Digitalisation and Automation of Road Materials Compaction: SPARC Intelligent Compaction Kit

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ABSTRACT

'Intelligent Compaction' (IC) broadly refers to the compaction of road materials, primarily using advanced sensing and automation, which achieves the target performance over their design life. Our recent international workshop on intelligent compaction highlighted that countries like US and China have implemented IC technology in practice as a mandatory requirement for contractors almost 6 years ahead of Australia. Our online questionnaire survey results indicated that the slow adoption of IC technology in Australia is mainly due to the lack of standards or specifications for the use of IC technology and the lack of confidence among contractors who already have an existing fleet of conventional rollers for compaction. There are some retrofittable kits available in the market that can facilitate IC with conventional rollers. However, the main limitation of these kits is that they provide only one parameter out of various intelligent compaction meter values (ICMVs). We are developing an innovative kit with cutting-edge hardware and software tools to facilitate performance-based compaction of road materials. The key features of our kit include [i] facilitating simultaneous visualisation of multiple ICMVs on both onboard and remote systems in real-time during compaction, [ii] providing versatility to retrofit a conventional roller, [iii] flexibility to incorporate corrections for different ICMV indicators, [iv] facilitates customising to construction specifications in line with the ongoing industrial digitalisation, and [v] integrable with the existing post-processing software such as Veta to view and analyse the collected IC data. In this paper, we provide the basic design concepts of the kit, its functionalities and capabilities with initial test results. The design concepts of the kit prototype will be further refined in the future based on the field trials undertaken on different materials using different roller types. The experiences gained through using our kit in actual construction projects will pave the way to develop robust and data-oriented specifications for IC to be used by the Australian road construction industry.

Keywords: intelligent compaction, road pavements, rollers, intelligent compaction measurement value, retrofit kit, performance-based specifications

1 INTRODUCTION

Road pavement materials are traditionally compacted using conventional rollers, and post-compaction spot tests are performed to assess the compaction quality and uniformity. Spot tests include a nuclear moisture-density gauge (NDG) for density and moisture measurements, lightweight deflectometer (LWD) for modulus measurement, static plate loading tests (PLT) for stiffness measurement, and sand replacement method for density measurement. The main drawback of these measurements is that they do not represent the entire compaction area. The intelligent compaction (IC) technology fills this gap by measuring material response or compaction level continuously in real-time with an instrumented vibratory roller and varying the frequency and amplitude of the roller automatically to optimise the compaction process. The technology provides the roller operator with real-time continuous feedback of the level of compaction through colour-coded maps, which helps prevent under compaction or over compaction for the entire compaction area. Figure 1 shows schematically the sensors and their locations in an IC roller.

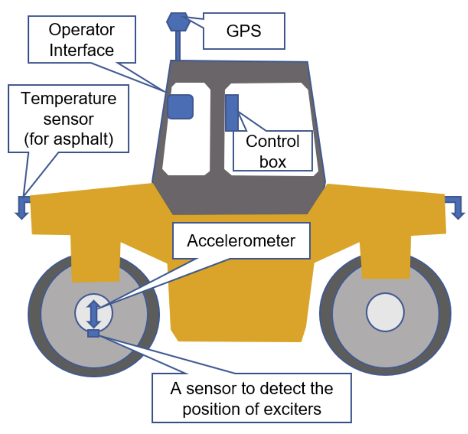

Figure 1. Schematic diagram of an intelligent compaction (IC) roller [adapted from Sivagnanasuntharam et al. (2021)]

A handful of roller manufacturers are currently making specialised drum rollers with built-in IC technology, such as BOMAG and Dynapac (Savan et al., 2015). The recent international workshop on intelligent compaction organised by SPARC (Smart

Pavements Australia Research Collaboration) Hub highlighted that countries like US and China have implemented IC technology in practice as a mandatory requirement for contractors almost 6 years ahead of Australia. The slow adoption of IC technology in Australia could be due to the lack of confidence among contractors who already have an existing fleet of conventional rollers for the compaction of geomaterials. There are some retrofittable kits available in the market that can facilitate IC with conventional rollers. However, the main limitations of these kits are that they provide only one parameter out of various intelligent compaction meter values (ICMVs) and they do not record the raw data collected from sensors, such as accelerometers.

The SPARC Hub IC team develops an innovative IC kit with cutting-edge hardware and software tools to address the above issues. The prototype of the kit is built from scratch and is designed to handle multiple ICMV parameters within the limits of retrofitting capabilities. The key features of the current version of the SPARC IC kit include:

- [i] facilitates simultaneous visualisation of multiple ICMVs on both onboard and remote systems in real time during compaction;
- [ii] provides versatility to retrofit a conventional roller;
- [iii] flexibility to incorporate corrections for different ICMV indicators;
- [iv] facilitates customising to construction specifications in line with the ongoing industrial digitalisation; and
- [v] integrable with the existing post-processing software, such as Veta, to view and analyse the collected IC data.

In this paper, we provide the basic design concepts of the SPARC IC kit, its functionalities and capabilities with initial test results. The design concepts of the SPARC IC kit prototype will be further refined in the future based on the field trials undertaken on different materials using different roller types. The experiences gained through using the SPARC IC kit in actual construction projects will pave the way to develop robust and data-oriented specifications for IC to be used by the Australian road construction industry within the intelligent construction of pavement earthworks in line with the Industry 4.0 revolution.

2 CURRENT STATUS OF IC TECHNOLOGY IN AUSTRALIA

We undertook an online questionnaire survey to access the current state of the IC technology adaptation in Australia for both soil and asphalt compaction and understand the challenges in implementing IC in Australia from the end-user (contractors) point of view. Over 60 responses were received from the local road construction companies and agencies. Figure 2 summarises the survey results.

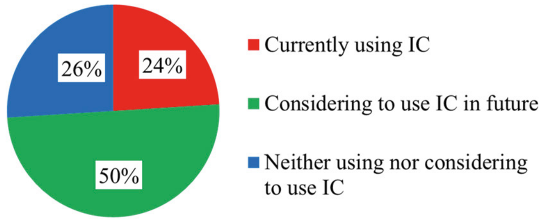

Figure 2. Current and future usage of IC in Australia

According to the responses recorded, IC is currently used for both soil and asphalt compaction equally, and it is expected that the proportion of IC usage for asphalt will show an increase in the future. Figure 3 shows the purpose of the usage of IC technology by the current users in Australia. The majority of the responses are either using IC technology or considering using it for both quality assurance (QA) and quality control (QC).

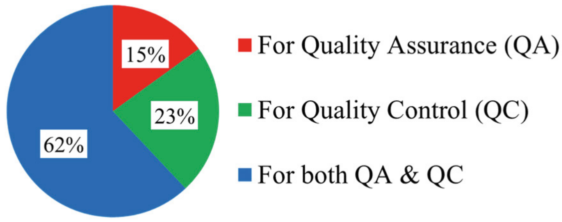

Figure 3. Purpose of the usage of IC technology

Based on the responses received for our online questionnaire survey, the followings are identified as issues associated with implementing IC technology in Australia that require further research:

- Responses indicated that IC technology is too expensive. A comprehensive cost-effectiveness study for IC in Australia is required to support the industry to decide whether it is worth investing in IC technology. In this regard, SPARC Hub IC projects undertake a comprehensive cost-effectiveness analysis of IC for both asphalt and soil.
- Responses indicated that the accuracy of ICMV is uncertain. A critical evaluation of the available ICMVs is required to identify the reasons for this uncertainty. Research activities should focus on developing methods to eliminate or reduce uncertainties.
- Responses indicated that lack of standards or specifications for the use of IC in Australia. A study should be undertaken to develop national wide IC specifications in Australia for asphalt and soil.
- The state-of-the-art IC technology is incapable of extracting the properties of each layer in a road pavement system (Sivagnanasuntharam et al., 2021). Instead, IC parameters recorded during compaction represent the properties of the equivalent pavement system, which is governed by the depth of influence of the roller.
- The industry is unsure about the post-construction usage of the IC data. IC data can be used to compare the performance of the road in the long run and can be used as

evidence to justify the compaction quality when any pre-mature failure occurs due to various reasons. IC data can also be used as a basis to make decisions for regular maintenance of the road sectors. In addition, IC data can be used as input for further developments such as the digital twin of road infrastructure.

- One of the challenges of IC is reported as 'setting up the system properly and ensuring the obtained data is accurate'. This issue is associated with retrofitting the IC kit to the existing conventional rollers. For example, if an accelerometer is supposed to be attached vertically to the roller but is attached at an inclined plane, measurements by the accelerometer may then have errors.
- The industry believes that IC technology can deliver uniform compaction. However, uniformity with respect to ICMV may not guarantee uniformity in the density due to the other factors that influence the measured ICMV. Therefore, a rigorous understanding of the correlation between ICMV and density is required for both asphalt and soil, considering other factors such as temperature for asphalt and moisture for the soil. In the SPARC IC projects, hypotheses are developed to improve the correlation between ICMV and density by taking into account the effects of these parameters. Experimental and numerical studies are undertaken to examine these hypotheses.

3 SPARC INTELLIGENT COMPACTION (IC) KIT

The SPARC IC kit is developed using Python language. The kit can run on both the Linux and Windows platforms. The prototype version is currently tested on Raspbian OS. The performance speed of the kit and raw data quality depends on the modular components of the hardware. The hardware of the kit is developed using state-of-the-art development circuit boards and components. The hardware of the kit is in modular form and the components can be easily replaced or upgraded. Figure 4 shows a picture of the 3D printed kit. It should be noted that for commercialisation purposes, these hardware components need to be integrated into one commercial-grade printed circuit board (PCB) and the enclosure of the kit needs to be designed to have at least an IP67 rating for outdoor use. Also, the codebase used for developing the analytics needs to be run through a software QA team to perform unit testing.

Figure 4. 3D printed SPARC IC kit

Figure 5 depicts a schematic overview of the functionality of the SPARC IC kit. The variables that are measured using sensors during the compaction process (i.e., the input parameters for calculations) are shown on the left side of the diagram and various intelligent compaction measurement values (ICMVs) determined by the kit are shown on the right side of the diagram.

The raw input data (as shown in Figure 5) for processing ICMVs are sampled from retrofitted sensors on the roller. The vertical and horizontal drum accelerations are measured with a triaxial accelerometer, roller speed and position are measured non-intrusively with high precision from a GPS-RTK unit, and the pavement material deformation data during each roller pass is measured by a high-precision laser array installed on the roller, respectively. Figure 6 schematically presents the hardware components of the kit and how they are integrated into a single-board computer (SBC).

The real-time raw sensor data is processed by the SPARC IC kit to produce different ICMVs and generate a colour-coded map. An example colour-coded map generated by the SPARC kit is shown in Figure 7. This map can be viewed by the roller operator in real-time during compaction and it can also be viewed remotely using a mobile phone or a computer. The kit records these ICMV data and can perform preliminary analysis without the need for additional equipment.

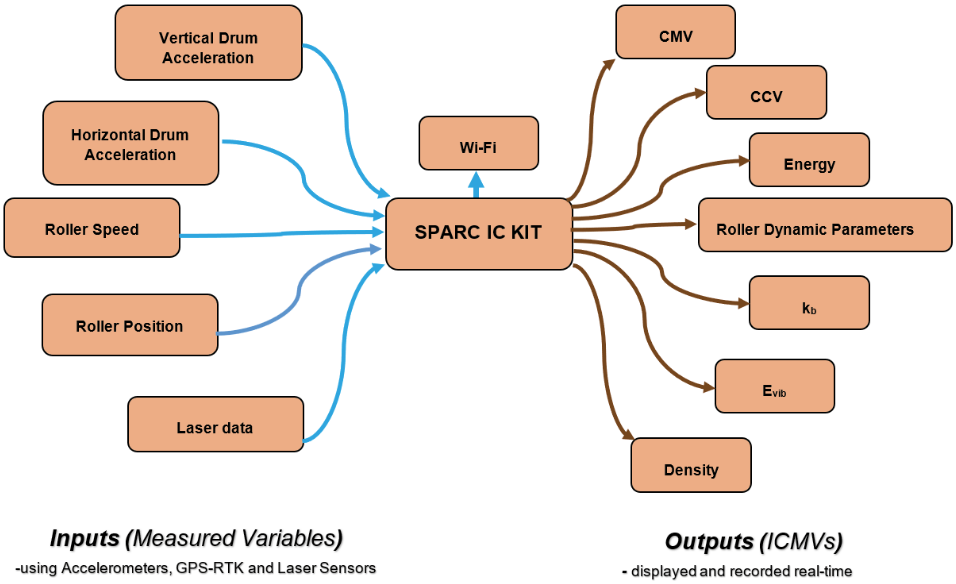

Figure 5. An overview of the functionality of the SPARC IC kit

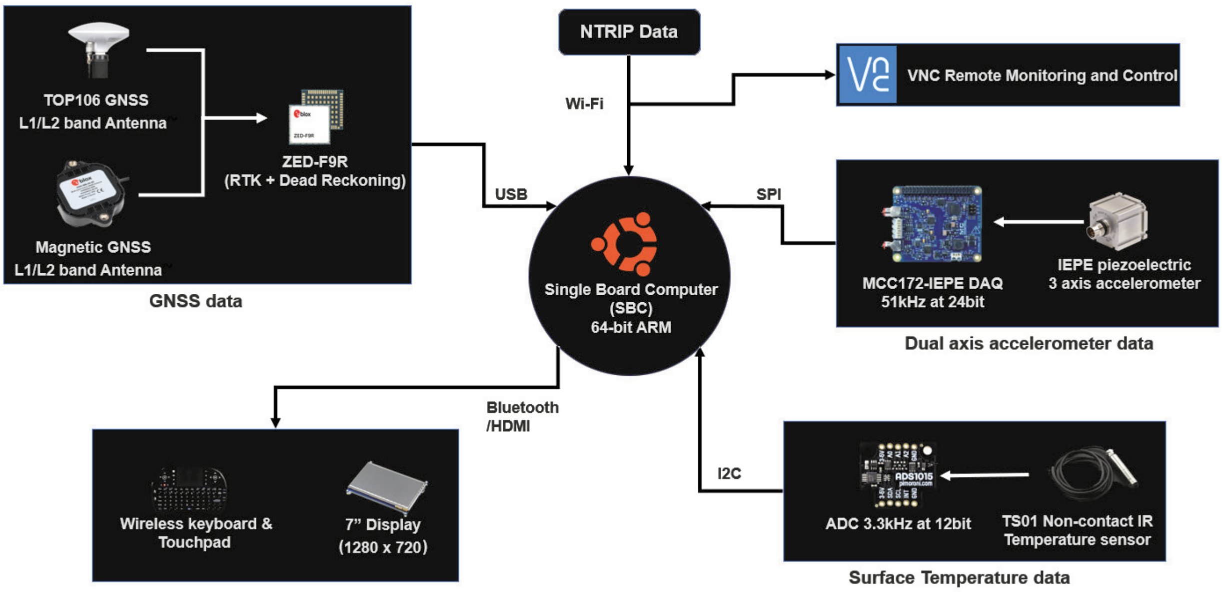

Figure 6. Hardware overview of the SPARC IC kit

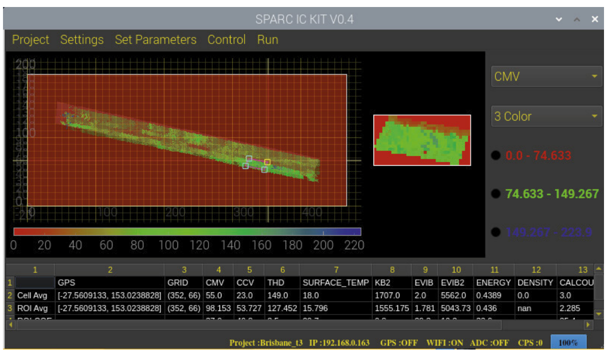

Figure 7. An example colour-coded map generated by SPARC IC kit for CMV parameter

4 INTELLIGENT COMPACTION METER VALUES (ICMVS)

Since the 1980s, various roller manufacturers and researchers have developed different types of measurement systems for assessing the ground condition based on the accelerometer readings, such as compaction meter value (CMV), compaction control value (CCV), roller integrated stiffness (k_b) and vibratory modulus (E_{VIB}). Intelligent compaction measurement value (ICMV) is the common term used for accelerometer-based vibration measurement systems mounted on vibratory rollers.

SPARC IC kit uses the raw data recorded by the accelerometer attached to the vibratory drum of the roller to calculate different ICMVs simultaneously in real time during compaction. Figure 8 illustrates the general procedure for calculating various ICMVs. As shown in this figure, the vertical displacement of the roller drum is calculated using the amplitude of the fundamental frequency (A_Ω) of roller vibration.

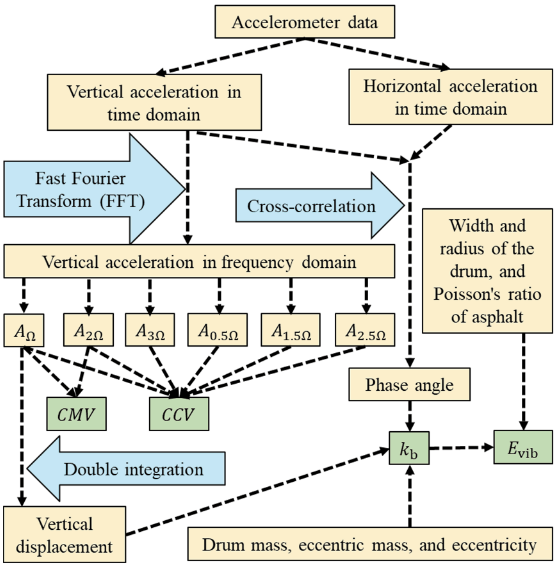

Figure 8. ICMV calculation procedure (Sivagnanasuntharam et al., 2022)

According to the roadmap for IC presented by the US Federal Highway Administration (2017), CMV and CCV are considered as Level 1 ICMV parameter while roller-integrated stiffness (k_b) and vibratory modulus (E_{VIB}) are considered as Level 3 ICMV parameter. The CMV and CCV require only the vertical acceleration of the roller drum as the input. During the compaction process, the accelerometer generates an acceleration signal in the time domain. Therefore, a fast Fourier transform (FFT) is performed to obtain the vertical acceleration signal in the frequency domain (Figure 9). In addition to vertical accelerometer data, the calculation of roller-integrated stiffness (k_b) and vibratory modulus (E_{VIB}) requires the following input parameters: drum width, drum radius, drum mass, eccentric mass, eccentricity, and Poisson's ratio of the material that can be pre-defined and the phase angle (defined as the phase lag between the excitation force of the roller drum and ground reaction force) that needs to be measured during compaction.

The phase angle can be measured with either a proximity sensor, such as the Hall effect sensor (Rinehart and Mooney, 2005) or an encoder. When an IC roller is manufactured by its original equipment manufacturer (OEM), this sensor is integrated inside the roller drum to measure phase angle (see Figure 1). However, retrofitting a conventional roller with such a sensor is not practicable. Accordingly, we have developed a novel method using the cross-correlation technique to estimate the phase angle without the need for a sensor. This method was successfully integrated into the SPARC IC kit, and it is being tested in the IC field trials.

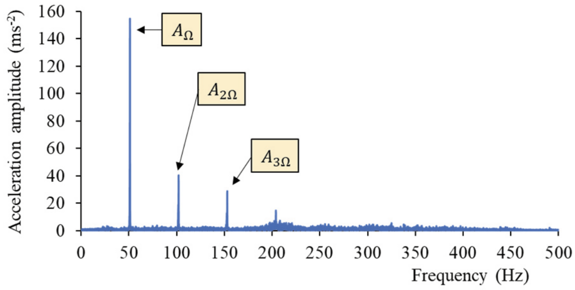

Figure 9. Vertical acceleration of roller drum in the frequency domain: an example (A_Ω, $A_{2\Omega}$, and $A_{3\Omega}$ are the amplitudes of the acceleration of the fundamental, first and second harmonic components)

5 CALIBRATION AND VALIDATION OF SPARC IC KIT

SPARC IC kit needs to be calibrated for all the ICMV parameters it calculates. The calibration process involves three main phases.

1. Primitive desk calibration was completed for both ICMV parameters and DAQ system to get the ICMV values in the desired range.
2. A 4-tonne double-drum roller was hired to undertake targeted field experiments in the SPARC test pit (5 m by 10 m). Controlled outdoor tests have been undertaken on unbound granular material and subgrade soil for the calibration of different ICMVs where the SPARC IC kit is attached to the roller to collect ICMV data processed in real-time (Figure 10). Figure 11 shows an example of ICMV data produced by the SPARC IC kit during the compaction of soil and unbound granular layers, respectively. The data collected using the kit is then analysed to improve the ICMV calculations. Inside the same test pit, tests have also been performed on the compacted soil using a Nuclear Density Gauge (NDG, soil density measurement), two types of lightweight deflectometer (LWD, soil dynamic modulus measurement), an L-band instrument (ELBARA III, proximal measurement of soil moisture) and a ground-penetrating radar (GPR, proximal measurement of soil moisture) to evaluate the potential use of these devices for enhancing the quality management of IC.
3. Targeted field trials are planned using an IC roller produced by OEM (original equipment manufacturer) to validate the ICMV parameters calculated by the SPARC IC kit. The OEM IC roller will be instrumented with the SPARC IC kit for this purpose.

Figure 10. A double-drum roller instrumented with SPARC IC kit (Site: SPARC test pit in Notting Hill, Victoria)

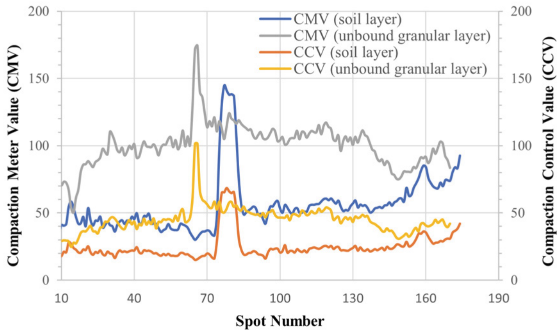

Figure 11. An example of CMV and CCV data generated by the SPARC IC kit during a roller pass

6 FUTURE WORKS

6.1 Post Processing Software

Post-processing software is being developed to process the raw accelerometer data, generate frequency spectrums, and produce ICMV values offline. This program helps analyse, validate and compare various performance parameters offline.

6.2 Proximal Measurement of Density

Based on our recent theoretical developments and experimental results, we have filed a patent on the innovation of proximal measurement of pavement material density and other properties in real-time during compaction. When this technology is fully developed, it has the potential to transform globally the geomaterials compaction to the highest level (Level 5 – a road map for IC by FHWA, 2017). The proximal measurement of density in real-time during compaction requires laser sensors, and the associated analytics can be integrated into the kit. The technique is currently being tested under different field conditions, and when it is fully developed, it will be integrated into the kit to display the estimated density of the material in a colour-code map along with ICMVs.

6.3 Calibration of Correction Factor for Underlying Support Effect

We identified that the effect of underlying support on ICMV (E_{VIB}) measured by IC rollers is one of the main causes of the poor correlation between ICMV and spot density measurements. We developed a practical method to decouple the influence of underlying support on E_{VIB}. The method was integrated into the SPARC IC kit to perform the real-time calculation of an index for the modulus of the material layer that is being compacted. The proposed method was tested in a small-scale asphalt testbed construction using an IC roller. However, it needs to be examined further for different materials and roller types.

6.4 Field Trials

The functionality of the SPARC IC kit is still to be tested comprehensively in field scenarios. This needs to be undertaken in phases of testing under different conditions and subsequent refinements. During these trials, performance requirements for the compaction material, such as target density and moisture content for soil, can also be incorporated for display and decision-making.

7 ACKNOWLEDGMENTS

This research work is part of a research project (Project No. IH18.03.6) sponsored by the SPARC Hub (https://sparchub.org.au) at the Department of Civil Eng, Monash University funded by the Australian Research Council (ARC) Industrial Transformation Research Hub (ITRH) Scheme (Grant No. IH180100010). The financial and in-kind support of Austroads, EIC Activities of CIMIC Group, and Monash University is gratefully acknowledged. Also, the financial support of ARC is highly acknowledged.

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