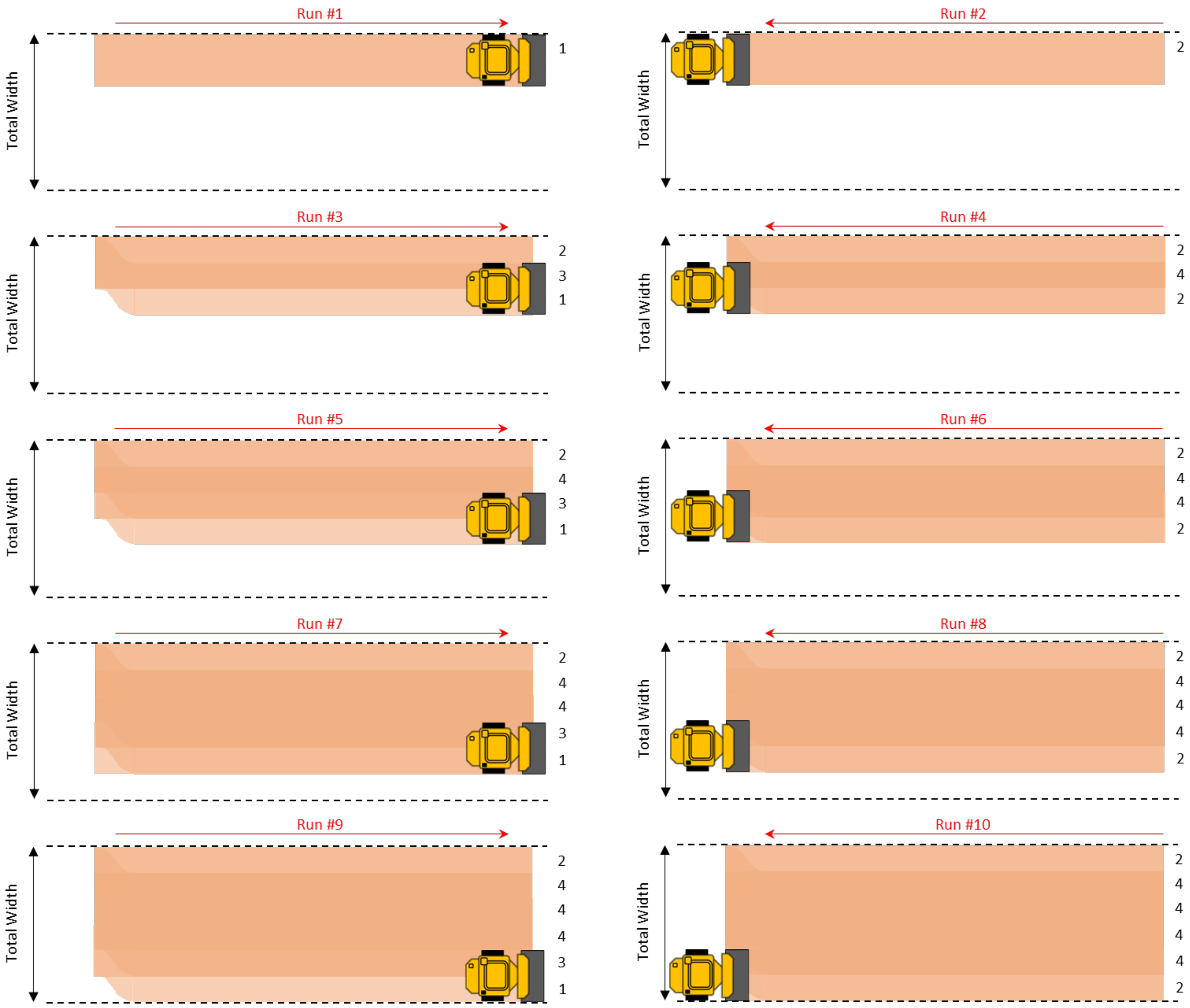


Table 4.1: Percentage of required extra work

Placement width/ roller width	Target no. of passes	Required no. of roller runs		Extra runs required	
		Without overlap	With overlap (half drum)	#	%
1	4	4	4	0	0%
2	4	8	10	2	25%
3	4	12	14	2	17%
4	4	16	18	2	13%

Based on the IC data in Veta, the amount of work done onsite was 140,036 Pass-m^2 (Table 4.2), which is 84,753 Pass-m^2 more than required (equal to over 150% extra work).

Table 4.2: Passing profile for the wearing course (area and percentage of different passes)

Bin name	Coverage (%)	Area covered (m²)	Pass-m²
20+ Passes	15.2	1,676.8	35,213
19 Passes	4.1	451.0	8,570
18 Passes	4.9	543.2	9,778
17 Passes	5.4	596.6	10,143
16 Passes	5.8	643.4	10,294
15 Passes	5.9	656.8	9,852

Bin name	Coverage (%)	Area covered (m²)	Pass-m²
14 Passes	6.0	666.7	9,334
13 Passes	6.1	677.1	8,803
12 Passes	6.0	661.9	7,943
11 Passes	5.6	622.7	6,850
10 Passes	5.6	615.0	6,150
9 Passes	5.0	547.5	4,928
8 Passes	4.5	499.4	3,995
7 Passes	3.7	409.4	2,866
6 Passes	3.2	352.0	2,112
5 Passes	2.4	262.1	1,310
4 Passes	2.1	227.2	909
3 Passes	1.3	143.8	432
2 Passes	2.2	240.5	481
1 Pass	0.7	74.9	75
No passes	4.4	488.5	–
		Total	140,036

In this trial (and for the wearing course), a large part of the rolling work was not necessary and could have been avoided by using IC. This efficiency concept is one of the savings IC can provide to the road construction.

The influential role of IC technology and the improvement it makes will be more considerable when the missed area of 8.6% (areas with not enough passes), including 4.4% of the area with no pass are considered.

EME2

With the required area of 10,249 m^2, and 8 passes as the target for the EME2 mix plus 25% extra work required for overlap and operation, the extra rolling work done was 7.0%. The missed area (areas with not enough passes, less than 8 passes for EME2) was 32.5% (including 6.0% of the area with no pass).

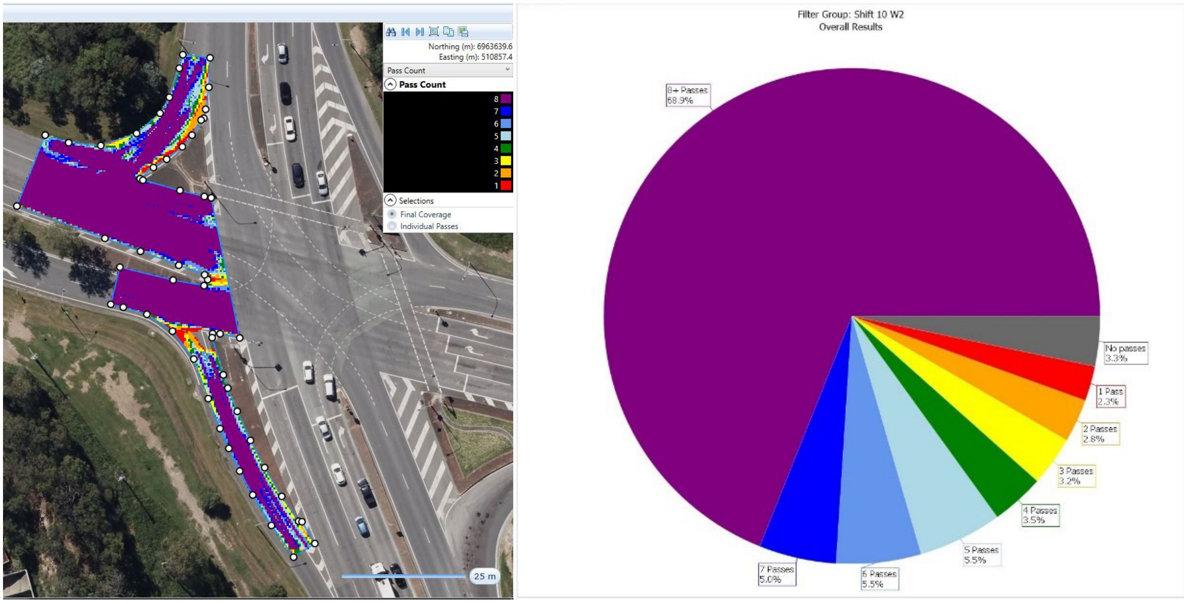
These 2 examples clearly show how the use of IC can direct the work to where it is required and increase productivity.

Coverage of lots and sublots

As IC technology provides the capability to analyse and assess the compaction work in different ways, it is possible to have a report on coverage for different sections/sublots of work and it does not need to be just one lot for the whole shift, etc. This way the results will not be averaged and the information on sublots will be more indicative and can be reviewed for more detailed monitoring. Although it is still possible to amalgamate all data together in Veta, by defining sublots and using them, it is also more likely to achieve better correlation as the data will not be averaged and regressed to all results.

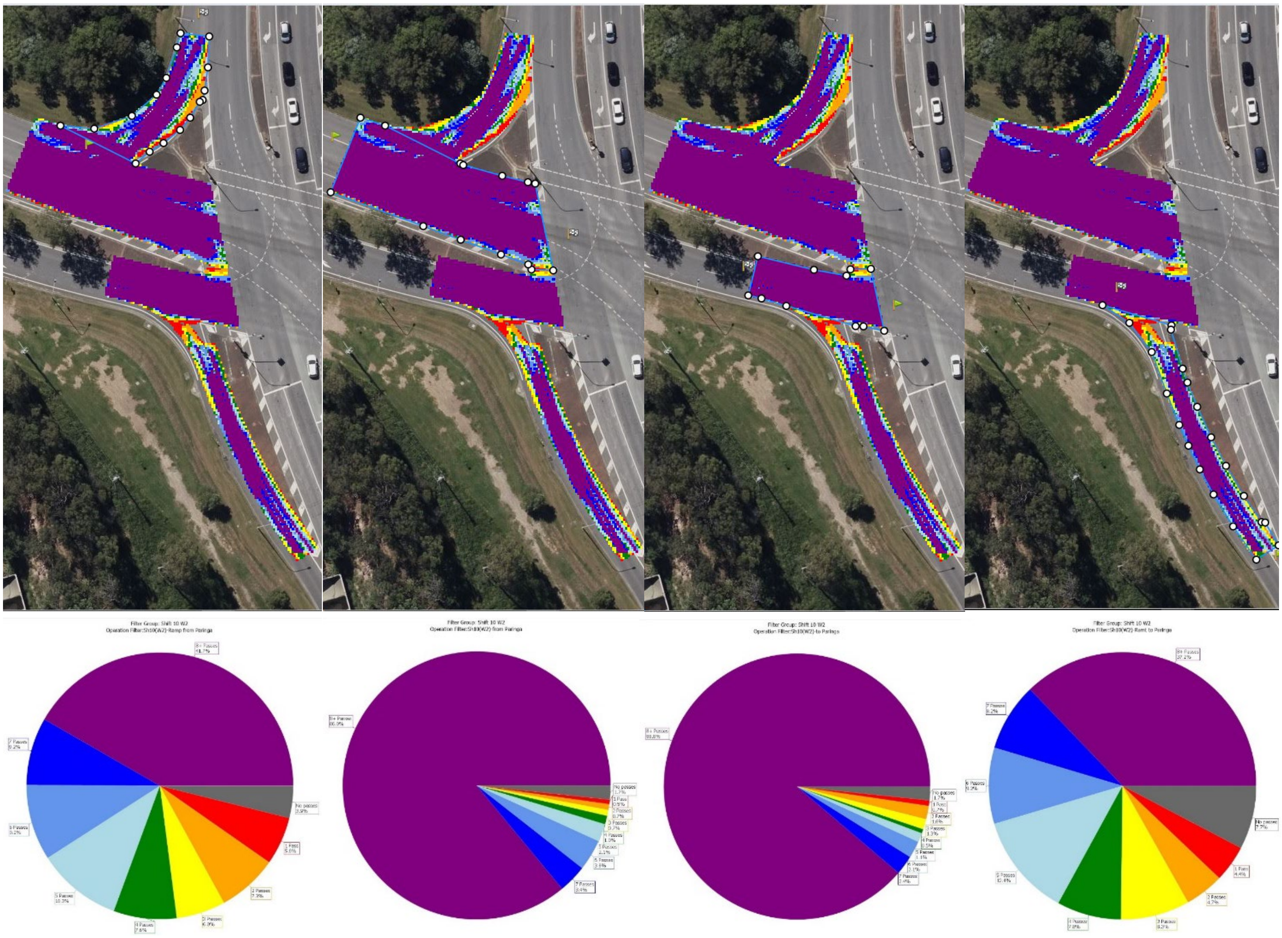
As an example, similar to Figure 4.10, one shift of work can be delivered and analysed/assessed (for quality control or acceptance) as one lot based on overall results.

Figure 4.10: Veta output – Port of Brisbane – wearing course – coverage for the whole lot



Alternatively, as shown on Figure 4.11, the work can be reviewed and assessed as a few sublots with coverage details on each sublot.

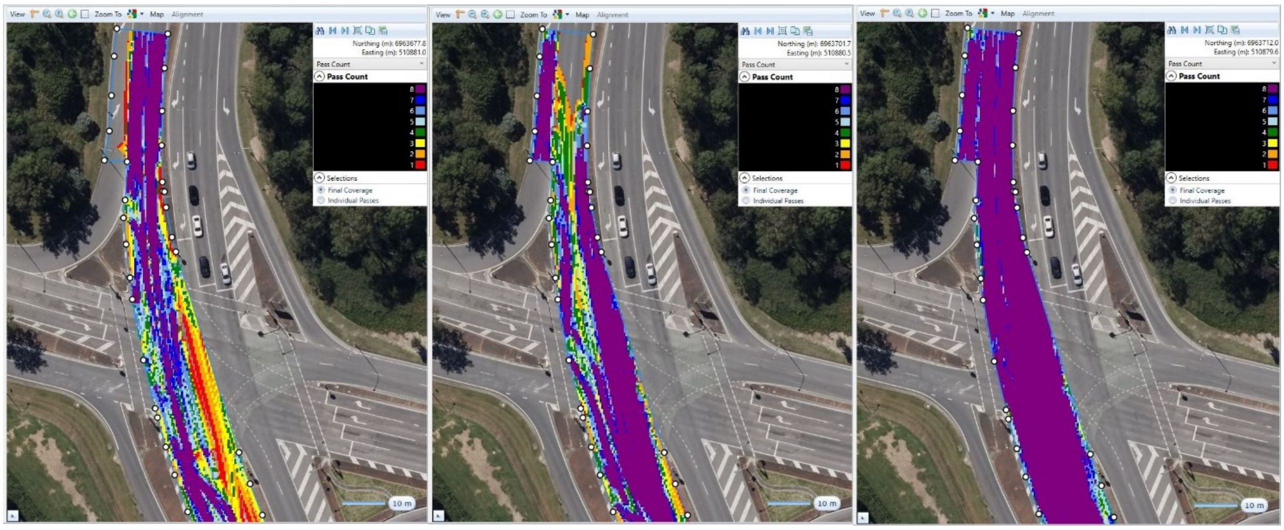
Figure 4.11: Veta output – Port of Brisbane – wearing course – different coverage for sublots



4.1.3 Rolling Pattern

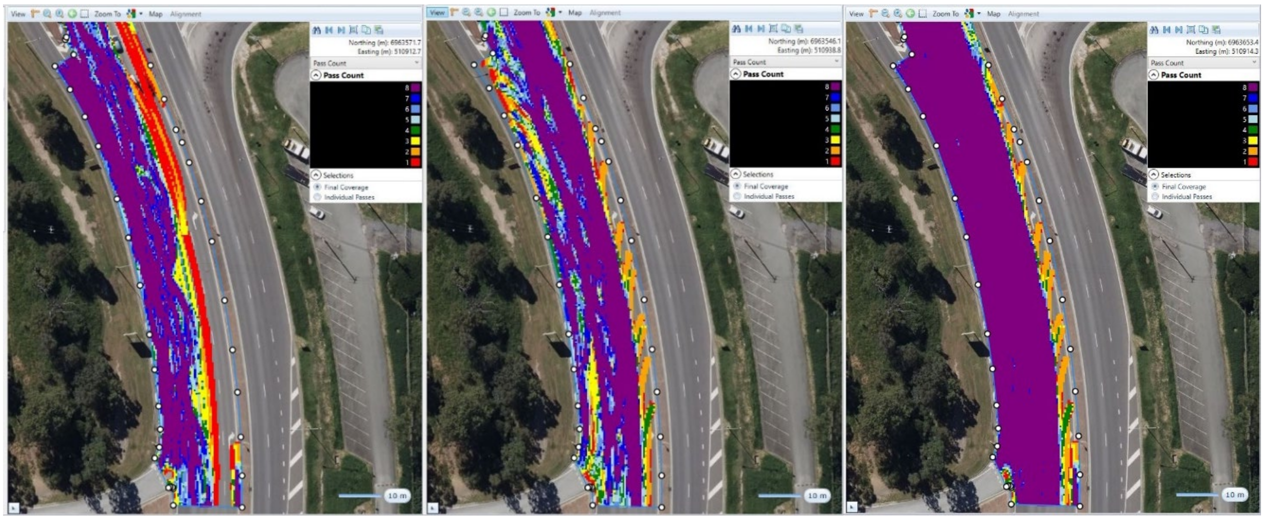
With the IC technology, the rolling pattern can be monitored, and the efficiency of each roller can be assessed. The compaction can also be impacted by the rolling pattern. Details in Figure 4.12 show the rolling pattern of each roller for a section of work (wearing course).

Figure 4.12: IC – rolling pattern (left figure: roller #1, middle figure: roller #2 & right figure: both rollers



As shown in the figures above, there is no pattern for each roller and there are some missing areas which do not meet the 8 pass criteria. Another example demonstrated in Figure 4.13 shows how the work was covered better by managing 2 rollers (knowing where to roll/operate) when the operators communicated. The IC extra feature which supports the display of all rollers is an option to manage the work well and avoid missing any area or pass.

Figure 4.13: IC – rolling pattern (left figure: roller #1, middle figure: roller #2 & right figure: both rollers)



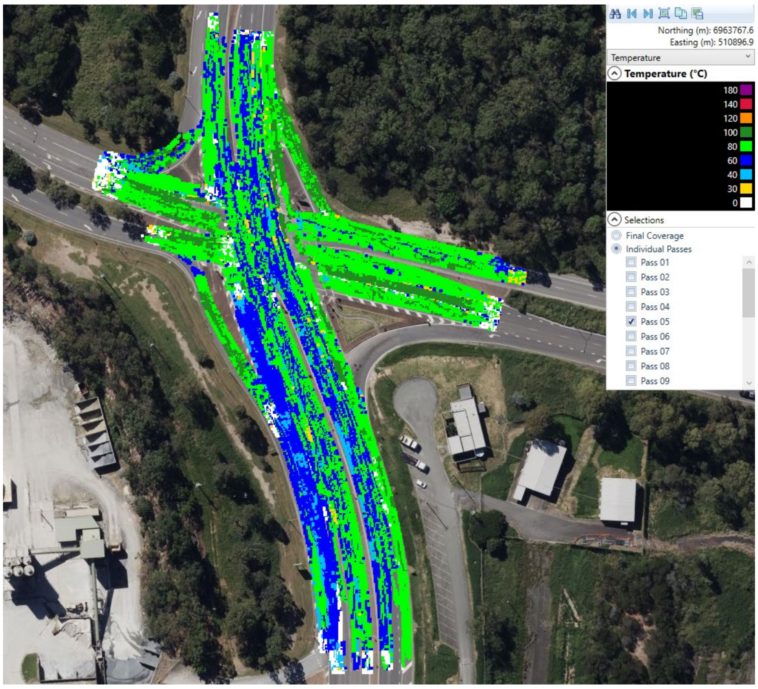
Note: The area on the right-hand side (turning lane) is the work which was done in another shift.

4.1.4 Temperature

One of the main factors influencing the successful compaction of asphalt is the temperature of the mix, and it is one of the main parameters for quality control and quality assurance of the asphalt project using IC technology.

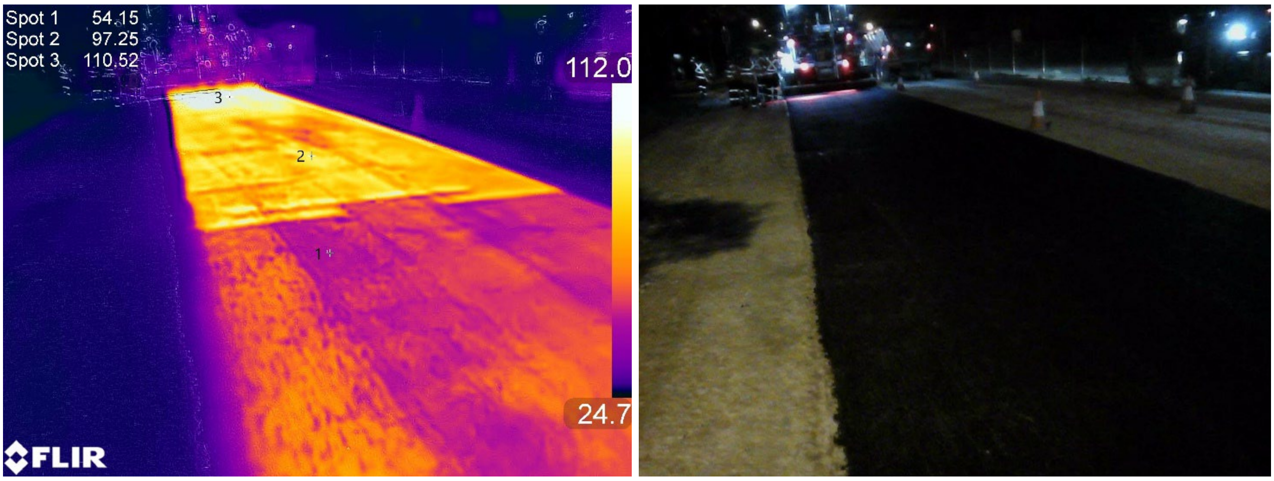
IC measures and records the surface temperature continuously and can provide the information on the temperature of the mix through the compaction process (temperature spectrum over passes). This allows the temperature to be checked at any stage of the work (e.g. check if the mix is hot enough at the beginning and also at the end of the compaction process). Figure 4.14 provides details of the surface temperature for the 5th pass of the trial.

Figure 4.14: Example of colour-coded map for temperature



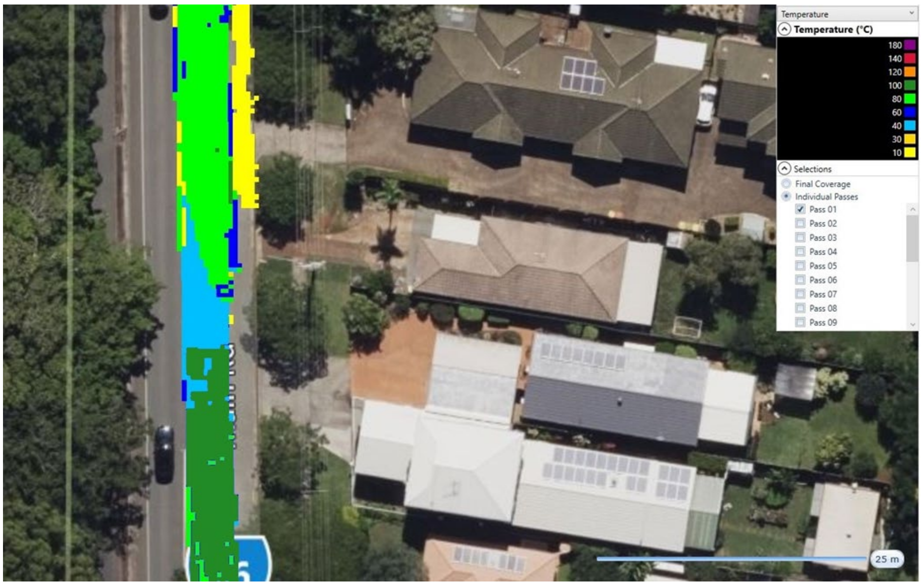
Temperature is one of the main criteria for quality control and IC does not just provide the overall information for the whole work. It also provides details on each point or area. To show how informative the detailed temperature scan on IC is, an occasion in which a paver was stopped for a while was chosen to see if such a situation could have also been detected or monitored by IC and/or reflected in the IC data. Photos in Figure 4.15 were taken onsite to present the event described above.

Figure 4.15: Temperature measured by temp. camera (just after paver moved, following a long stop)



Reviewing the IC temperature data for pass #1, 4 areas/colours are shown in Figure 4.16. Light green (area placed with asphalt mix from truck N, rolled after placement), light blue (area placed with asphalt mix from truck N, not rolled due to the paver waiting), dark green (area placed with asphalt mix from truck N+1) and yellow (for the old surface which roller moved over and parked while the paver was stopped). Different areas clearly demonstrate the impact of the waiting paver.

Figure 4.16: IC temperature data, recorded at the same location – Pass #1



Note: This work was not part of the trial. The project manager happened to be onsite and observed the work.

4.1.5 Rolling Speed

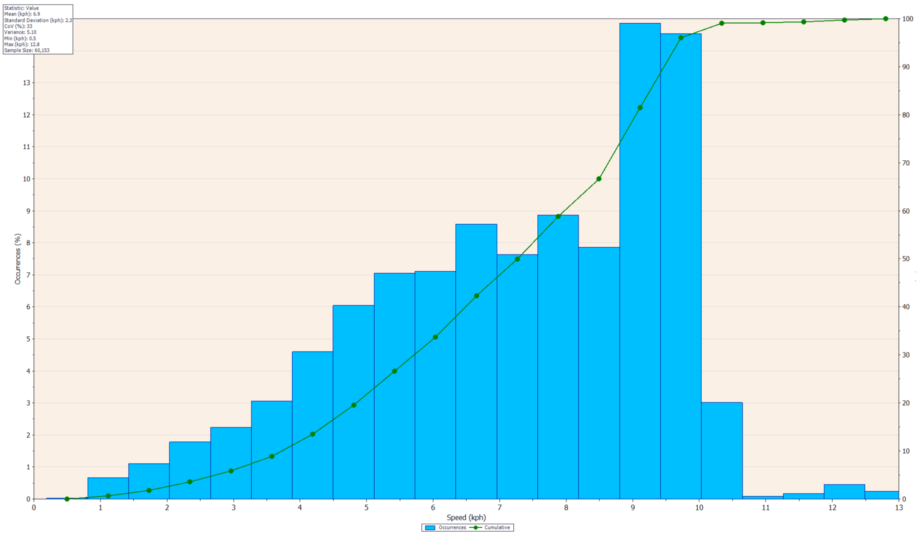
Rolling speed is one of the parameters which has impact on the rolling process to get the right compaction.I It is important to monitor the rolling speed (roller's speed) as it directly influences the compaction results and the quality of the final asphalt surface. The following are important considerations with regards to rolling speed:

- Rollers should travel at uniform speed, which is sufficiently slow to prevent displacement of the mix. Acceleration and braking should be carried out as smoothly as possible. Roller speeds should be in the following ranges:
  - steel wheeled rollers – not exceeding 5 km/h
  - vibratory rollers – 8 to 10 km/h
  - pneumatic-tyred rollers – 6 to 10 km/h (Austroads 2019) *Guide to Pavement Technology Part 8*).
- When roller speed is increased too high, there will be less impact per area covered by the roller and the duration of impact will be shorter. Thus, the required compaction is unlikely to be achieved.
- High-speed rolling tends to disrupt the mechanical bond of the particles, and travel speed, particularly during the initial passes, should be restricted.

IC technology measures, displays and records the rolling speed at each point (IC grid cell) which can be easily reviewed by the operator, foreman and anyone who has access to the system, to check the speed and also uniformity of the rolling work.

In addition to the real-time speed during the compaction work, the graphs, maps and statistics are provided and ready to use at any time. Figure 4.17 shows an example of the provided graph and statistics for a shift.

Figure 4.17: Example statistical charts – rolling speed

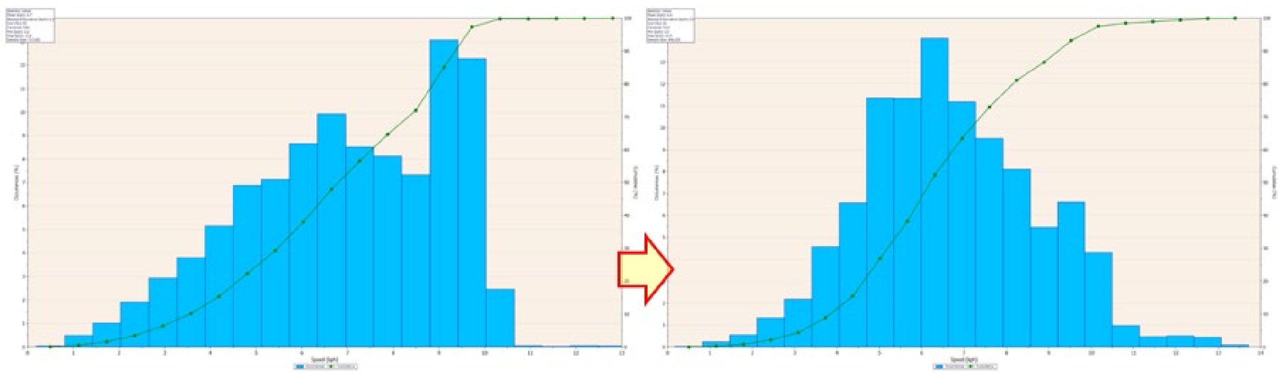


Statistic	Value
Mean (kph)	6.9
Standard Deviation (kph)	2.3
CoV (%)	33
Variance	5.10
Min (kph)	0.5
Max (kph)	12.8
Sample Size	60,153

The outputs (in the form of maps, graphs and tables) are provided for the final pass or each individual pass and can also be correlated to compaction (to see if there is any connection between speed and low compaction). Having the IC technology, and particularly the map (for comparison), gives the operator a better understanding of the situation and is a great tool to limit the rolling speed to the acceptable range (as the display can be set to demonstrate the out-of-range speeds in a particular colour).

Figure 4.18 is an example of improving (reducing) the rolling speed by using the IC technology (i.e. just knowing the fact that speed is monitored and recorded).

Figure 4.18: Change of rolling speed after using IC



4.2 Veta – Ability to Filter Data

Veta has a useful feature to filter data which can be applied to display and/or analyse the data for different purposes. This powerful tool accommodates different needs and strategies. Filters can be applied on different aspects and attributes. Table 4.3 and Table 4.4 explain some of the filters within Veta.

Table 4.3: Data filters in Veta

Attribute (data filters)	Filter options	Example of use/application
Compaction mode	• Oscillation • Static • Vibratory	Determine where each mode was used. Include/exclude modes from display and analysis.
Direction	• Forward • Reverse • Neutral	Include/exclude directions from display and analysis (e.g. in some common practices reverse rolling is not counted in number of passes).

Attribute (data filters)	Filter options	Example of use/application
Amplitude	Define the range	Include/exclude areas/points with the defined range (display and analysis). Define the areas/points with outlying values.
Frequency	Define the range	Include acceptable range for display and analysis. Define the areas/points with outlying values.
Pass counts	• Final cover • Each pass	Display/analyse based on particular pass.
Speed	Define the range	Include areas with acceptable or defined range (display and analysis). Define the areas/points with outlying speed.
Temperature	Define the range	Include/exclude areas with defined range (for display/analysis). Define the areas/points with outlying temperature.
ICMV (E_{vib}, CMV, MDP, etc.)	Define the range	Include/exclude areas with defined range for display and analysis.

Table 4.4: Operation filters in Veta

Attribute (operation filters)	Filter options	Example of use/application
Location	• Offset • Customised: defined by the boundary points. Points can be manually put in (sketched) or use the coordinates from file/rover.	Not all the areas under the roller should be included in display and/or analysis, particularly for the coverage.
Location exclusions	• Offset • Customised	Excluding operational exclusion zones from analysis and assessment, e.g. bridges, areas on top of utilities (and cannot be compacted with vibration), etc.
Machine ID	• Selecting the machine	Differentiate between rollers. Exclude work of certain roller. Compare the work output of different machines.
Time	• Define the time range	Select/include the data captured in a certain period of time. Compare operator's performance (speed, rolling pattern, area, etc.). Compare the outcome at different time of operation.

4.3 Veta – Project QC and QA

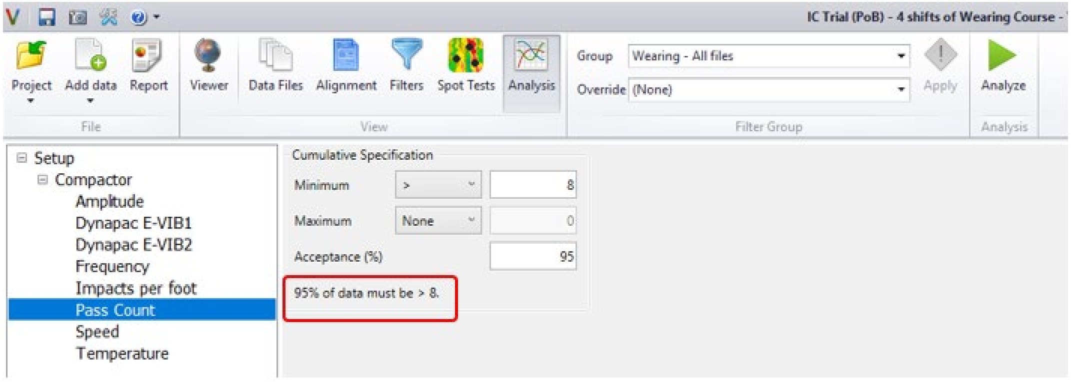
Veta has the capability of assessing each lot and sublot based on defined criteria, and on any IC attribute. The project acceptable criteria (or any defined business rule from the contract or specification) can be put into the system to identify the conformance of the work lots accordingly.

As an example, rolling coverage and temperature are demonstrated in the next two paragraphs.

Acceptance – coverage

As the most important criteria for IC delivery, the minimum required number of passes for the minimum coverage is defined to assess the work lots. Figure 4.19 shows how this criterion can be defined in the system and applied for different lots (and also sublots).

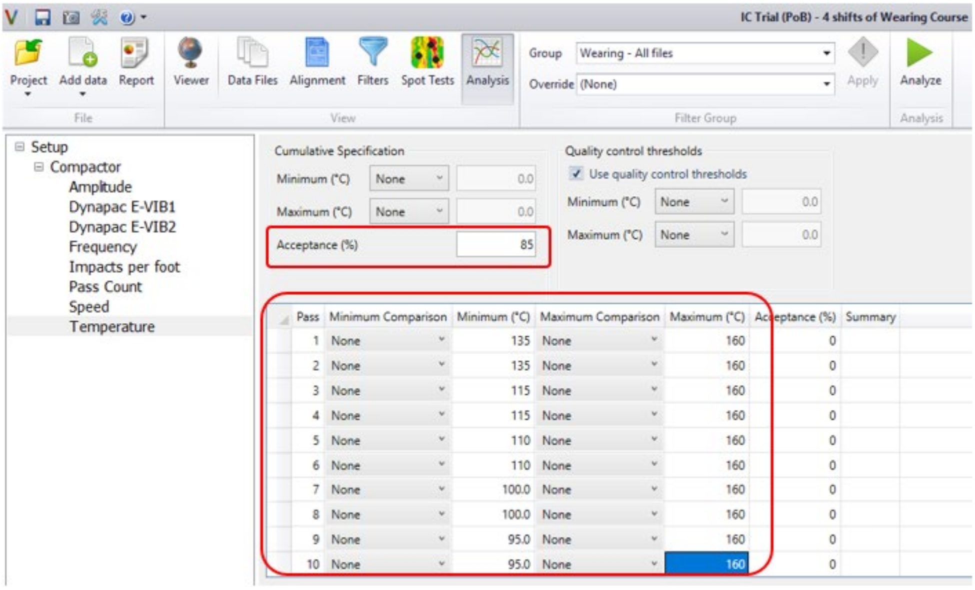
Figure 4.19: Applying the acceptence criteria for coverage



Acceptance – temperature:

As shown in Figure 4.20, the required temperature for asphalt work can be defined for each lot and a minimum defined percentage of the area should meet the criteria for conformance of that lot.

Figure 4.20: Applying the acceptance criteria for different attributes – surface temperature for each pass



This can be individually defined for each pass to assure the conformance of temperature of the surface at the end of the rolling/compaction work as well. The different criteria and levels of acceptance can be used for project quality control and quality assurance.

4.4 Veta – Correlation

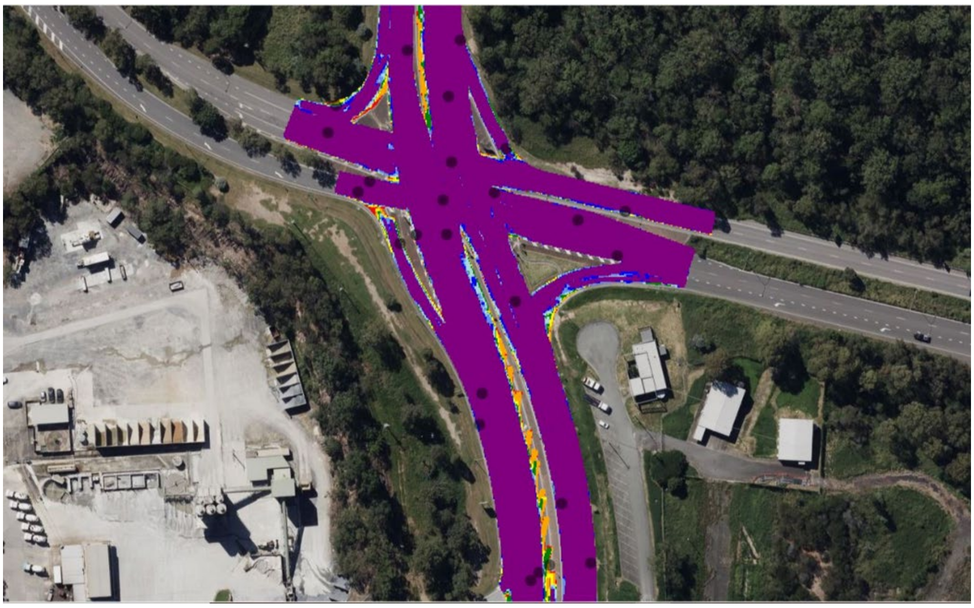
Finding the correlation between current practice/methodology and IC is the key task for job delivery, quality control and work acceptance. The correlation process for asphalt is not the same as granular materials in which the target ICMV is defined because the ICMV for asphalt is impacted by the temperature of the mix at the time of rolling, and as the temperature varies point to point, no unique target ICMV can be defined.

Based on the tests and IC data, the required number of passes can be defined as the outcome of the correlation.

4.4.1 Correlation – Core Test – Wearing Course

The results of core tests undertaken for the 50 mm wearing course (AC14H-A10E) was entered into the system. The results can be displayed in the system similar to Figure 4.21.

Figure 4.21: Core test results on the wearing course (including locations) in Veta



The graph in Figure 4.22 was generated by the Veta package.

Figure 4.22: Correlation – wearing course (AC14H-A10E) – number of pass vs density (core)

Considering the average maximum density of 2,640 kg/m^3, the required number of passes are shown in the graph above which matches the practical site experience working with this mix.

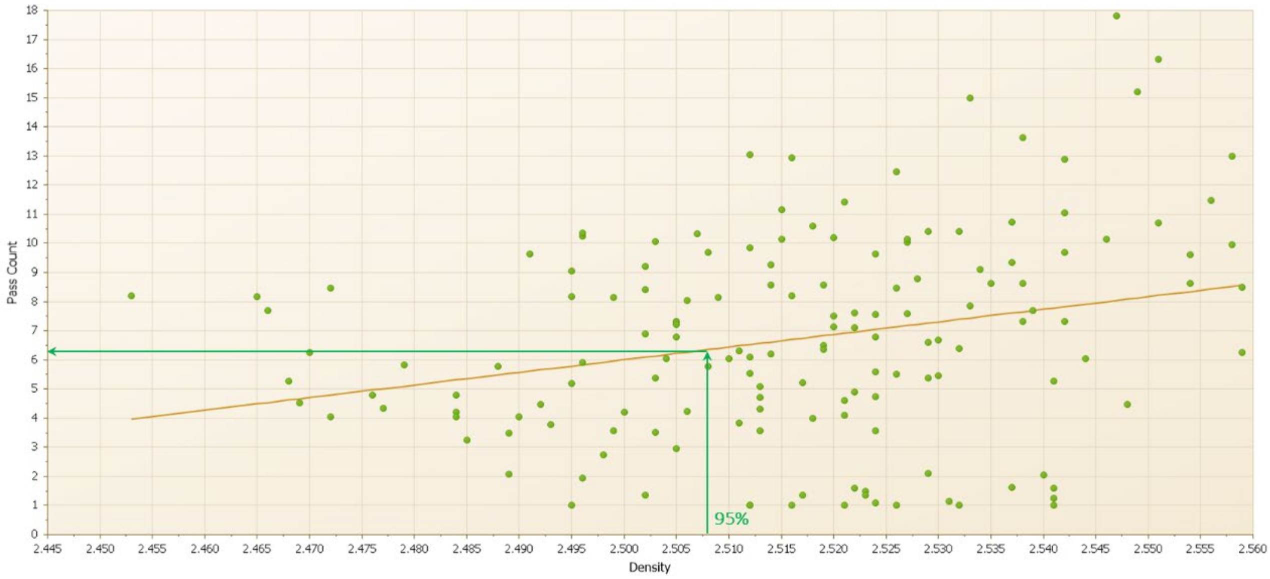
4.4.2 Correlation – PQI Test – Wearing Course

The PQI test results were also used with the same approach for correlating the testing with the IC outputs and their locations and distribution is shown in Figure 4.23.

Figure 4.23: PQI test results on the wearing course (including locations) in Veta

A similar outcome was concluded for the wearing course and the results are demonstrated in Figure 4.24.

Figure 4.24: Correlation – wearing course (AC14H-A10E) – number of pass vs density (PQI)



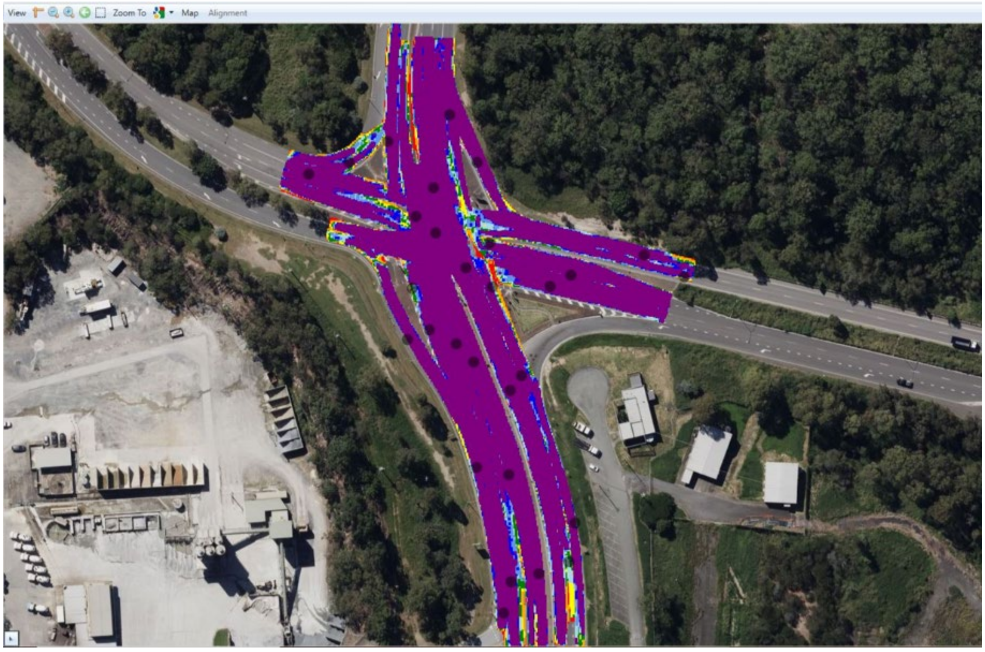
Note on definition of 'Pass'

In IC technology, the term 'pass' refers to each move the roller goes over a grid cell (based on the rule described in Figure 2.23). As this is the definition of pass among a majority of crew (not all), it is preferred to confirm this in advance with the crew onsite and also the team who is going to work on the IC data, analysis and reporting.

4.4.3 Correlation – Core Test – EME2

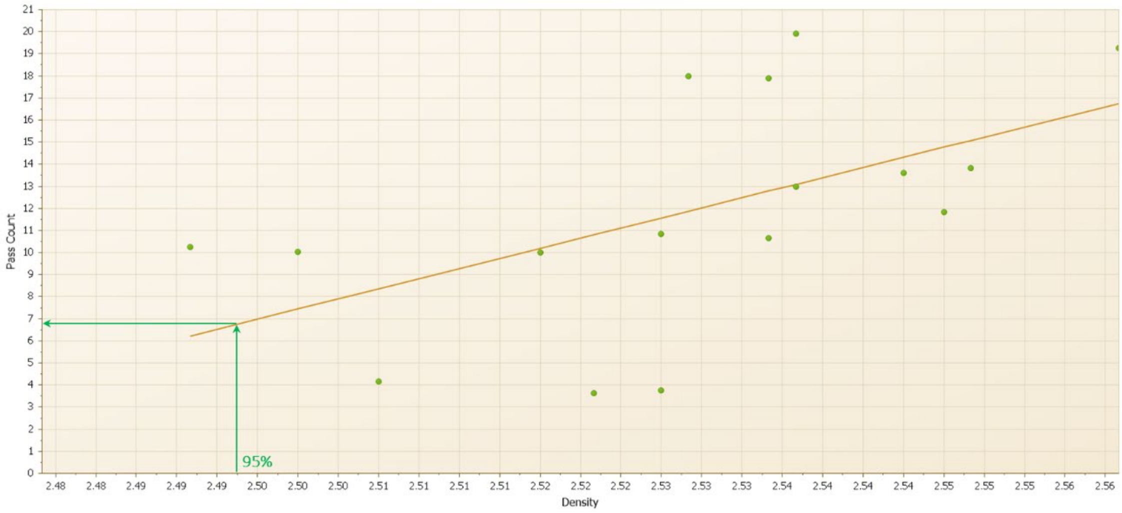
The same methodology was applied for EME2 layers for the correlation of target number of passes. The location and distribution of the test points are shown in Figure 4.25.

Figure 4.25: Core test results on EME2 (including locations) in Veta



The result of correlation graph is demonstrated in Figure 4.26.

Figure 4.26: Correlation – EME2 – number of pass vs density (core)



Based on this graph, to get the compaction on the 100 mm EME2 layer, over 7 passes are required. The experience (minimum of 8 passes for this mix and thickness) also confirms this number of passes.

5 Dissemination of the Knowledge

To promote the use of IC technology and its benefits and accelerate its implementation, the project team continued to present the findings, experiences and observations at the trial in webinars. The need for training to assist in the rollout of IC technology within the industry was also identified. Due to the COVID-19 outbreak, all of the knowledge transfer activities conducted this year were delivered online.

5.1 Webinar

Webinars on the IC concept and the findings of this project were presented online. The results from this year's work will be incorporated into future discussions with future development of IC technology in Queensland and Australia. The webinars were accessed by a large audience.

A webinar was hosted by AfPA where the IC concept and the P105 project details including the trials were presented. The webinar took place on 24th of March 2022 and was entitled 'Introduction to Intelligent Compaction' and covered the following topics:

- What is IC?
- Why use IC?
- IC systems/types
- Where IC can be used
- Benefits and challenges
- Case studies (gravel & asphalt layers).

The NACOE webinar on 9 June 2022 entitled 'Intelligent Compaction, the Future of Road Construction' was held by the project team. In addition to the concept, case studies and lessons learned from P105, representatives from manufacturers also presented their relevant IC products and services followed by a Q&A and panel discussion.

5.2 Training Sessions

On 23 and 24 June, the Australian flexible Pavement Association (AfPA) organised 2 half-day online virtual training sessions on intelligent compaction. NACOE provided support by organising the event and preparing the material. This training was the first one in Australia and the topics below were presented and covered:

- basics of IC technologies
  - IC concept and its use, IC elements (including hardware & software requirements)
  - IC benefits and challenges
- IC data collection and data characteristics
  - operational set-up
  - trial section and target ICMV
  - practical points (including the checklist prior to and after rolling work)
  - basics of Veta software including features, how to operate (filter groups, etc.)
  - data analysis and interpretation

- practice hands-on Veta analysis (understand in-depth IC) using different examples for soil
- troubleshooting.

5.3 Conference and Forum

The IC technology was one of the topics to be presented at the 2022 Engineering, Innovation, and Technology forum, but it was cancelled due to COVID-19.

6 Summary and Conclusion

The asphalt trial undertaken in Year 4 of NACOE project P105 was an experience to better understand the requirements (including the extra involvements, resources and infrastructures) to be able to plan, establish and deliver an IC project.

6.1 Summary and Lessons Learned

- As much as machinery and software packages are important for the use of IC technology, training also plays a very important role in terms of using the system appropriately. Without the right level of trained personnel, the whole practice cannot provide the best outcome expected from it. Instant changes and improvement were observed just showing the display screen to the operator.
- IC seems to work well for quality control purposes, but not yet for quality assurance on asphalt pavement layers as the ICMV (E_{vib} values in this case) can be misleading with asphalt as they are also impacted by the temperature of the asphalt.
- It is vital to set an integrated system that communicates well among all components of the system, have compatibility and understands the outputs from other elements of the system. The same settings on all measurements (GPS coordinates, roller settings, rover setting, etc.), planning and having example of outputs make the process smoother.
- Pre-mapping is a crucial part of the asphalt placement projects, because it not only defines the situation of the work prior to the construction of the asphalt layer, but it can also be used later in maintenance and asset management.
- The ICMV for asphalt is not yet an indicative attribute (as it is for granular pavement layers) as it can vary due to the temperature of asphalt mix.
- Some points on site operation include:

  - The time on different units like rollers, rovers, etc. and systems need to be set to the right local time as sometimes the data is required to be checked, referred back to or linked to other information based on the time of the operation or work.
  - It is suggested to look at the statistical analysis at the end of each work shift as it gives indicative information about work on that shift.
  - A high number of IC grid cells with a low E_{vib1} value and amplitude are common in IC practices and projects.

    In IC files, around 20% of the grid cells have a low E_{vib} value (E_{vib} of 1~10). Based on the manufacturer's explanation, E_{vib} values are recorded once the vibration frequency passes a certain threshold. The readings, however, are not really reliable if the frequencies vary too much. The E_{vib} tends to show low readings at frequencies below the nominal vibration frequency and there was a theory that low E_{vib} was caused during the work by the E_{vib} values recorded during start-up and rollout of the vibration at frequencies below the nominal (which usually happen close to the end of the rolling run/strip, just before the roller operator stops at the end of each run). This was checked onsite by monitoring and recording the location of the stop and start of the rollers, and later on, these exact locations were checked in Veta to verify if they had low E_{vib} values. A majority of the locations that had low E_{vib1} were located at the areas where the operator stopped the vibration (either before stop or after start of rolling).

    It is important to have a solution for this, as it may impact the correlation process. Although there are some solutions in the manufacturer's manual (such as filtering the speed, frequency, etc.) to

  overcome this issue, it is a work in progress to finalise a standard or suitable procedure as the display and inclusion of other attributes (like temperature, etc.) might be impacted/excluded.
  - If the outputs of 2 or more rollers are supposed to be compiled and imported (and analysed) together, they should have the same format for output files, otherwise the data cannot be aggregated to one single file. Different manufacturers has their own system, with output formats and packages which produce unique files to themselves, and it is necessary not to have 2 different brands in a shift work.
  - Defining and analysing the work as number of sublots can help the project to be monitored better as sublots can give more details of the work, and if there is a problem, the whole lot (or shift) does not need to be re-worked.
  - There are many factors (such as breakdown, use of non-IC roller, refill of roller, out of charge tools, etc.) that impact the operation of the rollers; therefore, these occasions need to be considered in operation planning.

- Developing and applying a checklist helps the establishment and output quality of work.
- During the practices, some limitations while using the Veta package were discovered. When intending to use the sub-lotting feature, the following details should be considered for the defined and selected sublots for the better outcome:

  - very wide works (over 12 m)
  - long jobs with horizontal curves
  - exclusion areas (with not whole width of the carriageway).

6.2 Conclusions and Recommendations

This report is a summary of the activities undertaken during Year 4 (2021–22) of the P105 project. The project team (TMR and the Australian Road Research Board (ARRB)) planned a trial at one of the TMR asphalt projects at Port of Brisbane (Lytton Road, Murarrie) and analysed it for compaction auditing. The IC technology (OEM Dynapac, E_{vib}) was trialled on 2 asphalt mixes including EME2 and a wearing course (AC14H-A10E).

From the compaction auditing trial, it was found that IC technology can readily identify the area which has not been covered enough (by required number of passes) and can be used to monitor the temperature of the asphalt mix during the operation, until the end of construction work. As E_{vib} (and other ICMVs) are sensitive to the asphalt temperature, the correlation cannot be made and a target ICMV cannot be defined yet. Therefore, the following is recommended:

- It is highly recommended to use IC for quality control purpose. At this stage the below criteria can be targeted for this purpose:

  - Coverage of target number of passes:
    As the number of passes is dependent on the mix type and thickness, it should be defined by the correlation process or experience. The required coverage for asphalt mix is usually set at 90%, but it is recommended to still accept 80% (with penalties) where less than 75% is not accepted.
    For this purpose, practical rules around an exclusion area should be defined (e.g. to exclude bridges, pipes, utilities, etc.) to identify the required area and how the exclusion should be applied.
    It is also recommended to review the definition of Lot for work.
  - Coverage of target ICMV:

For a granular pavement layer, the cover of target ICMV must be checked and assessed. This means a certain percentage of the compacted area should have ICMV equal to or greater than the target ICMV. The common practice is currently to have 90% of the area achieve minimum 90% of the target ICMV.

  - Surface temperature range:
    The common practice around the world is to monitor/control the mean temperature for each lot to be above 80 °C, but it is recommended to consider another parameter of temperature uniformity to also reflect the consistency of the work.
  - Rolling speed:
    In road construction, the speed range or limit for rollers can vary depending on several factors, including the type of roller and the specific operation being performed. However, it's important to note that excessive speeds can potentially lead to quality issues. As IC technology provides the capability to easily monitor rolling speed, it is recommended to introduce criteria for project acceptance. This criteria for each roller and work type can be a minimum percentage (e.g. minimum of 95% of the covered area) not to exceed the upper-speed limit (e.g. 7 km/h) or deviate from an acceptable speed range (e.g. minimum of 90% within the 2 km/h – 7 km/h range). By adhering to this limit or range, effective compaction of asphalt or other materials can be achieved without compromising the quality of the construction. Specific projects or organisations may have their own regulations on speed limits or acceptable ranges for the rollers. These limits may vary based on factors like the type of material being compacted, layer thickness, and the specific equipment used. The ultimate goal is to strike a balance between achieving proper compaction and ensuring uniformity and consistency throughout the construction process.

- For the E_{vib}, the nuclear density gauge (NDG) and non-nuclear density gauge (NNDG) measurements increase with increasing roller pass numbers with the change rate reducing with roller pass numbers.
- It is recommended to also use/look at the 'ICMV Progress' in addition to 'Target ICMV'.
  The ICMV Progress will show how much the ICMV changes on each pass. During compaction the ICMV changes significantly between passes. Once the stiffness of the material increases the progress from pass to pass will decrease as achieving less with each pass. Once this progress reduces or stops then it illustrates that the machine cannot compact the material (with this condition and in this situation) any further. The ICMV values are still used/analysed to look for weaker areas. If the ICMV progress in these 'weak' areas is still very small, it is understood that most likely the issue is not in the pavement material of this layer but in the subgrade (or other layers underneath) deflecting or the moisture is not right. This helps to better interpret the situation and make an informed decision. Additional to Target ICMV, the range/target for ICMV progress can be defined to stop rolling.
- Pre-mapping should be part of standard practice in asphalt projects to record the condition of the granular layer underneath and identifying the soft spots.
  The points below should be considered:

  - Pre-mapping stiff materials such as existing or milled asphalt pavements, or concrete pavements is not recommended.
  - A standard practice should be defined to identify the soft spots. This includes

    - the approach of analysing the data
    - the minimum area to be considered for soft spots.

  - Double jumps should be prevented during pre-mapping or common compaction operations.

- It is understood that current IC technologies are all based on proprietary technologies from each equipment supplier. The success of any project will rely on identifying and agreeing on a consistent data standard/interface being adopted (ideally nationally).
- As the GDA2020 is now covered in Veta, it is recommended to harmonise the files by contractually requiring this coordinate system to be used in projects.
- It was realised early in the project that there will be significant learning required for the industry to become familiar with the technology and incorporate it into construction practice and get significant benefit from it. It is recommended that this technology be further developed and promoted for use on TMR construction projects by continuing the information sessions, masterclasses and trainings.

6.3 Future Works

Based on the relevant studies done overseas, the experiences gained during the last 4 years of the P105 projects and the assessment of the gaps in knowledge and requirements, the items below hold potential for next stages or near future work:

- Working on acceptance criteria: More detailed assessment for the suitability of IC to be used for either or both quality control and quality assurance (lot conformance).
- Establish an IC output and standard forms for the delivery of IC projects (e.g. finalised output files and forms to submit for each IC project). This should also cover the requirements for future data storage.
- More checks and trials are required to finalise a standard process for repeatability of IC values (for equipment and comparison of data). This would lead to a process for calibration of IC machineries. It is an important part of the process as:
  - more than one roller may work together
  - the results of correlation should be applicable to the same material and thickness.
- An 'Implementation Plan' and steps ahead should be rolled out to completely establish IC technology in different project levels.
- More trials are necessary to compare the project quality control and quality assurance by current methodology and use of intelligent compaction.
- Additional works to better understand the correlation of temperature and ICMVs and recommended ranges for ICMVs temperature ranges.
- Acceptance rules for the exclusion areas for IC works need to be defined. These should be practical and cover operational issues and points and present the substitution in case of coverage failure.
- The impact/effect of rolling speed on ICMVs should be explored.
  This task verifies the importance of speed during rolling operation and introduces acceptable speed range when defining a target ICMV (through the process) for an IC work.
- Putting criteria around rolling speed to determine the minimum percentage of area rolled within speed range, for the purpose of defining the project acceptance.
- The feasibility and benefits of providing a new definition for 'Lots' should be studied to more precisely monitor the compaction, by doing trials with different arrangements and comparing them.
- A tech brief should be created to provide the best available technical information regarding pre-mapping in order to clarify its advantages and limitations. Ranges of ICMV can also be defined for pre-mapping.
- Dissemination of knowledge and information sessions should continue.

- Long-term pavement performance monitoring is recommended in order to identify performance trends that may relate to IC measure values.

Figure 6.1 briefly lists the challenges of using IC and the future works required for better implementation.

Figure 6.1: Challenges for comprehensive implementation of IC technonology

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