DEPARTMENT OF TRANSPORTATION

Evaluation of Level 3-4 Intelligent Compaction Measurement Values (ICMV) for Soils Subgrade and Aggregate Subbase Compaction

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16. Abstract (Limit: 250 words)

Intelligent compaction (IC) is a roller-based innovative technology that provides real-time compaction monitoring and control. IC can monitor roller passes, vibration frequencies/amplitudes, and stiffness-related values of compacted materials or intelligent compaction measurement Values (ICMV). Various ICMVs have been introduced since 1978. Based on the five levels of ICMV in the 2017 *FHWA IC Road Map*, the current implementation of ICMV in the United States has been limited to Levels 1 and 2. However, Level 1 and 2 ICMVs fail to meet the *FHWA IC Road Map* criteria. To achieve the full potential of IC technology, Level 3 and above ICMVs are needed to gain the confidence of agencies and industry and the adoption of IC to soil and base compaction. This project aims to (1) evaluate Level 3-4 ICMV systems against Level 1 ICMV systems for soils, subbase, and base compaction and (2) develop a blueprint for future certification procedures of IC as an acceptance tool. This study also aligns with the goals of the ongoing HWA IC for foundation study and the TPF-5(478) pooled fund study. This final report details the ICMV background, field test efforts, analysis results, and an IC specification framework for compaction acceptance.

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Final Report

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EXECUTIVE SUMMARY

Background

Intelligent compaction (IC) is a roller-based innovative technology that provides real-time compaction monitoring and control. IC evolved from the original form — continuous compaction control (CCC) — by adding Global Positioning System (GPS). IC can monitor roller passes, asphalt surface temperatures, vibration frequencies/amplitudes, and stiffness-related values of compacted materials. The "stiffness-related values of compacted materials" obtained from accelerometer-based technology can be used to estimate the level of compaction. The generic term for this is Intelligent Compaction Measurement Values (ICMV). Various ICMVs have been introduced since 1978. The goal of this project is to evaluate advanced versions of ICMV.

The Federal Highway Administration (FHWA) research project DTFH6 l-07-R-00032, *Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials,* is part of the blueprint for the FHWA IC strategic plan and was initiated under the Transportation Pooled Fund (TPF) TPF-5(128). That TPF includes twelve participating state departments of transportation (DOTs): Minnesota, Georgia, Indiana, Kansas, Maryland, Mississippi, North Dakota, New York, Pennsylvania, Texas, Virginia, and Wisconsin. During the FHWA Everyday Count (EDC-2) IC support, the research team developed an *IC Road Map* to overcome gaps and reduce IC technologies and implementation barriers. The FHWA Tech Brief (FHWA HIF-17-046), *ICMV – A Road Map*, provides the most comprehensive description and classification of the ICMV for five levels. The classification is based on: (1) the goodness of correlation between ICMV and conventional spot tests, (2) the capability of obtaining ICMVs during a double-jump state, (3) whether to measure layer-specific mechanical or physical properties, and (4) whether it can be enhanced by artificial intelligence (AI) or Machine Learning (ML).

Based on the five levels of ICMV in the FHWA Tech Brief, the current implementation of ICMV in the United States has been limited to Level 1 and Level 2. Examples of Level 1 ICMV include compaction meter value (CMV), Hamm measurement value (HMV), and compaction control value (CCV). Level 2 ICMVs include machine drive power (MDP). These Level 1 and Level 2 lCMVs have failed to meet the abovementioned criteria in numerous past studies since the 1990s. This limits ICMV's applications and acceptance for soil compaction by state agencies and industry, resulting in IC implementation being limited to monitoring roller passes and coverages. To achieve the full potential of IC technology, Level 3 and above ICMVs are needed to meet the criteria stated above. Implementing Level 3 and above ICMVs can also lay the foundation for future IC certification programs for compaction acceptance and true auto-feedback controls.

There are also ongoing related efforts to advance the IC for foundation technologies by FHWA and TPF-5(478) studies. The FHWA study *Feasibility of Utilizing Intelligent Compaction Equipment to Ensure Uniformity and Quality of Pavement Foundation* aims to evaluate the advanced IC technologies (including Level 3 and Level 4 ICMVS) for assessing the adequacy and uniformity of foundation (FHWA, 2023). This FHWA study will conduct three field demonstration projects in 2023, including the foundations for a new asphalt pavement construction project, an asphalt pavement rehabilitation project, and a new concrete pavement construction project. The TPF-5(478) study has recently published a mapping report and an open report to demonstrate *Innovative Technologies for Pavement Foundation Layer Construction* (TPF-5(478), 2022). The Open House report summarizes the Iowa DOT Open House activities held in Boone, Iowa, on October 28, 2022. The presentation slides are included in the appendices of this report. The mapping report summarizes the results of five Iowa DOT projects where e-compaction technology was used to assess pavement foundation conditions. It includes a discussion of each of the five projects, e-compaction reports, and key findings.

The research and implementation project described in this study aligns well with the National Road Research Alliance (NRRA), which assists USDOT in advancing pavement technologies and implementation. This project is to evaluate Level 3-4 ICMVs for soils subgrade and aggregate subbase compaction to take IC to the next levels. There is an immediate need to advance further IC technologies, both nationally and on a local level. State research personnel may use the methods and tools provided in this report to develop or refine soils, subbase, and base IC specifications. Therefore, this study aims to evaluate the Level 3-4 ICMV systems against Level 1 ICMV systems for soils, subbase, and base compaction and develop a blueprint for future certification procedures of IC.

Summary of the Study

This report documents the evaluation of Level 3-4 ICMV systems against Level 1 ICMV systems for soils, subbase, and base compaction to develop a blueprint for future certification procedures of IC. The following is a summary of this study:

- Level 3-4 ICMV solutions were identified and compared with Level 1 solutions.
- A Caterpillar IC roller was used to measure the compaction meter value (CMV) (Level 1 ICMV).
- The University of Texas at El Paso (UTEP) IC retrofit from the NCHRP Project 24-45 research was used to measure UTEP moduli (Level 4-5 ICMV). The UTEP IC retrofit data were also used to emulate CMV (Level 1), vibration modulus ($E_{vib,}$ Level 3), and soil stiffness (K_s, Level 3).
- The instrumentation of the Caterpillar IC roller with the UTEP IC retrofit system was successful.
- The field studies were conducted in two test cells at MnROAD during the 2022 reconstruction.
- IC mapping and spot tests were performed on the subgrade, subbase, and base of the two test cells. The spot tests include lightweight deflectometer (LWD) tests, nuclear density gauge (NDG), and GPS rover measurements. Soil samples were also taken for laboratory moisture and resilient modulus tests.
- The field and laboratory test data were processed and compared. Statistical analysis of CMV was performed. The Level 1 CMV was compared with spot test results. The emulated Level 3 E_{vib} and K_s and Level 1 CMV were compared. The comparison between UTEP moduli (Level 4-5) and spots showed the best correlation among all ICMVs.

Recommendations for Future Research and Implementation

Based on the findings of this project, the research team provides the following recommendation.

- A framework for future IC certification as an acceptance tool was recommended for future soils, subbase, and base IC compaction acceptance.
- The proposed framework includes: the ICMV requirements to be Level 3 and above (in mechanical or physical properties), the minimum correlation between ICMV and spot test, and the minimum stability and uniformity of production ICMV.
- The recommended spot tests are LWD and Nuclear Density Gauge (NDG) tests that most agencies use for compaction acceptance.
- Continuous compaction reference devices (CCRD) are recommended for future development as a higher-precision reference measurement tool to certify IC rollers.

CHAPTER 1: Introduction

1.1 Background

Intelligent compaction (IC) is a roller-based innovative technology that provides real-time compaction monitoring and control. IC evolved from the original form — continuous compaction control (CCC) — by adding Global Positioning System (GPS). IC can monitor roller passes, asphalt surface temperatures, vibration frequencies/amplitudes, and stiffness-related values of compacted materials. The "stiffness-related values of compacted materials" obtained from accelerometer-based technology can be used to estimate the level of compaction. The generic term for this is intelligent compaction measurement values (ICMV). Various ICMVs have been developed since 1978. The goal of this project is to evaluate advanced versions of ICMV.

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Based on the five levels of ICMV in the FHWA Tech Brief, the current implementation of ICMV in the United States has been limited to Level 1 and Level 2. Examples of Level 1 ICMV include compaction meter value (CMV), Hamm measurement value (HMV), and compaction control value (CCV). Level 2 ICMVs include machine drive power (MDP). These Level 1 and Level 2 lCMVs have failed to meet the abovementioned criteria in numerous past studies since the 1990s. Level 1 and Level 2 ICMVs limit IC's applications and acceptance for soil compaction by state agencies and industry. To achieve the full potential of IC technology, Level 3 and above ICMVs are needed to meet the criteria stated above. Implementing Level 3 and above ICMVs can also lay the foundation for future IC certification programs for compaction acceptance and true auto-feedback controls.

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The research and implementation project described in this contract aligns well with the National Road Research Alliance (NRRA), which assists the DOTs in advancing pavement technologies and implementation. This project is to evaluate Level 3-4 ICMVs for soils subgrade and aggregate subbase compaction to take IC to the next levels. There is an immediate need to further IC technologies, both nationally and on a local level. State research personnel may use the methods and tools developed under this project to develop or refine soils, subbase, and base IC specifications.

1.2 Project Objective

This report is part of a project that aims to evaluate the Level 3 and 4 ICMV systems against Level 1 ICMV systems for soils, subbase, and base compaction and develop a blueprint for future certification procedures of IC.

This report is a summary of the following tasks performed in this study:

Task 1. Identify Level 3-4 ICMV solutions to compare with Level 1 solutions

Task 2. Roller instrumentation and field tests

- Installation of Level 1 ICMV system on a single-drum IC roller
- Installation of NCHRP project 24-45 IC components (UTEP DAQ) on a single-drum IC roller
- Conducting field evaluation

Task 3. Analysis of field measurements

- Data reduction
- Statistical evaluation of the ICMV results
- Correlation analysis among ICMVs and spot tests
- Comparison between emulated Level 3-4 and Level 1 ICMVs

Task 4. Future IC certification

- Framework for a future certification program for single-drum IC rollers
- Minimum requirements for correlation between ICMV and spot tests from A test strip for IC specification

- Selection of ICMV uniformity metrics and their minimum requirements for IC specification
- Proposed companion acceptance tests based on IC measurements in compliment to reduced conventional spot tests.

1.3 Report Structure

The objective of this document is to summarize the information from Level 3-4 ICMV field evaluation and recommendation for the development of IC specification for soil subgrade and aggregate subbase compaction. The remainder of the document summarizes the ICMV system identification, data collection, analysis, results, and conclusions, as outlined in Table 1.

Table 1. Structure of this report.

Chapter Number	Chapter Title	Description
1	Introduction	Introduction (this chapter).
2	Identify Level 3-4 and Level 1 solutions	Level 3-4 ICMV solutions and Level 1 solutions for comparison.
3	IC Roller Instrumentation	Installation of ICMV systems on a single-drum IC roller.
4	Field Tests	Field tests included IC and spot tests.
5	Data Analysis	Performed data analysis of the field data.
6	Framework for Future IC Certification	Blueprint for future IC certification.
7	Summary and Recommendations	Summary of this study and the recommendation for future research and implementation.

CHAPTER 2: Identify Level 3-4 and Level 1 Solutions

2.1 Introduction

This chapter describes the Task 1 efforts of this project to identify Level 3-4 and Level 1 solutions.

2.2 Levels of ICMV

2.2.1 ICMV Mechanism

Comprehensive modeling of an IC system requires simulating the interacting system composed of the vibratory roller and asphalt or foundation layers. The available literature on the simulation of IC systems consisted of approaches for modeling the roller components and equipment or simplified to enhanced analysis approaches considering the soil-drum (or asphalt-drum) interaction. The model-based analysis of IC systems, if appropriately calibrated against field data, can facilitate moving toward the implementation of high-level IC and, in turn, accurately predicting pavement performance.

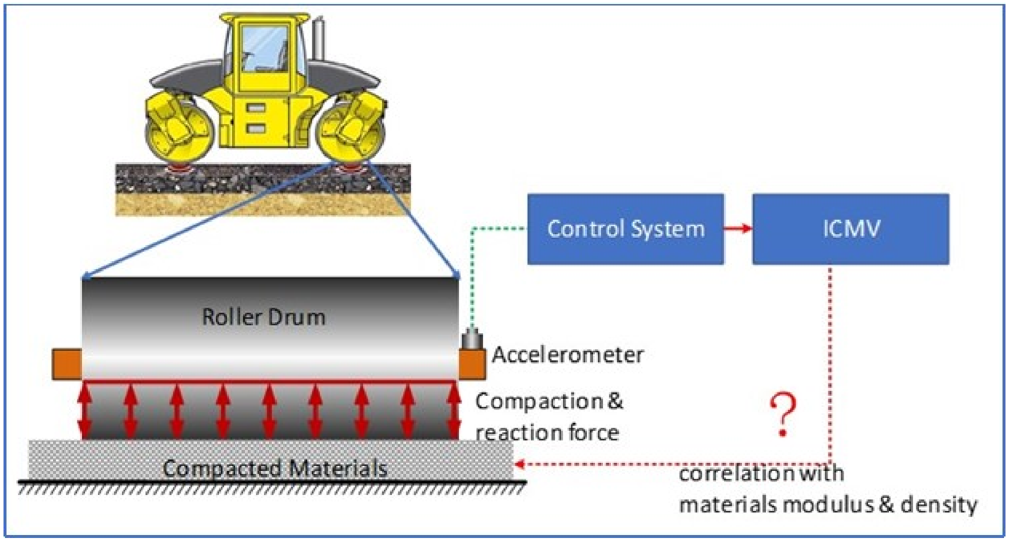
Aside from modeling, implementing IC technology is a challenging issue that transportation agencies must address. To this end, IC specifications were developed in the US and worldwide to ensure quality inspection, increased construction efficiency and pavement performance, and work safety.

The demand for real-time display of ICMV within 0.1 seconds (generally when a roller moves over 30 cm or 1 ft) dictates the usage of rapid methods such as analytical models. Traditionally, most of the industry solutions of ICMV were computed on hardware circuit boards instead of software to speed up the process. The expensive and lengthy off-project computing time required for numerical solutions prevents them from being practically used in the field to produce real-time ICMVs. Recent studies have used calibrated numerical simulation results with actual field measurements to train a genetic neural network (GNN) to speed up the ICMV solutions (Nazarian et al., 2020). Despite such GNN industry solutions, the field tests of DensityDirect from Volvo developed by Commuri (2011) have shown mixed results (Chang et al., 2018).

2.2.2 Common Mechanism of ICMV

On an IC system, an accelerometer is mounted on the vibration drum's axle. The exception is that the BOMAG Evib system uses two accelerometers. The acceleration signals are measured and recorded by the accelerometer(s) due to the interaction between the drum and compacted materials. The vertical acceleration signals, other roller properties, and operational information can then be analyzed with specific models in a controlled system to produce ICMV. Thus, ICMV reflects the mechanical properties of compacted materials. The term "ICMV" was created during the TPF IC pooled fund project in the late 1990s as a generic term to cover all past CCC technologies with positioning systems and future development (Chang et al., 2011).

The common mechanism for all ICMV solutions, as illustrated in Figure 1, is to measure the vertical acceleration at the center of the vibrating drum and to compute ICMV using various models and methods. This simple concept of measuring the properties of compacted materials during compaction allows for real-time compaction monitoring and control. Figure 1 also illustrates how ICMV is measured. The roller drum exerts a force on the compacted materials, and the compacted materials react with force back to the roller drum. The stiffer the compacted materials is, the larger the reactive force will be. A control system will then process the acceleration signals and compute ICMV.

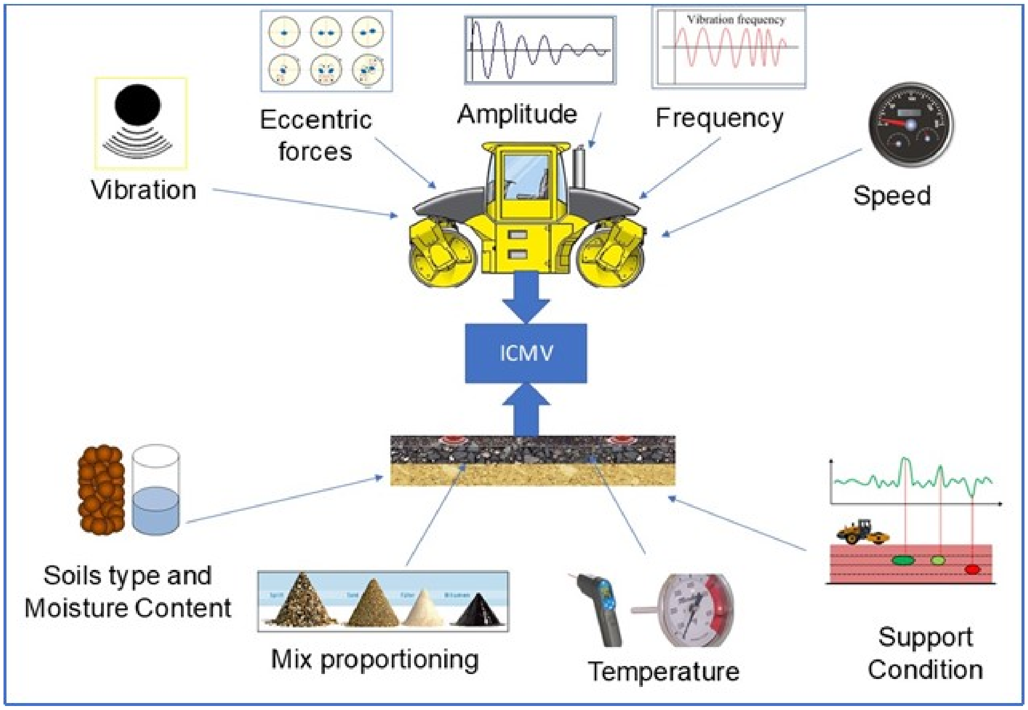


Source: FHWA (2017).

Figure 1. The common mechanism for all ICMV solutions

2.2.3 Factors Affecting and Challenging the ICMV Computation

As illustrated in Figure 2, numerous factors affect the ICMV computation. On the roller side, the vibration type, eccentric force amplitude and frequency, and roller speed are significant factors. From the compacted materials, the soil type and moisture content, asphalt mixture proportioning, asphalt mix temperature, and underlying support conditions are significant factors.

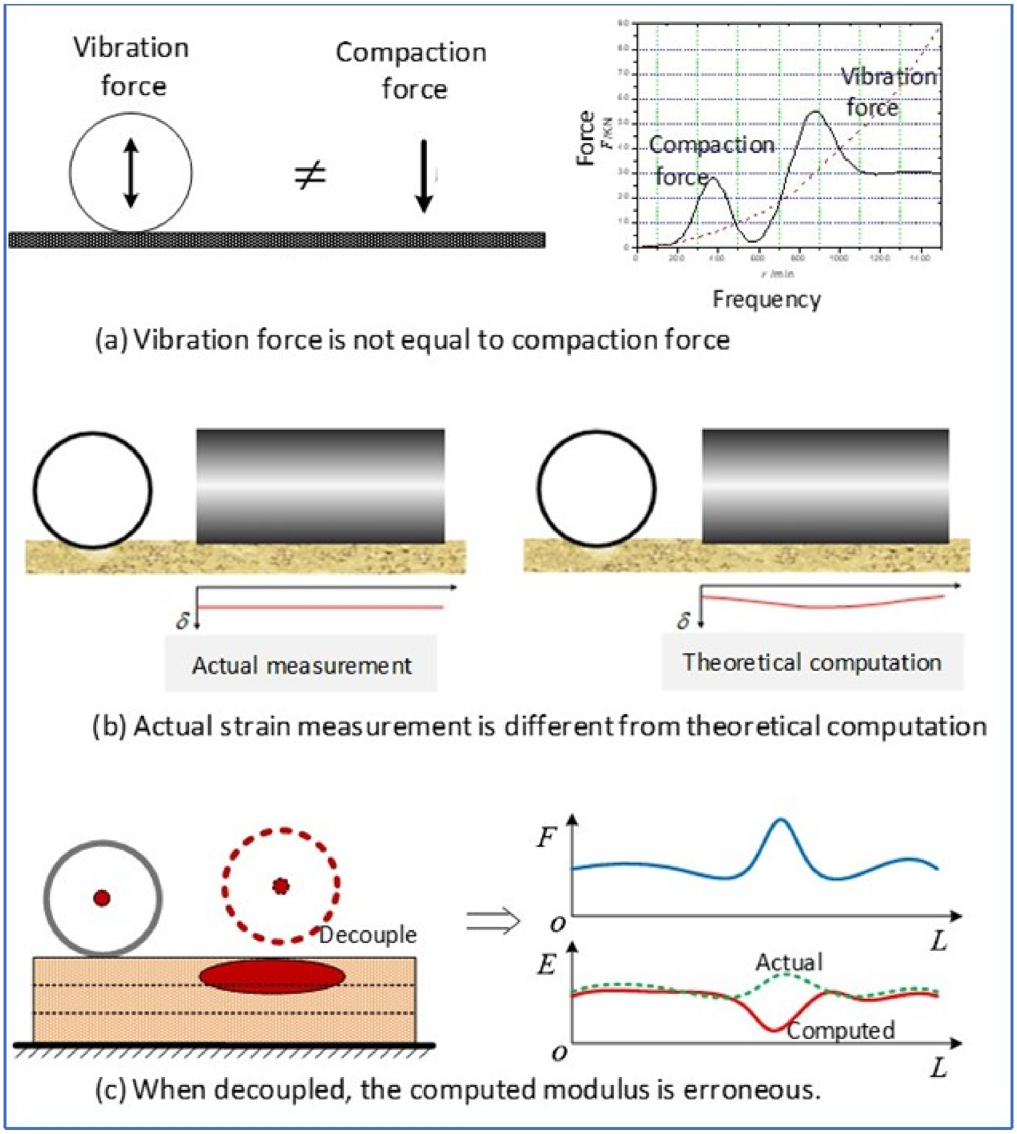


Source: FHWA (2017).

Figure 2. The factors that influence ICMV

The following items are the key examples of challenges in producing ICMV:

1. Vibration force is not equal to compaction force: The vibration force from the eccentric weight in the drum is not equivalent to the effective compaction force that asserts on compacted materials. The compaction force fluctuates as the vibration frequency increases. On the other hand, the vibration force increases monotonically with the increase in frequency. This is a frequent mistake for researchers who start modeling the drum and material interaction.
2. Actual strain measurement differs from theoretical computation: The actual strain and displacement under a drum are constant. However, Lundberg's and Hertz's theories of the cylindrical drum of finite length on compacted materials are commonly used to compute theoretical strain and displacement yield variable results across a drum width. Therefore, the theoretical computation needs adjustment to match actual field measurements.
3. When the drum is decoupled from the compacted material, the computed modulus is erroneous: When a drum and compacted materials lose contact or are decoupled, the computed modulus is often erroneously too low. Using the impact model and reactive force can overcome the difficulties of computing ICMV during double-jump movements of the roller drums (Figure 3).



Source: FHWA (2017).

Figure 3. Challenges for measuring ICMV

2.2.4 Classification of ICMV

2.2.4.1 Classification Criteria

ICMV has been evolving since 1976 with a variety of solutions. In 2017, FHWA published a Technical Brief titled "ICMV Road Map," which included the first systematic classification of ICMV in history and laid the road map for past, present, and future ICMV development (FHWA, 2017). The ICMV classification is based on the following five criteria:

- correlation with the material's mechanical (modulus) and physical (density) properties,
- validity during decoupling when a drum loses contact with the compacted materials,
- capability to allow performance analysis of the compacted materials,
- ability to yield layer-specific mechanical and physical properties of the compacted materials, and
- capability to be enhanced by advanced technology such as AI.

Five levels of ICMV that are categorized according to these criteria are defined in the subsequent sections. The ICMV Levels are from 1 to 5 by meeting more of the above criteria and approaching mechanistic and AI-enhanced. A review of ICMV background information is available in Appendix A (Xu and Chang, 2023). The ICMV background information includes the technical details for each level of ICMV and industry product examples, such as:

- Level 1 ICMVs: Compaction Meter Value (CMV), Compaction Control Value (CCV).
- Level 2 ICMVs: QMEGA, Machine Drive Power (MDP).
- Level 3 ICMVs: Soils Stiffness (K_s), Vibration modulus (E_{vib}).
- Level 4 ICMVs: No commercial products yet.
- Level 5 ICMVs: No commercial products yet.
- Level 4 and 5 ICMVs: UTEP Modulus.

2.2.4.2 Summary of the ICMV Levels

The evaluation scores of the five levels of ICMVs are summarized in Table 2. (FHWA, 2017)

Table 2. Five levels of ICMV solutions

Level	Model	Measurement Values	Correlation	Decouple	Layer Specific	Advanced IC
1	Empirical	Harmonic ratio	satisfactory	no	no	no
2	Energy	Energy index	unproven	no	no	no
3a	Discrete vibration	Stiffness coefficient	yes	no	no	satisfactory
3b	Roller drum movement	Resistance force	yes	yes	satisfactory	satisfactory
3c	Continuous static	Modulus	yes	no	yes	yes
4	Hybrid	Resistance force, Modulus	yes	yes	yes	yes
5	Continuous dynamic	Density, Modulus	yes	yes	yes	yes

Notes:

Correlation: The ICMV can meet correlation requirements with in-situ spot tests. The threshold value for the coefficient of correlation between ICMV and in-situ spot tests is generally accepted as $R \geq 0.70$ or $R^2 \geq 0.5$.

Decouple: The ICMV can produce a valid solution during a double jump or decouple when the roller drum and compacted material lose contact.

Layer Specific: The ICMV can produce layer-specific values.

Advanced IC: The ICMV can be combined with advanced technologies such as artificial intelligence and auto-feedback controls.

2.3 ICMV Selection for this Study

As the above sections described the ICMV Levels, there is a need to promote the development and usage of Level 3 and above to increase the confidence of the ICMV for compaction QC and acceptance. Thus, it is the primary goal of this study.

The research team initially identified several candidates for Level 3-4 ICMV systems. However, due to the restrictions on the transportation of goods, supply-chain disruption, and lockdown of the manufacturing facilities as a result of the global pandemic, the research team, with the confirmation of NRRA project management, elected to use the following system for this study:

- Caterpillar CMV (Level 1) from the Caterpillar OEM IC system
- Computed CMV_{UTEP} (Level 1) from the UTEP IC retrofit measurement
- Emulated Vibration modulus (E_{vib}) (Level 3) and soils stiffness (k_s) values (Level 3) from the UTEP IC system
- UTEP moduli (Levels 4 and5) from the UTEP IC system

CHAPTER 3: IC Roller Instrumentation

3.1 Overview

This chapter describes the efforts for Task 2 of this project. A brief description of the IC systems used in the project is presented. Since only one roller was used for the IC mapping of this study, the original equipment manufacturer (OEM) IC roller was retrofitted with an additional IC retrofit system. The followings are a detailed description of the IC systems and the ICMVs they produced.

3.2 ICMV instrumentation and Data Collection

3.2.1 CAT Level 1 ICMV OEM System

Caterpillar provided a single smooth drum IC roller (Model CS74B), shown in Figure 4. The roller's technical specifications are included in Figure 5. That roller was instrumented with CMV (Level 1 ICMV) and MDP (Level 2 ICMV). The MDP is not included in the analysis because it is a proprietary system used by only one vendor.

Figure 4. A single smooth drum IC roller (Caterpillar Model CS74B).

Weights

Operating Weight w/ ROPS/FOPS cab	16 000 kg	35,264 lb
w/ padfoot shell kit	17 395 kg	38,338 lb
w/ leveling blade	16 645 kg	36,687 lb
w/ padfoot shell kit and leveling blade	18 050 kg	39,777 lb
Weight at Drum w/ ROPS/FOPS cab	10 620 kg	23,410 lb
w/ padfoot shell kit	12 020 kg	26,494 lb
w/ leveling blade	11 580 kg	25,517 lb
w/ padfoot shell kit and leveling blade	12 980 kg	28,603 lb

Vibratory System Specifications

Frequency		
Standard	28 Hz	1680 vpm
During Eco-mode Operation	25.5 Hz	1527 vpm
Optional Variable Frequency	23.3-28 Hz	1400-1680 vpm
Nominal Amplitude @30.5 Hz (1830 vpm)		
High	2.1 mm	0.083 in
Low	0.98 mm	0.039 in
Centrifugal Force @ 30.5 Hz (1830 vpm)		
Maximum	332 kN	74,600 lb
Minimum	166 kN	37,300 lb
Static Linear Load		
w/ ROPS/FOPS Cab	49.7 kg/cm	278.7 lbs/in

Source: Caterpillar (2022)

Figure 5. Specifications of Caterpillar Roller Model CS74B.

3.2.1.1 GPS Radio and Receiver Component

Successful implementation and application of IC are highly dependent on the accuracy of the data collection. UTEP's GPS base station, contractor's base station, or DOT's virtual base station was used. Since GPS receivers are usually installed on top of the roller cabin, both the OEM and retrofit IC systems apply an offset to the collected GPS positions to correct the coordinate for the center of the front drum to generate the IC data maps. Therefore, to meet the survey-grade precision, the GPS readings from the IC systems needed to be calibrated with signals from a land-based GPS base station or virtual reference stations before any data collection. A physical or virtual base station and a hand-held rover could be utilized to perform the calibration process. The corrected GPS coordinates were applied to the in-cab control settings. The following process that met the FHWA generic specification on the calibration process of GPS was followed:

1. Verify that the hand-held survey-grade GPS rover(s) and IC roller are connected with the local/virtual base station.

2. Move the IC roller to a designated position to stabilize the GPS header computation and obtain an accurate GPS location.
3. Once the roller stops, record the last reading associated with the drum's center. Record the coordinates of both sides of the drum (Figure 6) using the hand-held survey-grade GPS rover that was previously synchronized with the base station.
4. The coordinates of the drum center shall be interpolated from the coordinates of the two sides of the drum. If the GPS receiver is not aligned with the centerline, the interpolation must consider this deviation.
5. Compare the coordinates reported by the IC roller with the interpolated coordinates from the GPS rover. Adjust the IC roller coordinates to match the interpolated numbers. The tolerance of the differences is 12 in. (300 mm) in the northing and easting directions.

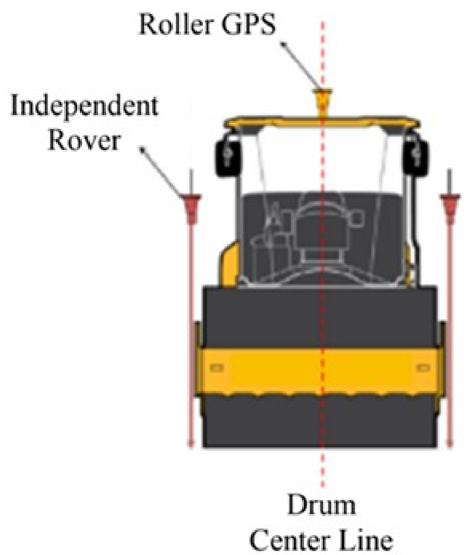


Figure 6. GPS instrumentation and verification.

As much as possible, MnDOT's statewide Virtual Base Station (VRS) was used. Caterpillar also set up an on-ground base station due to the unavailability of VRS services.

3.2.1.2 Installation of Accelerometer

One accelerometer was mounted in or about the drum to measure the CMV. The accurate and consistent ICMV measurement results depend on adequately installing the accelerometer for OEM or retrofit kit IC systems. For the after-market retrofit kit, one complication would be the deviation of the accelerometer from a 90° angle from a horizontal line. It makes it necessary for the retrofit kits to be installed by a certified technician to ensure proper connection and operation. The vibration sensor must be mounted vertically and secured in a position that can capture the actual vertical vibration of the drum. The roller configuration and installation parameters can be defined as part of the installation of the in-cab control box, or a design file could be uploaded.

3.2.1.3 Instrumentation of the Onboard Display

An onboard computer display was installed to show the location of the roller, the number of passes, amplitude, and frequency for vibratory rollers. The display provides real-time, color-coded maps of the ICMV. The display unit allows the transfer of data by automatic wireless uploading to a cloud computing storage system or via a USB drive.

The onboard computer (documentation unit) can measure, record, and export compaction data files containing all compaction parameters such as date and time, coordinates, roller pass number, speed and direction, vibration frequency and amplitude, and ICMV. The display unit was tested by a trial run under a known roller setting, coordinates, and calibration manual. At the same time, the documentation unit was tested by checking records and exported data against the displayed data and settings and plotting the measurements. The measurements file was uploaded to the cloud immediately after each mapping to notify if the documentation unit did not collect the data correctly and completely.

During the field study, the Trimble cloud service was not available. The raw CAT IC data was exported to a USB and pushed to Trimble's VisionLink to produce the gridded IC data.

3.2.2 UTEP Moduli ICMV Retrofit System

The UTEP IC retrofit was mounted to the CAT IC roller. The UTEP IC system can produce estimated UTEP moduli (Levels 4 and 5), emulated CMV (Level 1), emulated $E_{vib,}$ (Level 3), and emulated K_s (Level 3).

A data acquisition system (DAQ) developed during NCHRP project 24-45 research was used to collect vibration data from the IC roller drum and in-ground locations. The system, shown in Figure 7, Figure 8, and Figure 9, consists of an accelerometer mounted on the roller drum, a data acquisition box, a GPS antenna and receiver, a power supply, geophone sensors (embedded in-ground), and a laptop computer.

Source: Nazarian et al. (2020)

Figure 7. UTEP Moduli ICMV Components and data acquisition system.

Figure 8. UTEP Moduli ICMV Accelerometer (left) and onboard display (right).

Figure 9. UTEP Moduli ICMV GPS (left) and fully-instrumented roller (right).

3.2.3 Produced ICMVs

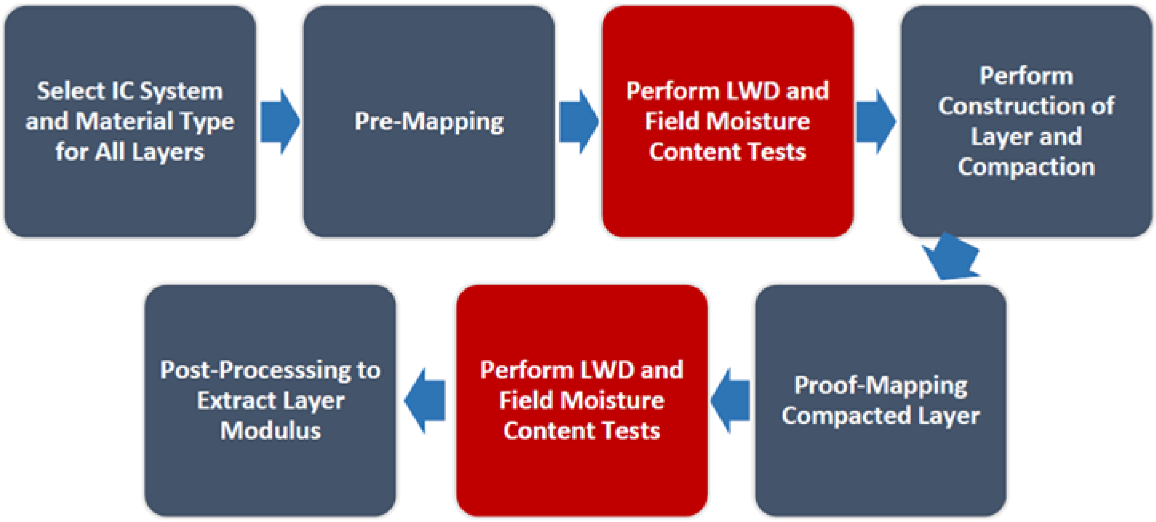
The ICMVs produced from the above IC systems include the followings.

- The Caterpillar OEM Level 1 ICMV: CMV was a part of the output from its IC system.
- The UTEP emulated OEM Level 1 ICMV: CMV was based on the method described in Appendix A.
- The UTEP emulated Level 3 ICMV K_s was based on the soil stiffness method described in Appendix A.
- The UTEP emulated Level 3 ICMV K_s was based on the vibration modulus method described in Appendix A.
- The Level 4 and 5 ICMVs UTEP Moduli were produced natively from the UTEP system.

CHAPTER 4: Field Demonstration Tests

4.1 Overview

The field tests were performed in two test cells (No. 2228 and 2229) of the MnROAD reconstruction project in 8 days in June 2022. Test cell No. 2229 contained a wicking geotextile between the subgrade and subbase layers. The IC and spot tests were performed on both test cells' subgrade, subbase, and base layers. The field implementation tests mirror the NCHRP project 24-45 study. The procedure of the IC field test is illustrated in the following flow chart.



Source: Nazarian et al (2020)

Figure 10. Flowchart of the Field Implementation Test Procedure

4.2 Experimental Plan

The experimental plan for field evaluation was similar to that for the NCHRP project 24-45 earthwork IC study. The laboratory testing included resilient modulus (MR) tests on the subgrade and unbound aggregate base (UAB) materials at several moisture contents. This report presents a detailed description of the efforts.

4.2.1 Field Test Schedule

The field test schedule of the experimental plan is summarized in Table 3. The actual field test differs from the experimental plan due to added tests in two cells and two layers of UAB.

Table 3. Field Test Schedule

Time	Tasks	Activities
2 Days before the First Visit	Coordination and Initial Set up	• Mark the test section and spot test locations (research team) • Arrange for field and roller instrumentation (MnDOT, research team). • Obtain GPS coordinates for spot test locations (research team). • Coordinate with the IC roller operator on how to collect, record, save, download, and transfer data for this project (contractor, MnDOT, and research team).
First Visit	Subgrade compaction and tests	• Prepare and compact the subgrade layer within the test section (contractor, research team). • Install geophones at a depth of 24 in. and 6 in. from the top of the subgrade. • Map the top of the subgrade with IC roller (contractor, research team). • Conduct in-situ testing with LWD/DCP (research team). • Conduct NDG tests (MnDOT) and obtain moisture samples for validation of NDG (research team).
Second Visit	Unbounded Aggregate Base (UAB) compaction and tests	• Pre-map subgrade within the test section (contractor, research team). • Prepare and compact UAB within the test section (contractor, research team). • Install geophone at a depth of 6 in. from the top of the aggregate base (research team). • Map the top of UAB with IC roller (contractor, research team) • Conduct in-situ testing with LWD/DCP (research team). • Conduct NDG tests (MnDOT) and obtain moisture samples for validation of NDG (research team).

4.2.2 Spot Test Equipment

The research team conducted several in-situ spot tests to correlate the results of IC and in-situ testing, including lightweight deflectometer (LWD) and nuclear density gauge (NDG) tests. After compacting each pavement layer to desired density, spot tests were conducted at 40 points, separated at 25 ft in longitudinal and 6 ft in transverse directions. Six tests, each with soft, medium, and stiff areas were used for the local calibration of the IC results. The other 34 points were used to validate the results of the calibrated models. MnDOT provided the LWD and conducted the NDG tests at some of the LWD test locations.

4.2.3 Material Characterization

MnDOT personnel sampled the subgrade and UAB layers for laboratory testing. These laboratory evaluations aim to determine the correlation between the extracted mechanical properties of compacted geomaterials under field conditions and those estimated under laboratory conditions. The testing on these geomaterial samples included gradation, Atterberg limits when applicable, and Proctor moisture-density tests (per AASHTO T-99 for subgrade and T-180 for UAB materials). The resilient modulus tests were also carried out as per AASHTO T-307 in duplicate at the following moisture contents (as successfully utilized in NCHRP project 10-84 and NCHRP project 24-45 for spot tests):

- OMC.
- OMC±1% or OMC±10%OMC (if OMC<10%).
- OMC±2% or OMC±20%OMC (if OMC>10%).

4.3 IC Field Tests

This section describes the step-by-step IC test procedure. The field demonstrations include pre-mapping the existing subgrade within the test section, placing and compacting subbase or base foundation materials within the test section, and performing spot tests within the test section.

4.3.1 Test Cell Markings

The spot test locations are in a grid pattern (Figure 11). After identifying the (25 ft by 250 ft) test strip, the research team marked the grid-pattern locations for spot testing (NDG, DCP, LWD) and ICMV mapping (Figure 12). For mapping ICMV measurements, rectangular sublots around grid points defined by the geo-referenced spot test locations were established following the test layout. All actual ICMV measurements with the accelerometer falling inside each sublot were averaged to obtain a representative ICMV. The grid pattern for this spot test marking is determined based on lane widths and roller dimensions. Therefore, four lines A, B, C, and D, were marked for this two-lane road, with each passing line width of approximately six ft. The roller drum diameter of 7 ft provided a one-foot overlap. In the longitudinal direction, the grid spacing was 25 ft, as Nazarian et al. (2020) recommended for a 250-foot section (Figure 13).

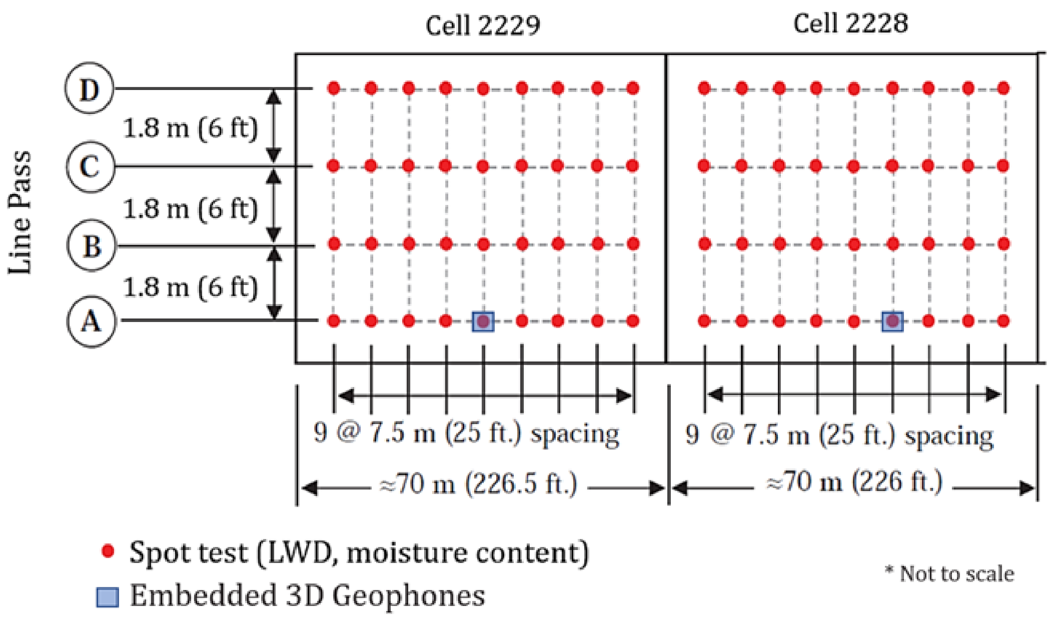


Figure 11. Mapping and Spot Test Patterns and Embedded Geophone Locations.

Figure 12. Test Cell Markings on Subgrade.

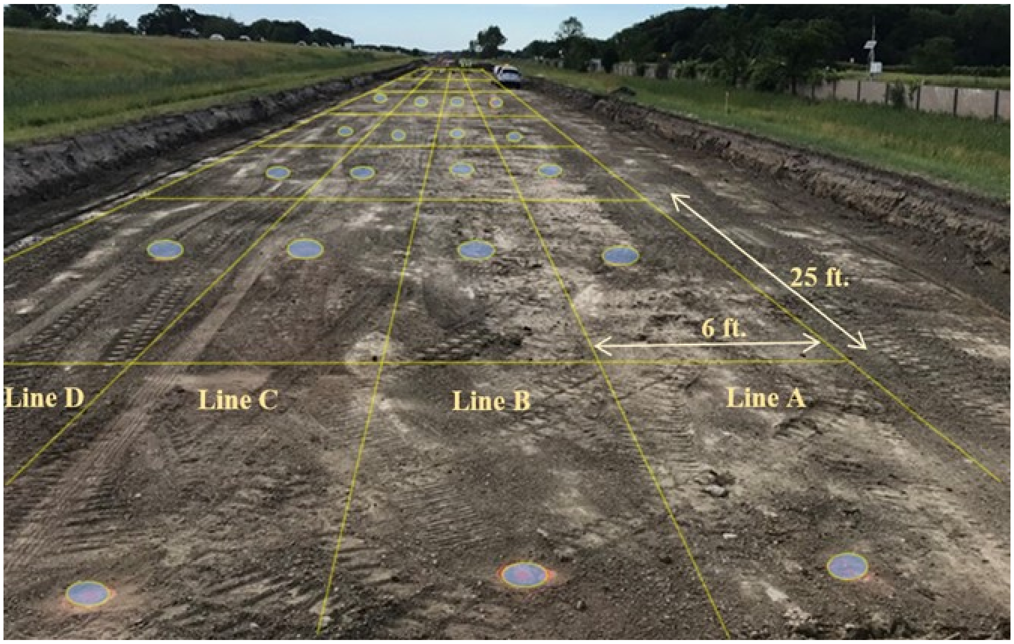


Figure 13. Layout for Mapping and Spot Tests on Subgrade.

4.3.2 Field Instrumentation

Geophones were embedded at different depths in the subsurface and connected to a data acquisition system to monitor the propagation of roller vibration within the geomaterials. The geophones and data acquisition system are shown in Figure 14. A second GPS unit on the data acquisition system was used to synchronize the geophone data with the accelerometers mounted on the rollers. The geophones were embedded before the new test layers were placed to monitor the soil layer responses during the IC operation. The geophones recorded the vertical amplitudes of vibration.

Figure 14. Geophones (left) IC calibration system (right) 3D geophone installation (Nazarian et al., 2020)

With assistance from MnDOT personnel, the research team dug the holes, buried geophones, and re-filled them with the same soils. Geophones were embedded at different depths in the subgrade layer (Figure 15 and Figure 16) to directly measure the IC roller's induced in-ground acceleration (and forces) (Figure 17). Like any other grid point, the GPS coordinates of the geophone were marked and recorded to calibrate the numerical model, as described in Chapter 3 and Nazarian et al. (2020).

In this project, the geophones were planned to verify other Level 3-4 ICMV solutions and double-check the transfer functions of function between the response and ANN output developed in NCHRP project 24-45. The verification was unnecessary since we decided to emulate Level 3 responses (Ks and E_{vib}) due to the physical Level 3-4 devices being unavailable due to the COVID-caused supply-chain disruptions. Double-checking the transfer functions proved that the NCHARP 24-45 solution was appropriate. The embedded geophones are not needed for the calibration to produce the UTEP Level 4 and 5 ICMVs. Therefore, there will not be any extra equipment or calibration for UTEP Level 4 and 5 ICMVs measurements compared with other ICMVs.

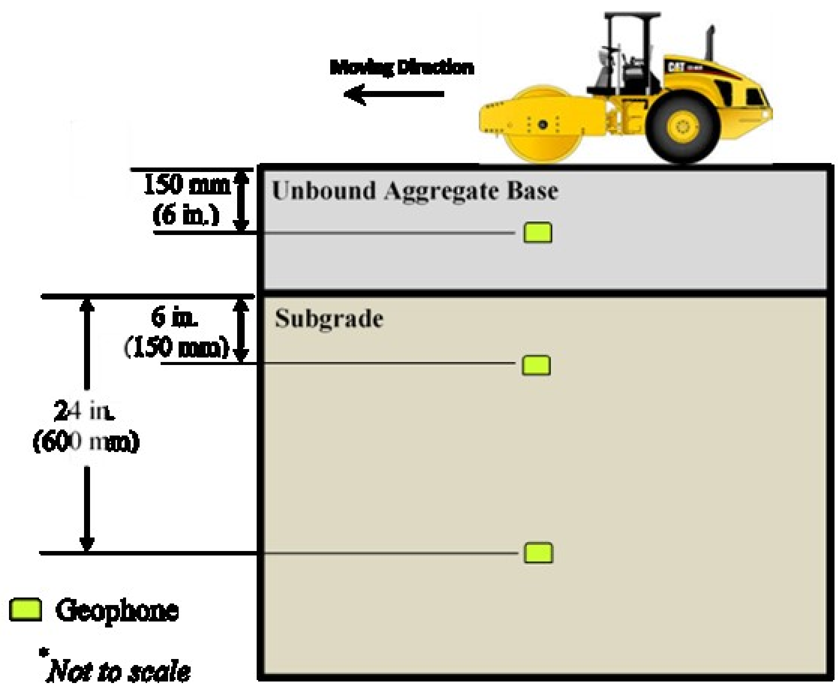


Figure 15. Instrumentation of the Subgrade/UAB Layers

Figure 16. Instrumentation of the geophones in the subgrade.

Figure 17. Monitoring of the geophone signals for IC data calibration.

4.3.3 IC Mapping

The pre-mapping process was conducted on the existing subgrade at low amplitude and low-frequency vibration settings with a forwarding pass of the IC roller over the section at a uniform speed of no more than three (3) mph (Figure 18) Figure 19). The same roller setting was used for the mapping of the subbase and base layers.

During the pre-mapping and mapping process, sensors mounted on the IC rollers collected vibration data, while embedded ground sensors were used to collect ground responses. It is recommended that compaction or pre-mapping is performed as close as possible to the subsequent paving to prevent significant (greater than 2%) moisture changes in the granular materials before construction. As a result of pre-mapping, color-coded maps of ICMV and the coefficient of variation (COV) of ICMV were generated to assess the uniformity of the existing layer. After pre-mapping the subgrade, the subbase and base layers were placed, constructed, and compacted uniformly according to the specifications. The mapping process was conducted on top of each compacted layer soon after the completion of compaction (see Figure 20 through Figure 22).

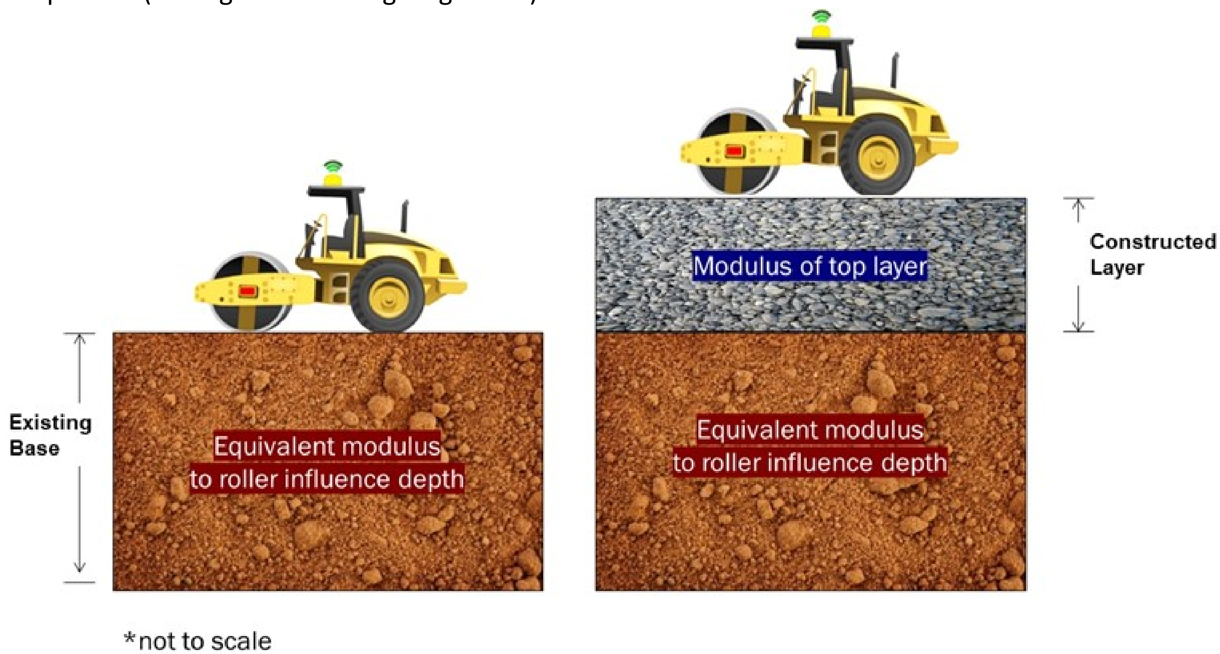


Figure 18. Schematic of IC Pre-Mapping Subgrade and Mapping Subbase.

Figure 19. IC Pre-Mapping Subgrade.

Figure 20. Placing and Compacting the Subbase Layer Materials.

Figure 21. Test Cell Markings for Spot Tests on Subbase.

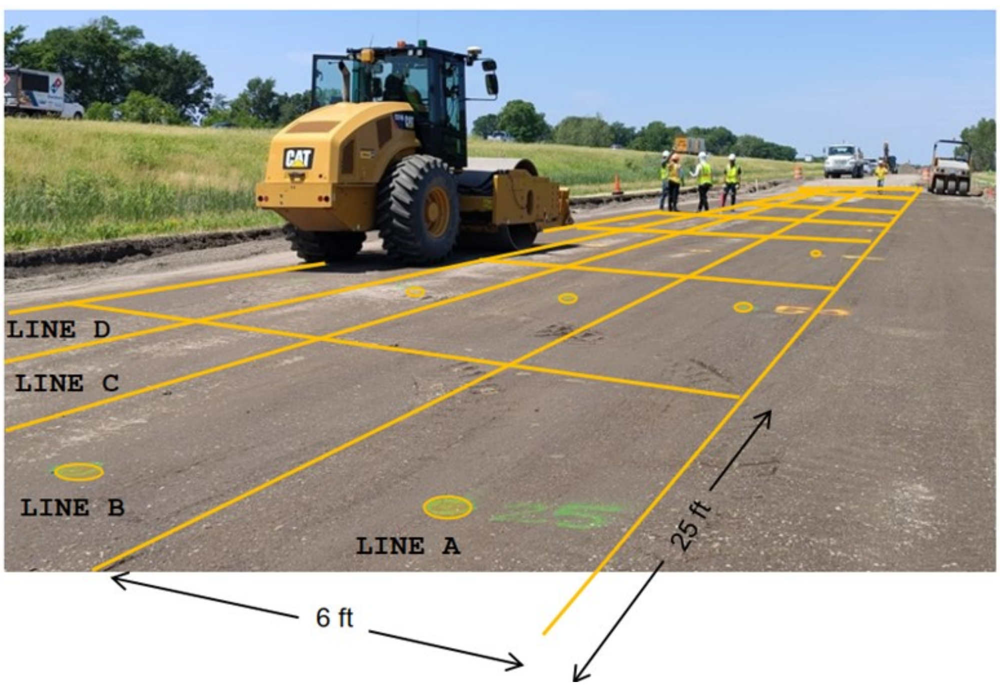


Figure 22. IC Mapping the Subbase.

4.3.4 Spot Tests

Spot testing at grid points was carried out right after pre-mapping or mapping the compacted layers to ensure minimal moisture change (less than 2%). Spot tests, including NDG, LWD, and DCP, were performed following ASTM D6938-17, ASTM E2835-21, and ASTM D6951/D6951M-18, respectively (see Figure 23 through Figure 25). The minimum frequency of spot tests at the previously marked grid locations is based on the size of the lots, the number of sublots, and the number of tests per sublot as per NCHRP project 24-45. For production-level projects, the tests should be conducted at 5 or 6 spots in soft, medium, and stiff sections based on ICMV values to develop correlation curves. The LWD spot tests were performed at every grid point to validate the results from the process. The NDG spot tests were performed at one grid point in a checkerboard pattern.

Figure 23. LWD Spot Tests.

Figure 24. DCP Spot Tests.

Figure 25. NDG Density and Moisture tests and Soils Sampling.

4.3.5 IC Mapping and Spot Tests for UAB Layers

Instrumentation of this layer with geophones, compaction, mapping, and spot testing followed the same process as the subgrade. The same vibration settings were used for the IC roller pre-mapping and mapping. As a result of the mapping, uniformly compacted areas can be identified as those with the COV of ICMV of less than or equal to 25% in ICMV color-coded maps. The location of the spot tests can then be determined based on these uniform areas. These spot tests must be performed as soon as possible after the compaction and before the material loses 2% of its placement moisture. Modulus should be adjusted for the moisture content during spot testing (E_{eff}) as required by AASHTO T 310. Color-coded maps of stiffness were generated to assess the compaction uniformity and identify soft areas, and the results were compared with the target stiffness identified in AASHTO T 307.

4.4 Laboratory Tests

The laboratory testing included moisture measurement of samples obtained at all grid points to verify NDG results, Proctor tests, and resilient modulus (MR) tests on the subgrade and unbound aggregate base (UAB) specimens from the stockpile at several moisture contents and stress levels.
The resilient modulus test was conducted to extract the nonlinear input parameters $k_i^{'}$ values for the ANN model, which are the regression parameters in Eq. (1).

$$MR_{opt} = k_1^{'} P_a \left[\frac{\theta}{P_a} + 1\right]^{k_2^{'}} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3^{'}} \tag{1}$$

where θ = bulk stress, τ_{oct} = octahedral shear stress, P_a = atmospheric pressure (101.3 MPa, 14.7 psi), and $k_i^{'}$ = nonlinear regression parameters.

There are several means of obtaining k_i', as described in NCHRP Project 24-45. The nonlinear parameters, k_i', can be directly calculated from Eq. (1) or converted from regression parameters of resilient modulus relationship from the Pavement ME Design.

Based on the results of resilient modulus tests, the correlations, and relationships to calculate k_i' were established, as shown in Figure 26 and Figure 27. The k_i' values from the plots were used as inputs to adjust the resilient modulus values for the ANN model.

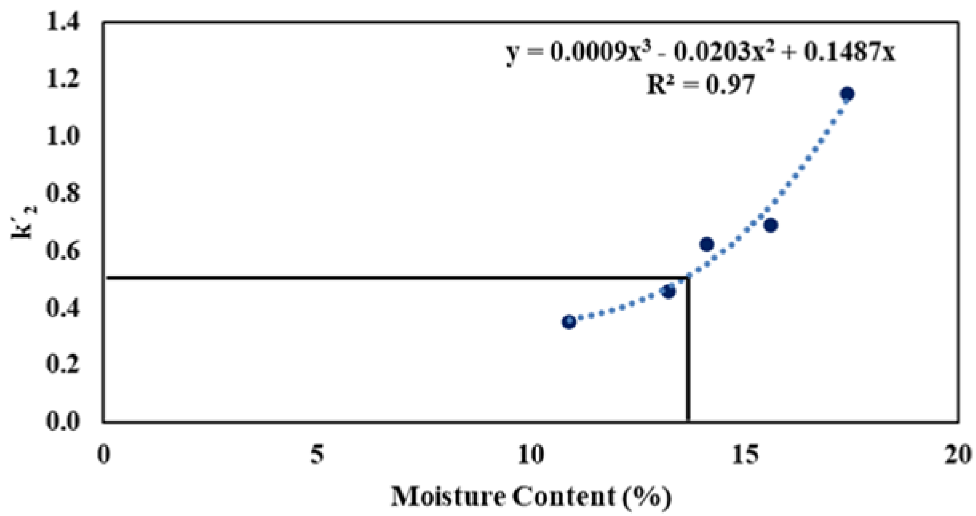


Figure 26. The relationships between k_2' and moisture content from resilient modulus tests on the subgrade samples

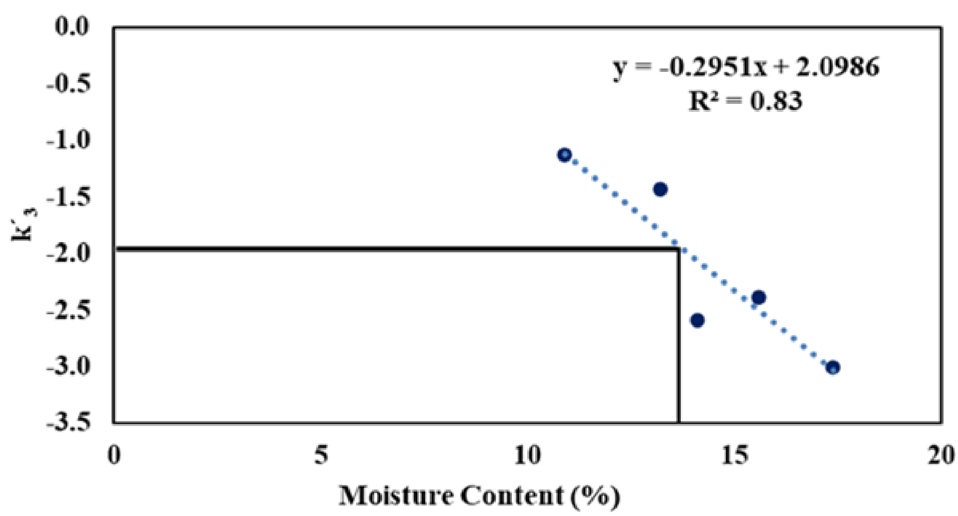


Figure 27. The relationships between k_3' and moisture content from resilient modulus tests on the subgrade samples

CHAPTER 5: Data Analysis

5.1 Overview

This chapter is associated with Task 3 efforts of the project. Statistical analysis of the ICMV results, the correlation between ICMVs and spot test measurements, and a comparative study of Level 3-4 and Level 1 ICMVs are presented. The MDP data were not included since it is a proprietary measurement by one vendor.

5.2 Data Reduction

Upon collecting field data, the research team processed and organized the data, including:

- Extract data from instruments
- Organize and filter data
- Correlation analysis
- Document information (such as changes in operation and weather conditions).

5.2.1 Extract Data from Instruments

The instruments that were used to store and export the collected data during field tests are an IC roller, UTEP IC system, LWD device, GPS rover, and NDG. The data from laboratory tests, such as resilient modulus devices, was also exported. A USB or memory drive was usually used to extract data. However, the extracted data were in different formats that may need further processing.

5.2.2 Organize and Filter Data

IC roller data were imported into Veta to visualize, filter, compare, and analyze. Filtering is essential to extract the appropriate data to match other tests. The ICMV from the IC roller included CMV. The data were filtered in Veta to remove extracted data collected and were organized by date, test cell, and pavement layer. UTEP IC data was also processed to generate CMV for comparison, called CMV_{UTEP}. Within each 6 ft by 25 ft rectangular sublot (see Figure 13), on average, 35 CMV measurements were computed. UTEP IC data (CMV_{UTEP}) was converted to a format readable by Veta for analysis and comparison.

In addition to analysis and visualization in Veta, the results of UTEP IC data, Level 3 ICMVs such as E_{vib} and K_s, and spot tests were calculated and reported per rectangular grid with color-coded maps, as recommended in NCHRP project 24-45. As a data quality control, rectangles with COV greater than 50% or measured at frequencies beyond ±5 Hz of the operating frequency were removed to avoid erroneous ICMVs. The ±5 Hz value is typically used in soils IC specifications worldwide to avoid erroneous IC data collected at varying frequencies. This data QA process is essential to extract high-quality data for the subsequent analysis. The data collected by the LWD device was exported in CSV files that could also be imported into the LWD software to back-calculate the geomaterial’s modulus. The In-situ moisture and the density data from NDG were also reported by corresponding grid coordinates or grid numbers in a CSV file. Note that NDG tests were not conducted at all grids. Laboratory moisture and density measurements of the samples taken at test grids were calculated and reported.

5.2.3 Correlation Analysis

As reported in the literature, it is not easy to establish a direct correlation between the modulus and density or moisture content of soil layers (Mooney and Rinehart 2009, Pacheco and Nazarian 2011, Nazarian et al. 2014 and Siddagangaiah et al. 2014). Therefore, a qualitative correlation was conducted between Level 1 ICMVs and Level 3-4 ICMVs and between ICMVs and spot test results.

5.3 Statistical Evaluation of Level 1 ICMV Results

To statistically evaluate ICMVs, the data collected in each cell was analyzed separately. In each rectangular grid of a specific cell, the ICMVs were averaged to be the representative ICMVs of the area enclosed in the rectangle. Then, the statistical metrics such as mean, standard deviation, and coefficient of variation (COV) of all rectangles were calculated to evaluate variations in the geomaterial properties of compacted areas within each cell.

To evaluate the uniformity throughout the site by generating color-coded maps of ICMVs, one approach (recommended in NCHRP Project 24-45) is to produce maps of ICMVs accompanied by the maps of COV of ICMVs to identify grids with less compaction. In this approach:

- A rectangle with representative ICMV greater than the average ICMV of the cell: relatively stiff (green)
- A rectangle with a representative ICMV of 75% of the average ICMV of the cell or higher but below the average ICMV: moderately stiff (yellow)
- A rectangle with representative ICMV less than 75% of the average ICMV of the cell: less stiff (red)

Similarly, to assess the variability of ICMVs, if the COV of the averaged ICMVs is:

- Equal or less than 25%: less variable (green)
- Between 25% and 35%: moderately variable (yellow)
- Greater than 35%: more variable (red)

The above approach indicates how the areas relatively compare and does not necessarily imply that they are insufficient and do not meet stiffness requirements.

5.3.1 Test Cell 2228

Based on the criteria described above, the color-coded maps of CMV and COV of CMV from the UTEP system (CMV_{UTEP}) after mapping the subgrade, subbase, and base of Cell 2228 were generated and illustrated in Figure 28 and Figure 29, respectively. As shown in Figure 28, CMVs are lower on the left side of the mapped area, primarily in lines C and D. However, this difference is insignificant as most grids are colored green or yellow. A similar observation was made in Figure 29, with more yellow- and red-colored rectangles on the left side of the mapped area.

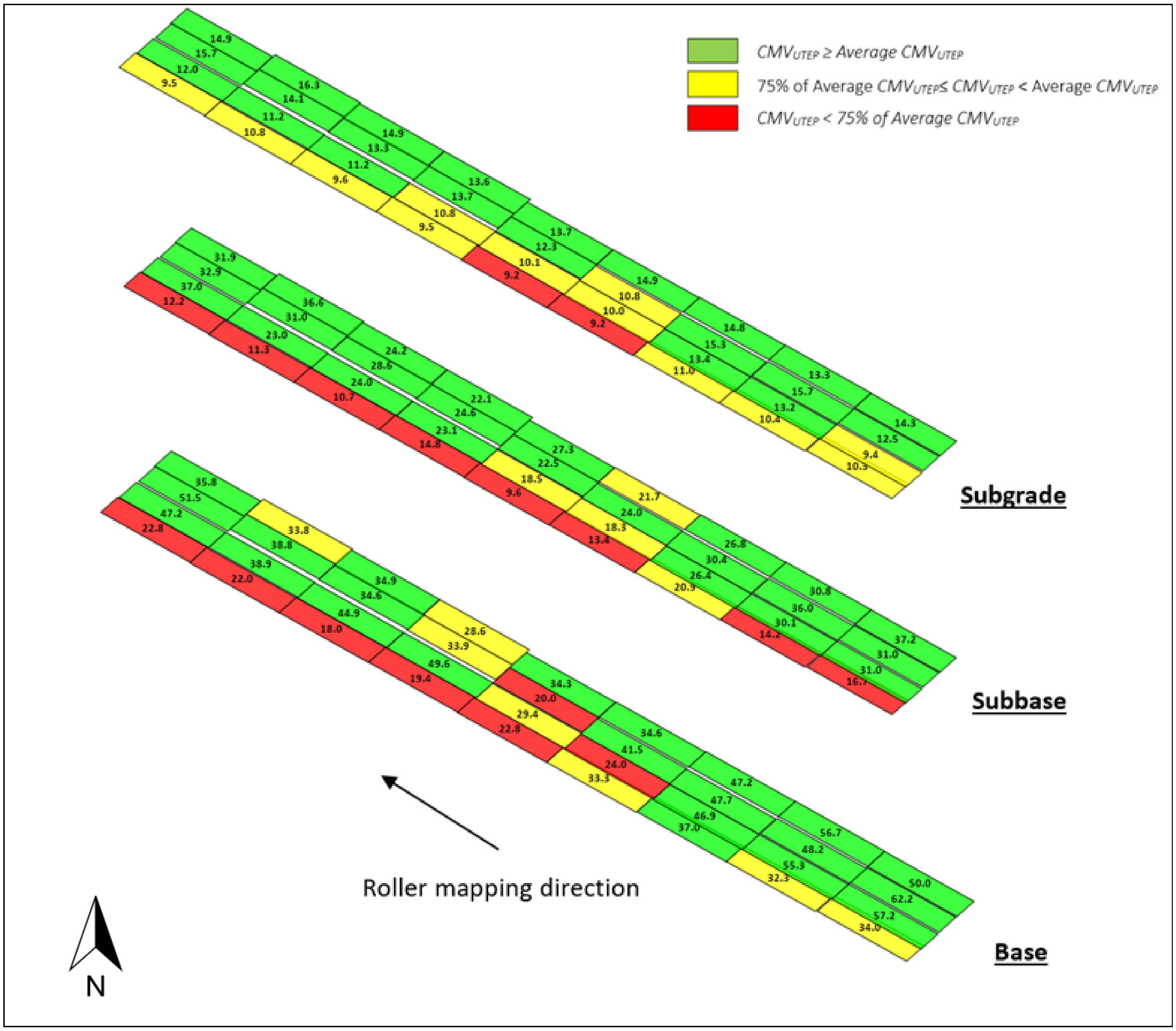


Figure 28. Color-coded maps of CMV_{UTEP} measurements of subgrade, subbase, and base of Cell 2228

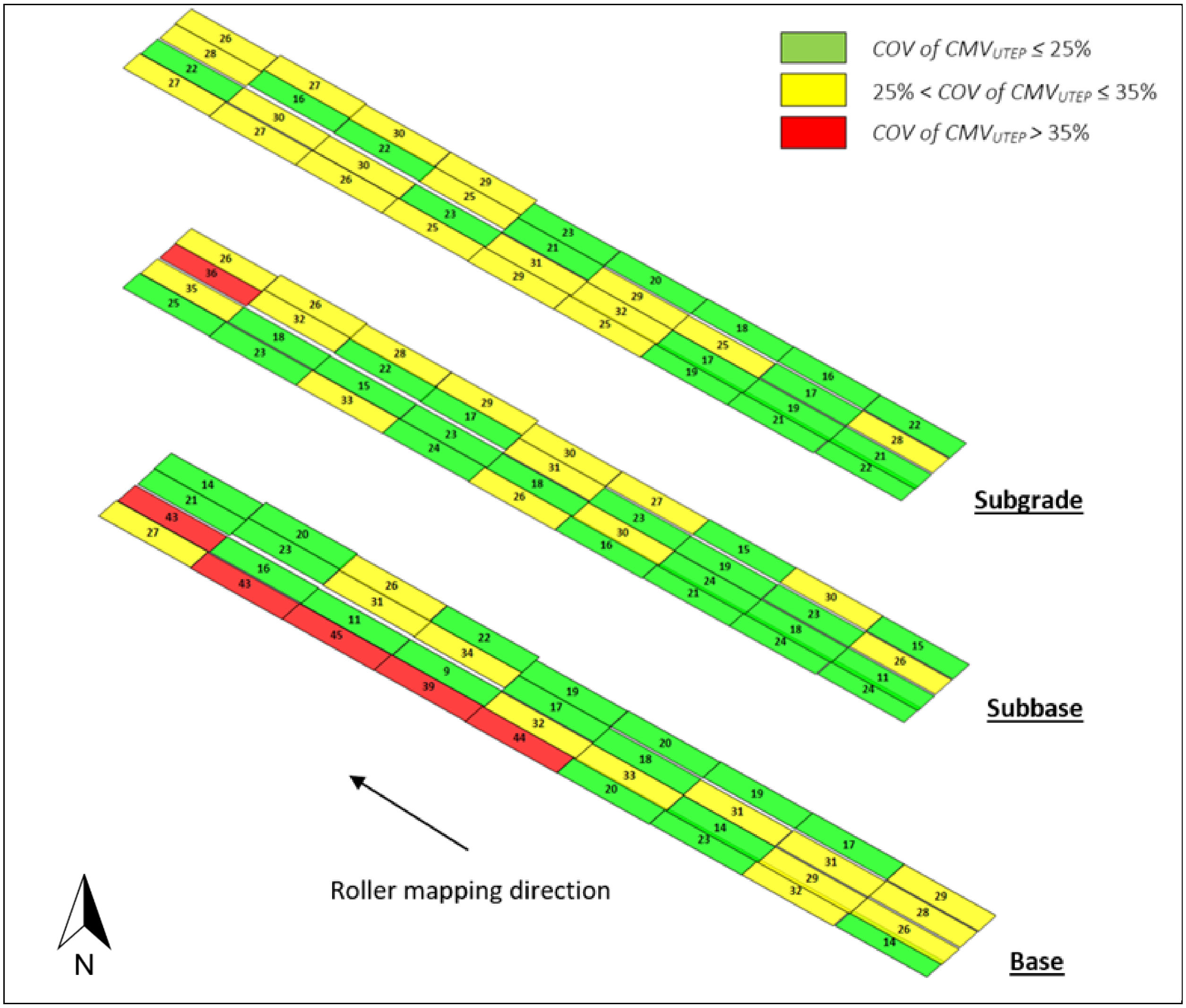
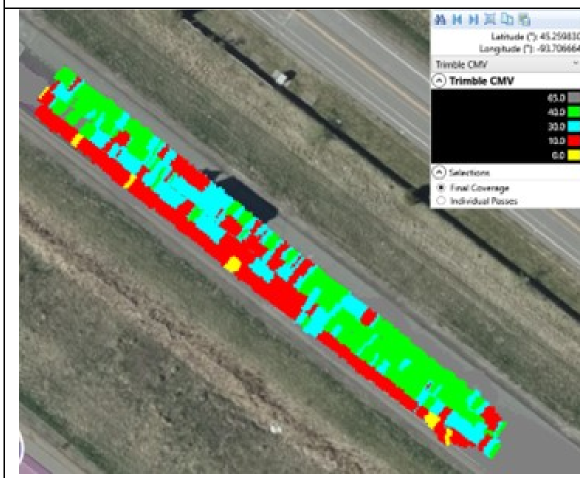


Figure 29. Color-coded maps of COV of CMV_{UTEP} measurements of subgrade, subbase, and base of Cell 2228

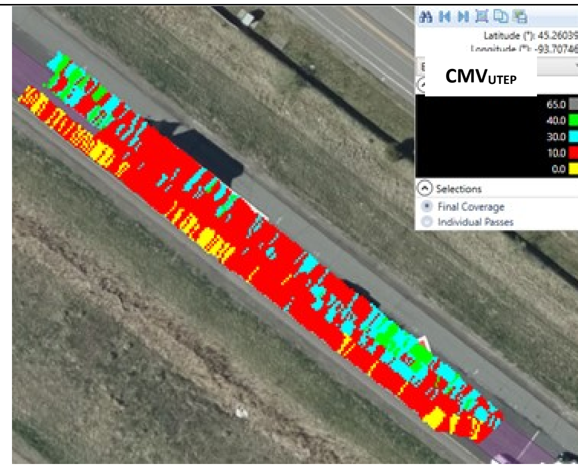
To compare the CMV measurements from the IC roller with CMV computed from the UTEP IC system in Cell 2228, both data sets were visualized in Veta, as illustrated in Figure 30. A comparatively similar trend was observed between the CMV measurements of the IC roller and CMV measurements from the UTEP system. The stiffer areas are located on the right side of the mapped area.

Subgrade – IC roller data

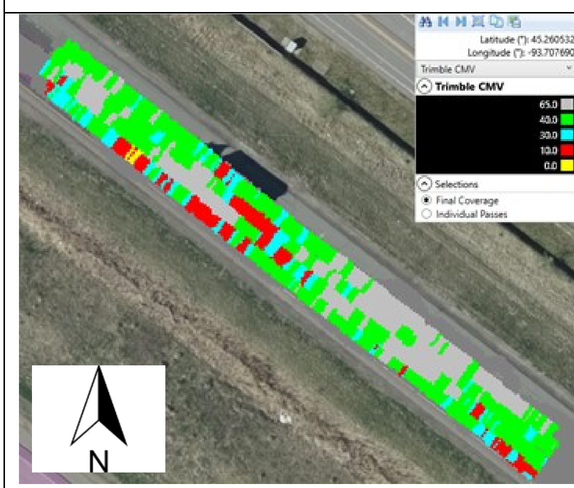
Subgrade – UTEP IC system



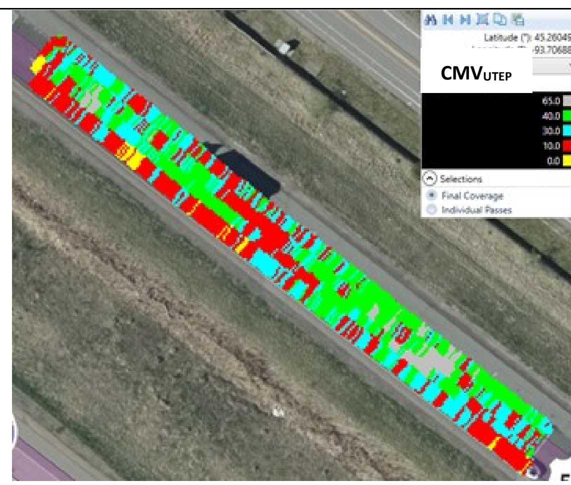
Subbase – IC roller data



Subbase – UTEP IC system



Base – IC roller data



Base – UTEP IC system

Figure 30. Comparison between CMV from IC roller and CMV from UTEP IC system for the subgrade, subbase, and base of Cell 2228

5.3.2 Test Cell 2229

Figure 31 and Figure 32 show the color-coded maps of CMV and its variation (COV of CMV) from the UTEP system (CMV_{UTEP}) after mapping the subgrade, subbase, and base of Cell 2229. Similar to Cell 2228, the CMVs are lower on the left side (lines C and D) of Cell 2229 than on the right side. The variation in CMVs of Cell 2229 appears to be higher than in Cell 2228.

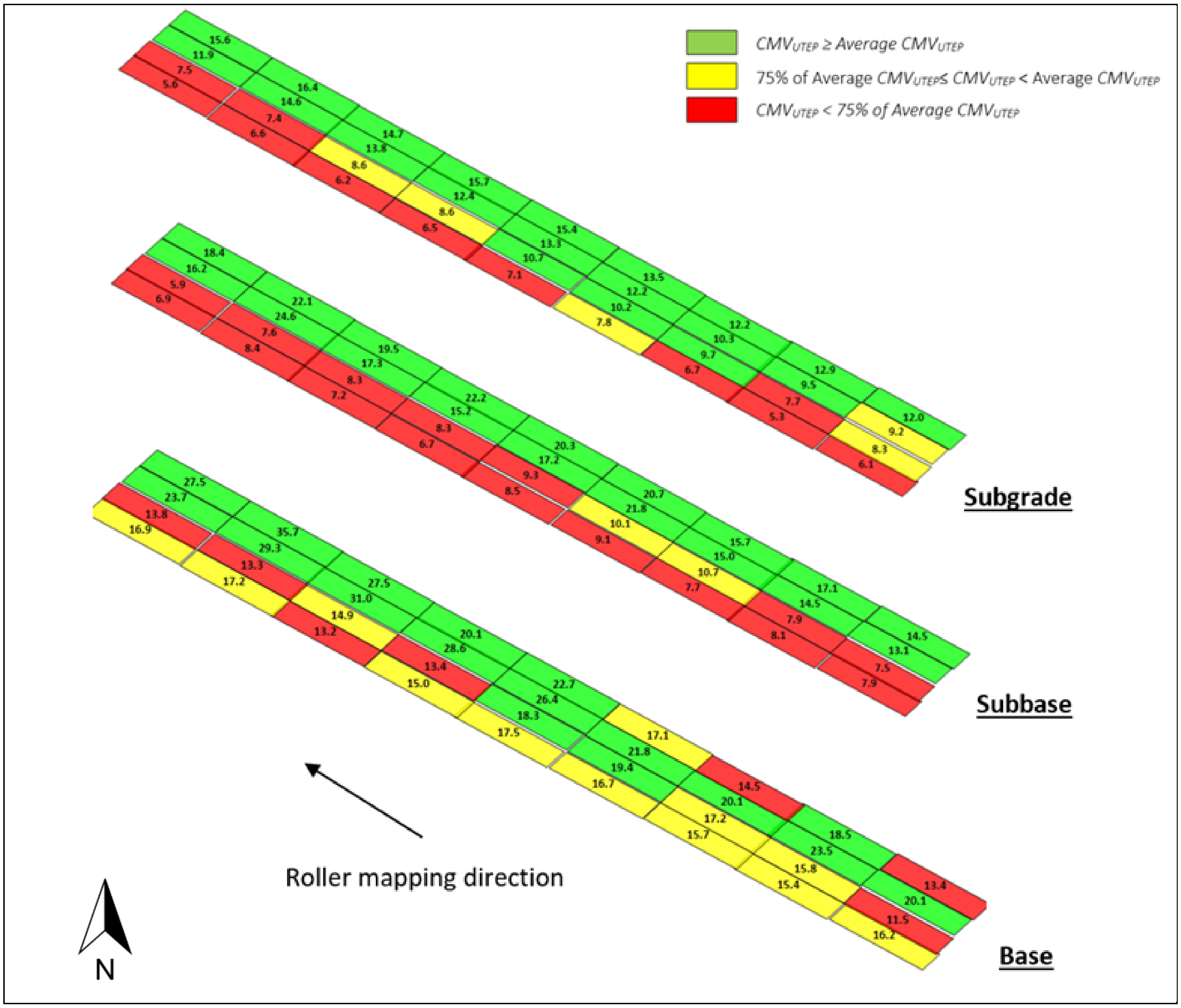


Figure 31. Color-coded maps of CMV_{UTEP} measurements of subgrade, subbase and base of Cell 2229

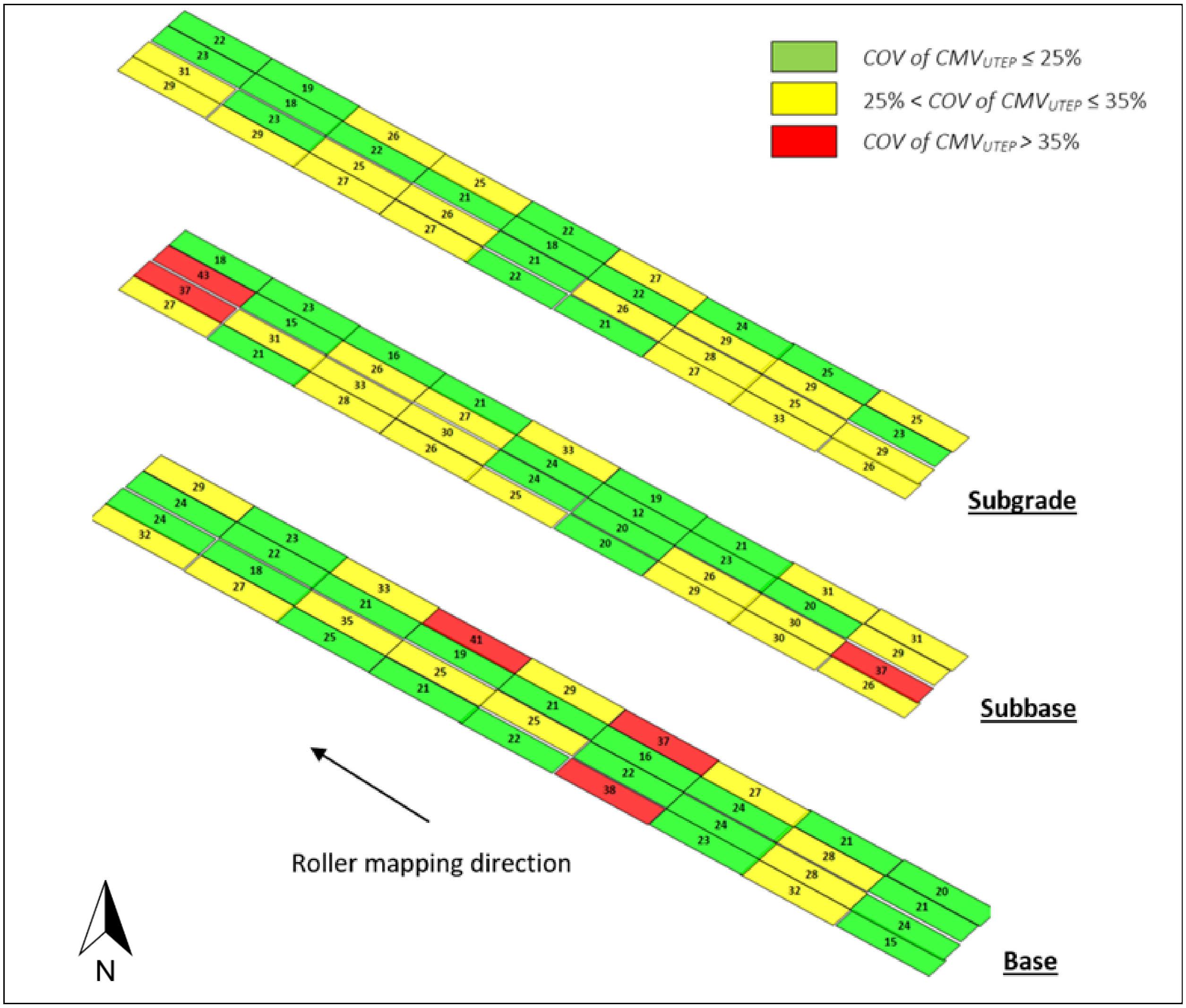


Figure 32. Color-coded maps of COV of CMV_{UTEP} measurements of subgrade, subbase, and base of Cell 2229

To compare the CMV measurements from the IC roller with CMV computed from UTEP's system in Cell 2229, both data sets were visualized in Veta, as illustrated in Figure 33. The trend of the change in the value of CMV measurements from the two systems is similar. By comparing Figure 30 and Figure 33, there are more softer areas in Cell 2229 than in Cell 2228.

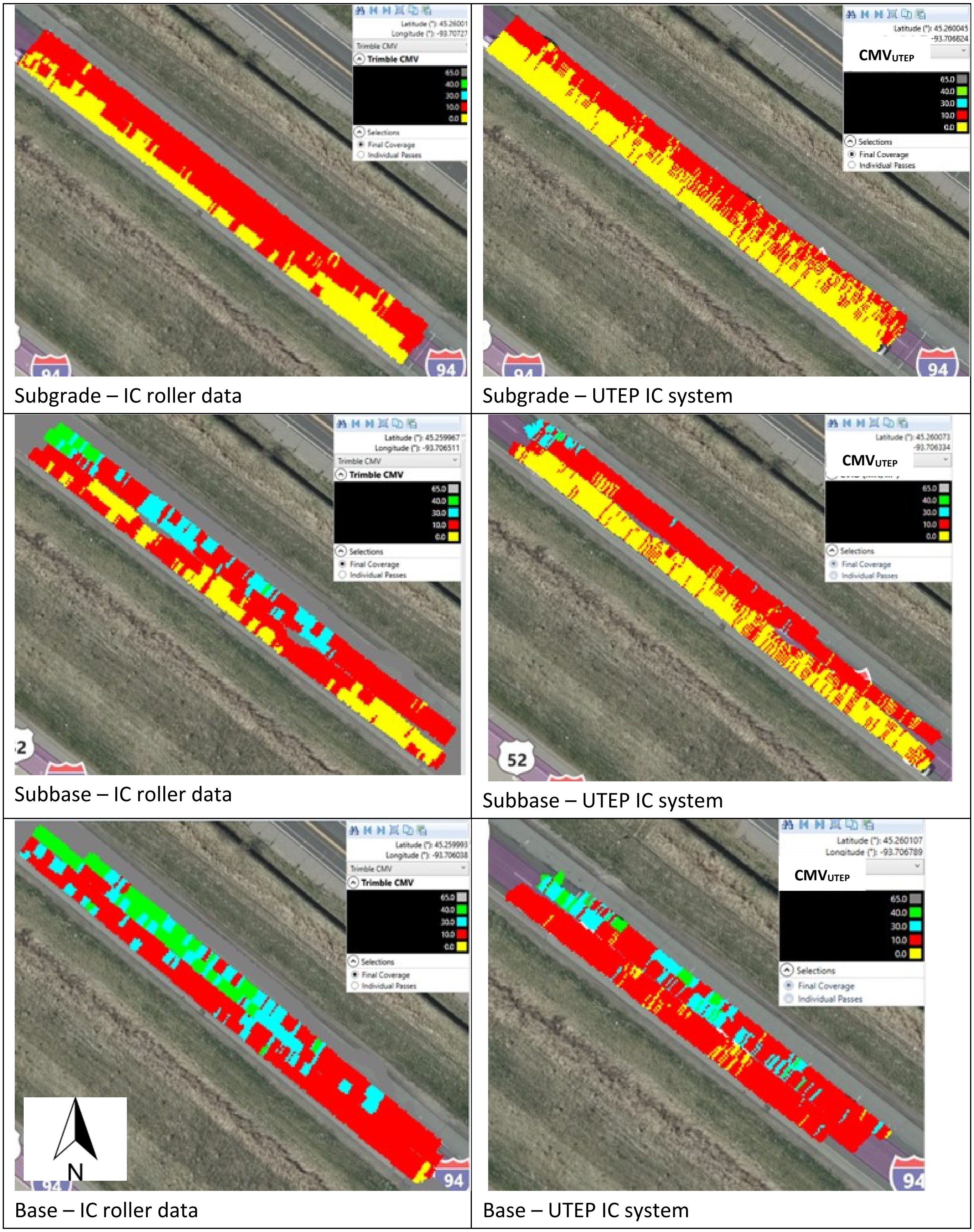


Figure 33. Comparison between CMV from IC roller and CMV from UTEP IC system for the subgrade, subbase, and base of Cell 2229

5.4 Correlation Analysis Between Level 1 ICMVs and Spot Tests

The spot tests on each grid of the mapped area include LWD and NDG, among others. LWD modulus can be back-calculated and used for comparison as a measure of stiffness. On the other hand, the density measurements from NDG are difficult to correlate to ICMV. However, both comparisons between ICMV and LWD modulus and ICMV and density are presented here.

5.4.1 Test Cell 2228

Figure 34, Figure 35, and Figure 36 illustrate a comparison between averaged CMV_{UTEP} , back-calculated LWD modulus, and NDG measurements of density. As observed from ICMV results in the previous section, most of the soft areas identified from LWD are also located on the left side of the mapped subgrade. It seems that the variability of the LWD moduli is higher than CMV_{UTEP}, which is expected due to uncertainties involved in the LWD test that may arise from the low compaction load, small contact surface, and shallower influence depth compared to the IC roller. LWD modulus only represents an average of two to three spot test measurements conducted in a 150 ft^2 area. The roller provides coverage of 7 ft width (drum width) and about 30-40 measurements within a length of 25 ft. However, the densities measured by NDG do not correlate with the compacted area's stiffness properties. The density is very consistent throughout the site despite the variable stiffness. This observation indicates the necessity of using a mechanical property such as modulus or stiffness along with density as the acceptance metrics of compaction of geomaterial.

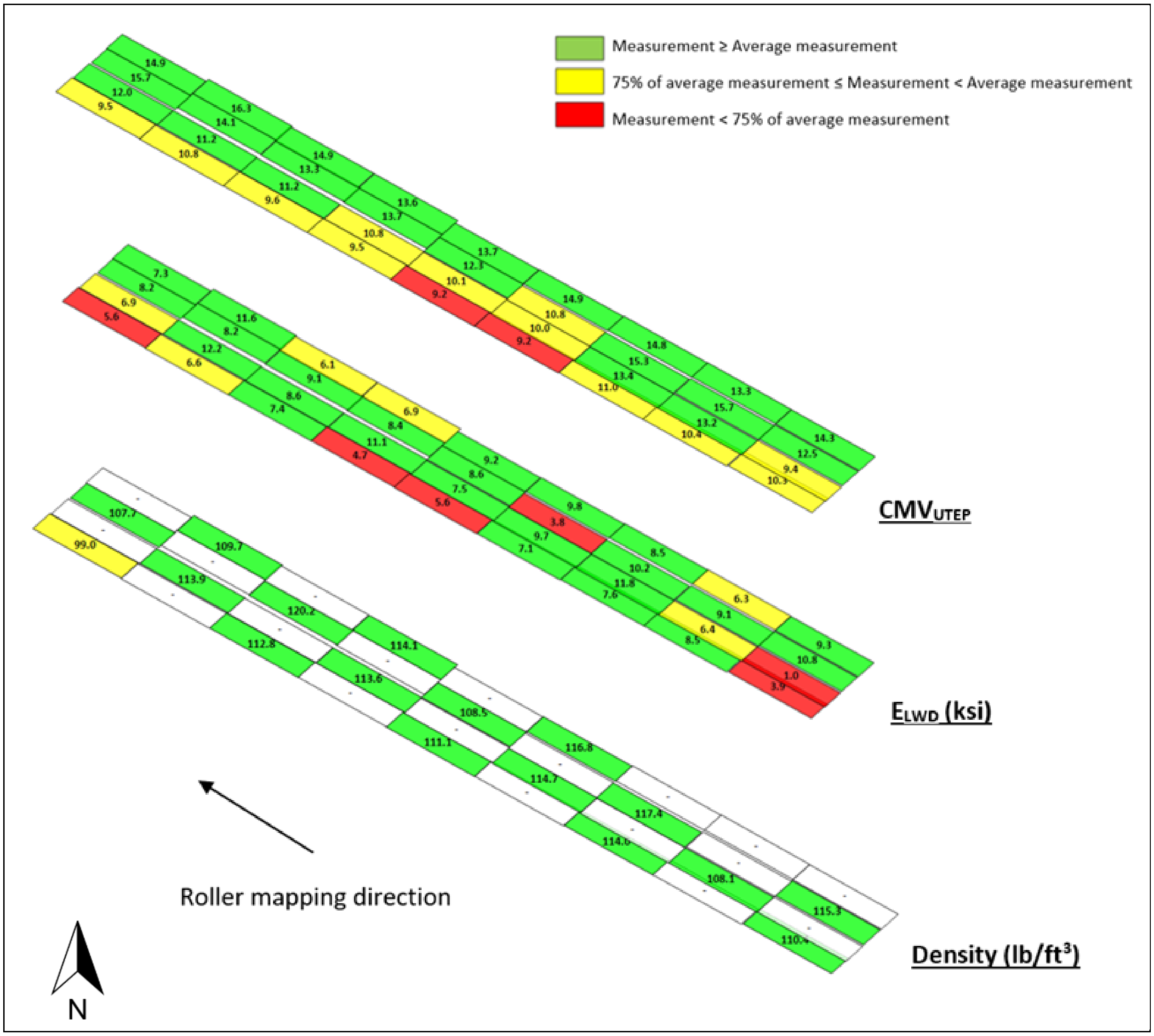


Figure 34. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the subgrade of Cell 2228

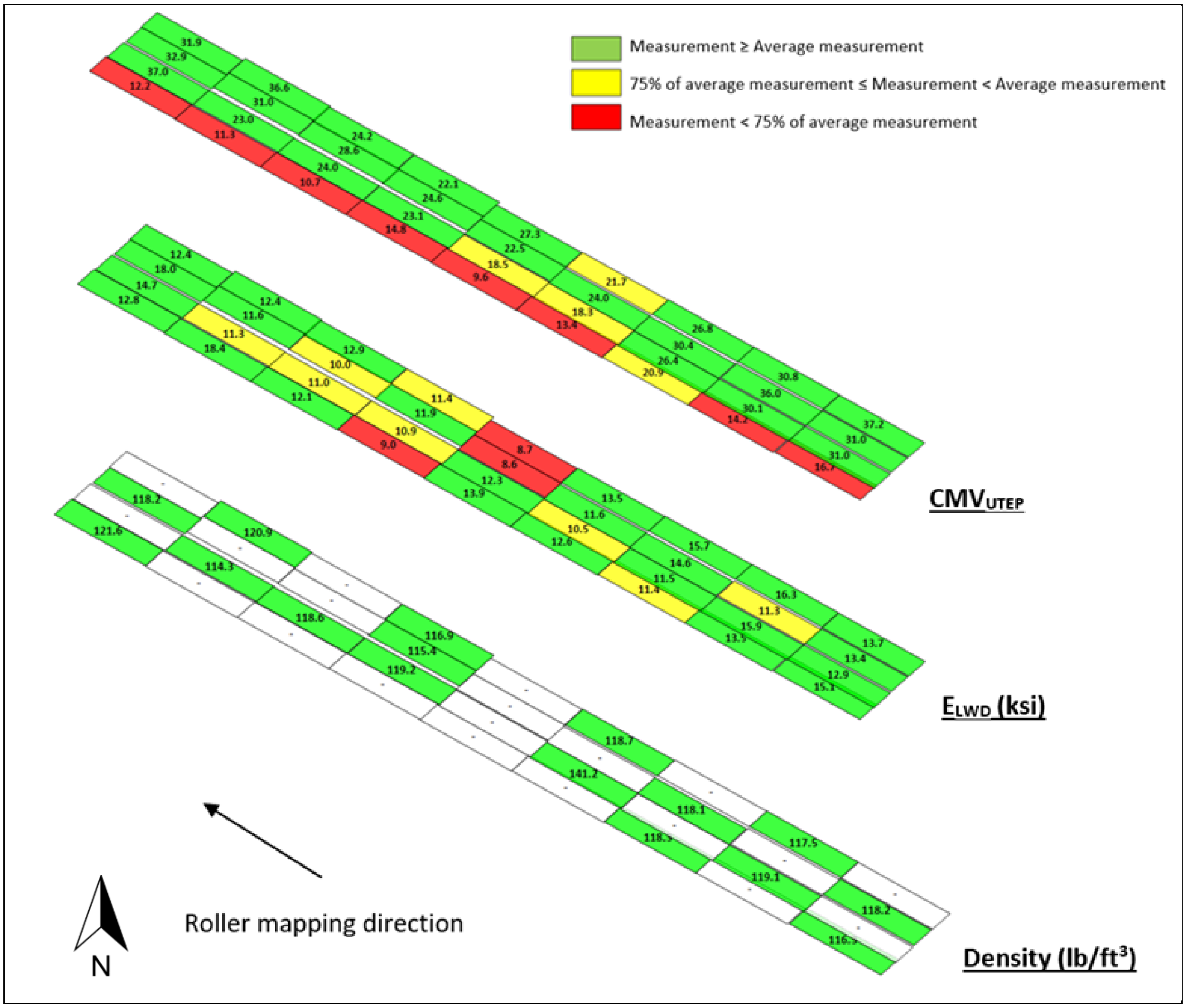


Figure 35. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the subbase of Cell 2228

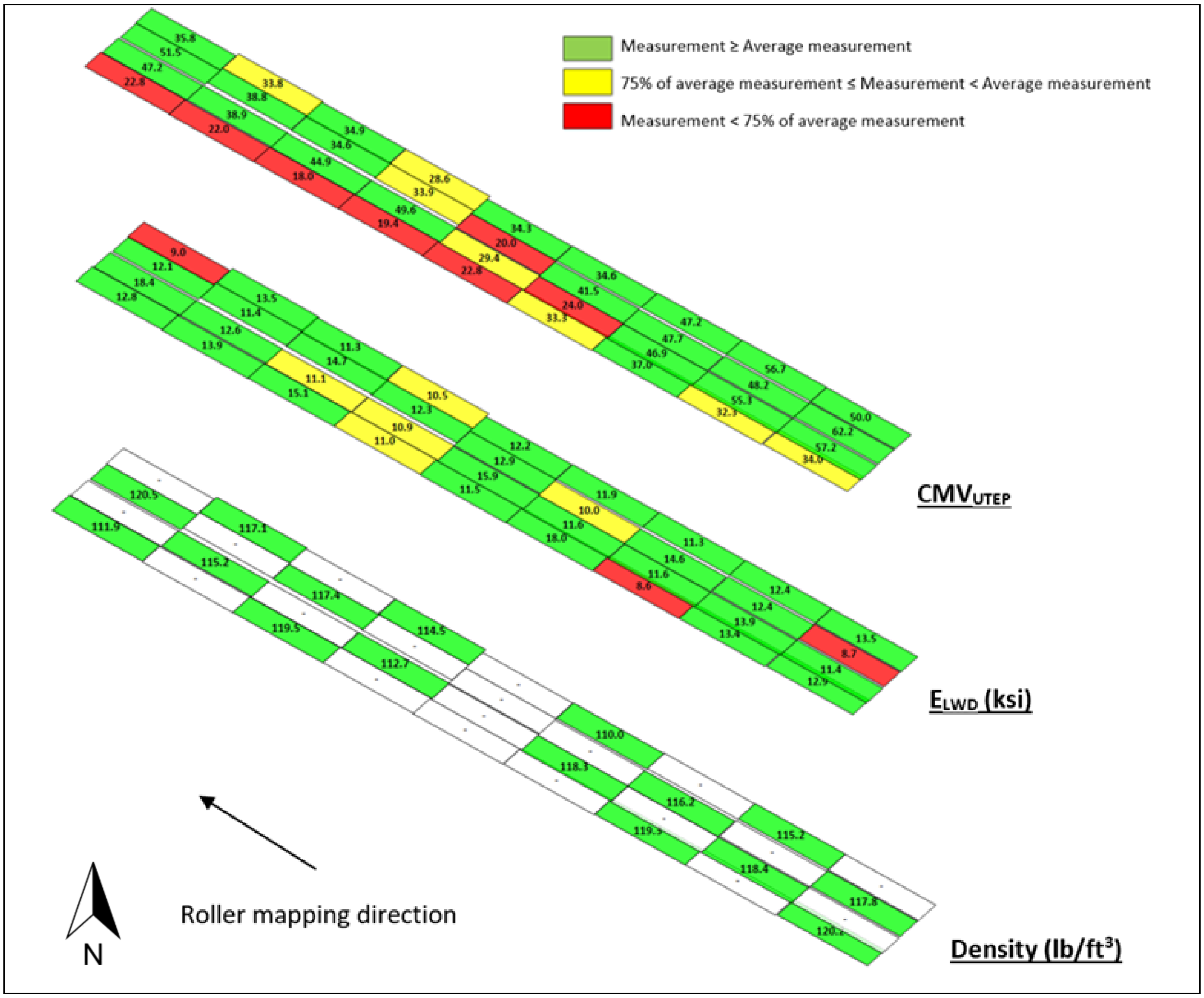


Figure 36. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the base of Cell 2228

5.4.2 Test Cell 2229

As observed in Figure 37, Figure 38, and Figure 39, lower stiffness of geomaterial was seen at the beginning of Cell 2229 based on the results of CMV measurements and LWD tests. Most soft areas are on the mapped area's left side (Lines C and D). However, the density measurements do not show considerable variation and correlation with the stiffness properties of compacted geomaterial.

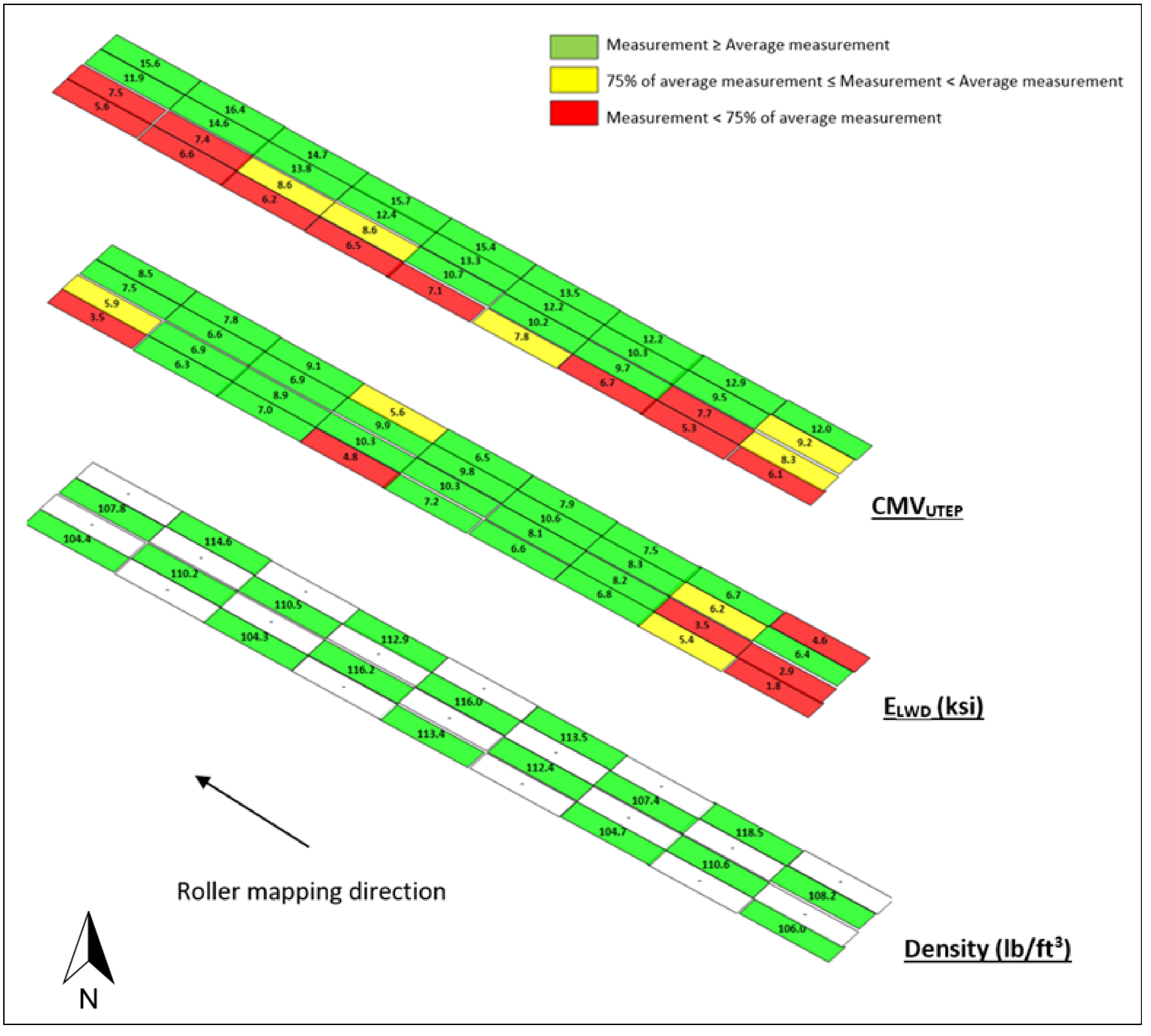


Figure 37. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the subgrade of Cell 2229

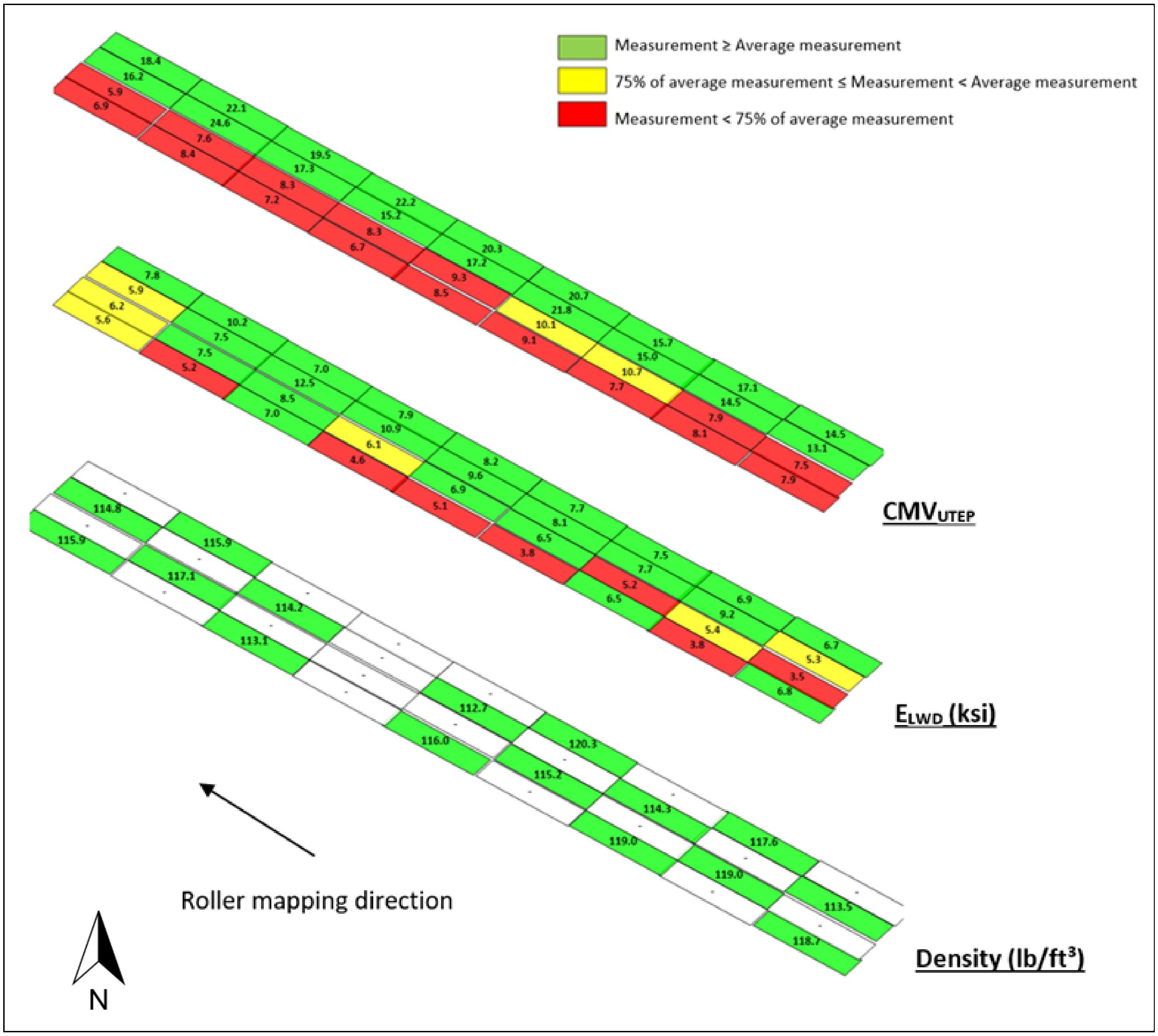


Figure 38. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the subbase of Cell 2229

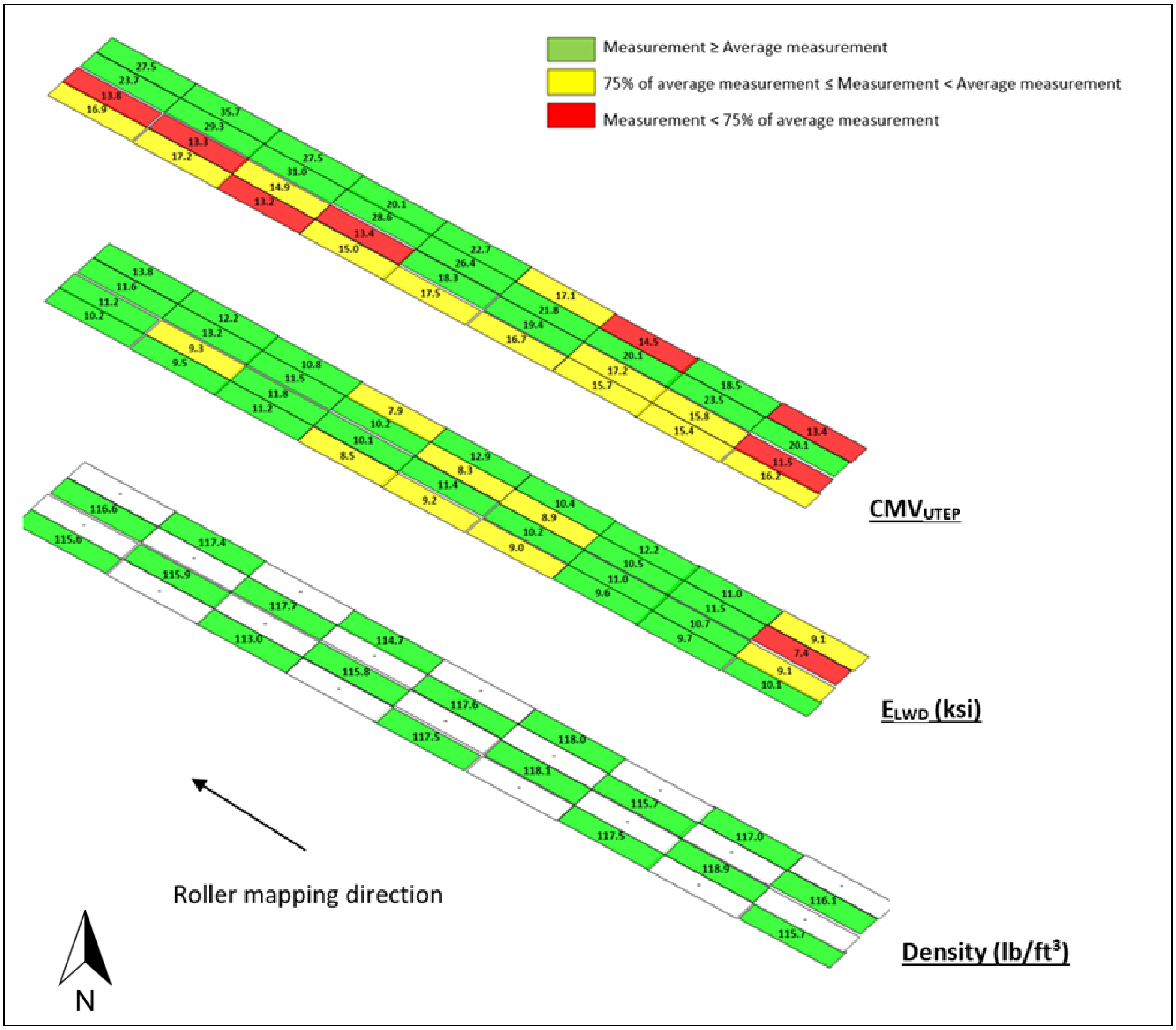


Figure 39. Comparison between CMV_{UTEP}, LWD back-calculated modulus, and NDG density of the base of Cell 2229

A good correlation between the results of ICMV and spot tests was observed as the soft areas identified by both measurements are aligned.

5.5 Comparison Between Emulated Level 3 ICMVs and Level 1 ICMVs

Evib and k_s, computed from the UTEP IC system, were used in this study as Level 3 ICMVs. The UTEP moduli, considered Level 4 and 5 ICMVs, are presented later in the section. The data collected using the UTEP system was processed to emulate E_{vib} and k_s to be compared with CMV, Level 1 ICMV.

The methods to compute E_{vib} and k_s are described in Appendix A. The parameters needed for this computation include compacted material properties, roller properties, and loading parameters. However, not all these parameters are available from the roller. Therefore, some assumptions were made to solve the equations of E_{vib} and k_s. For instance, the roller's phase lag between the excitation force and the displacement was not available and needed to be estimated to compute k_s. The contact force F_s needs to be defined as the sum of the forces due to the eccentric mass rotation and drum acceleration to calculate E_{vib}.

5.5.1 Test Cell 2228

A comparison between Level 3 ICMVs E_{vib}, $k_{s,}$ and Level 1 CMV_{UTEP} for the subgrade of Cell 2228 is shown in Figure 40. Although a similar trend was observed for different ICMV levels (soft areas on the left), it is clear that the variation of Level 3 ICMV is less significant compared to Level 1 ICMV. Therefore, tighter limits for color-coding maps are needed to identify the soft areas of Level 3 ICMV. By incorporating 98% and 99% limits, the maps of different ICMV levels follow the same trend.

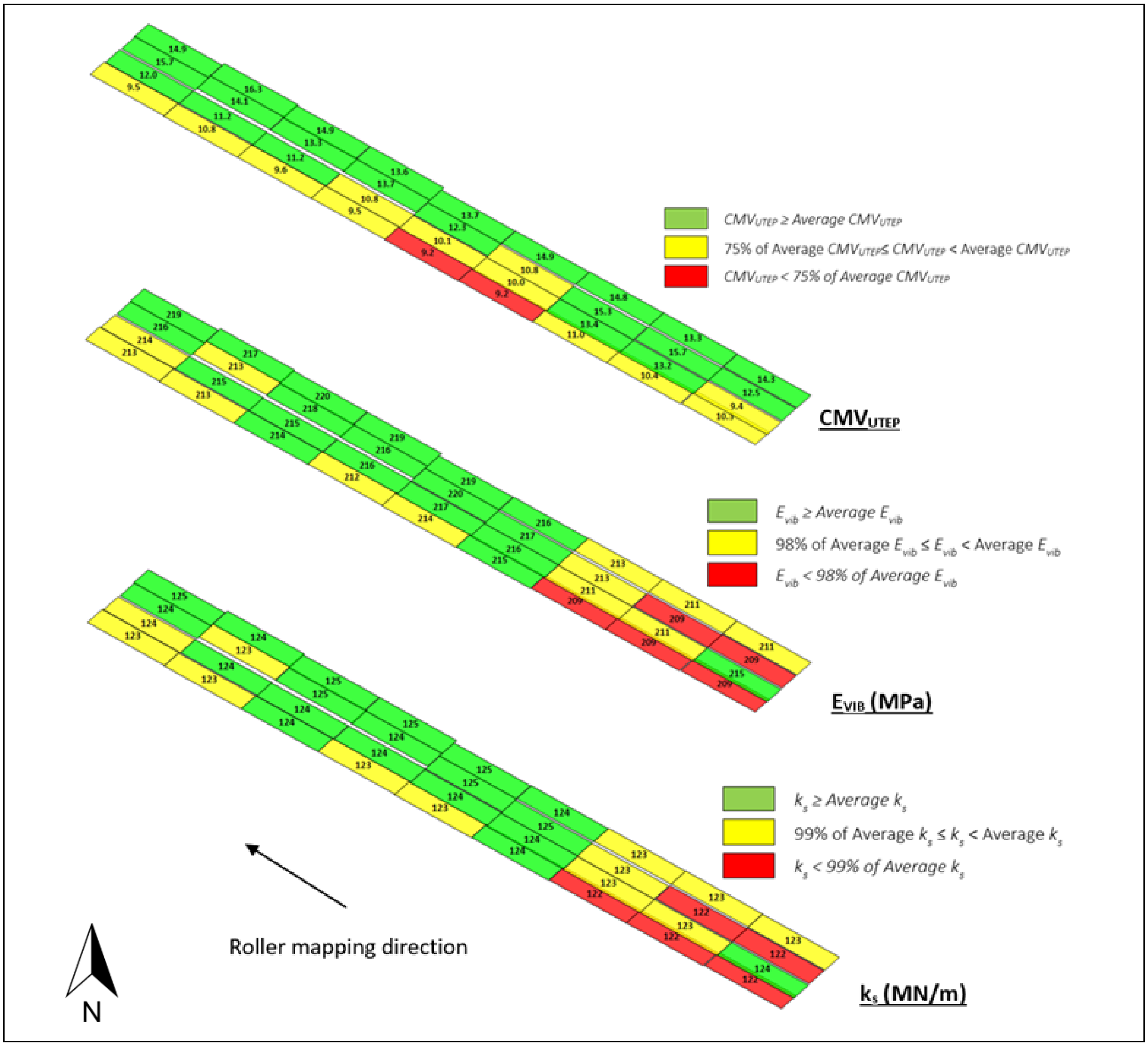


Figure 40. Comparison between CMV_{UTEP} (Level 1 ICMV) and E_{vib} (MPa) and $k_{s,}$ (MN/m) (Level 3 ICMV) of the subgrade of Cell 2228.

5.5.2 Test Cell 2229

As observed in previous sections, Cell 2229 showed comparatively higher variations and relatively lower CMV measurements. The same observation was made for Level 3 ICMVs E_{vib}, k_s, as illustrated in Figure 41. A similar trend shows in Cell 2228 with minimal variations in the value of E_{vib} and k_s. Also, there is a pattern of softer areas on the left side of the compacted cell.

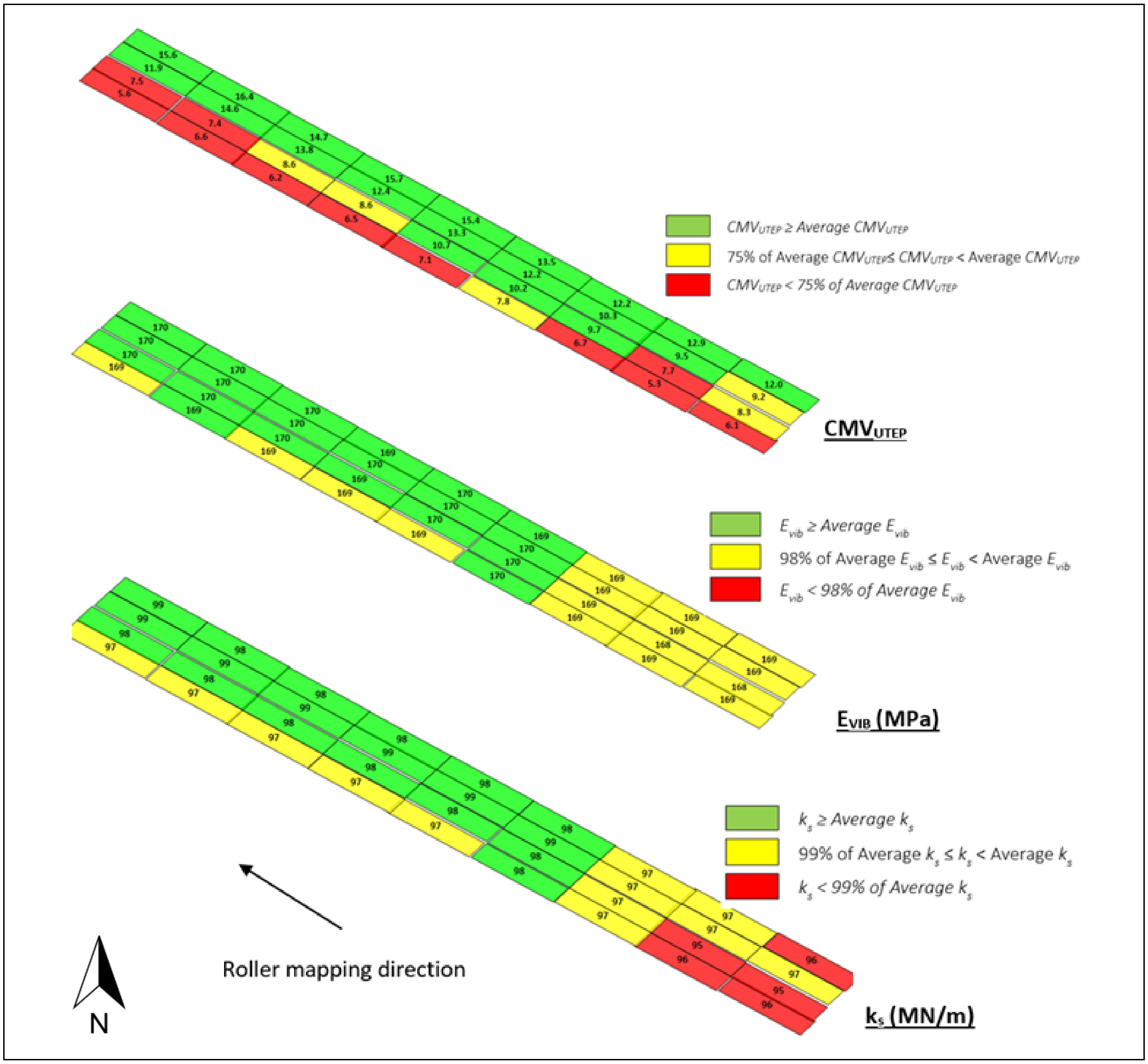


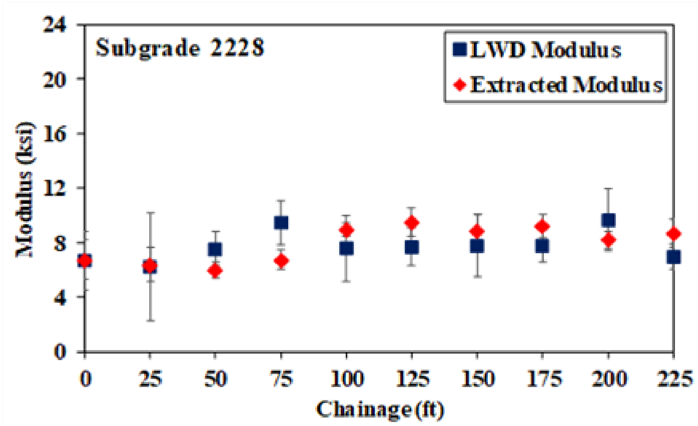
Figure 41. Comparison between CMV_{UTEP} (Level 1 ICMV) and E_{vib} (MPa) and k_s, (MN/m) (Level 3 ICMV) of the subgrade of Cell 2229.

5.6 Comparison Between UTEP Moduli Level 4-5 and Spot Tests

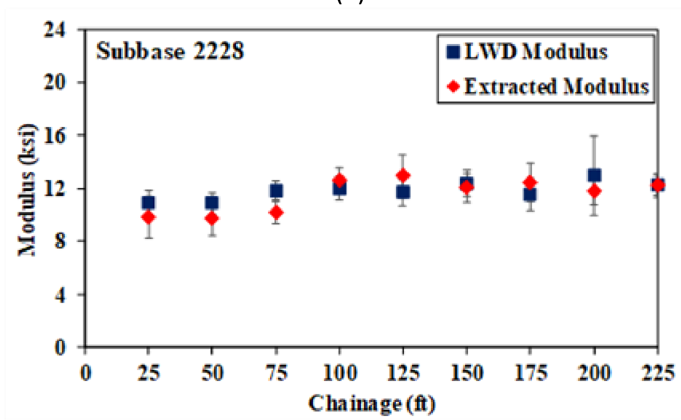
Nazarian et al. (2020) proposed two approaches for estimating the modulus of pavement layers. The first approach is to use an ANN inverse solver that utilizes the displacement (calibrated from numerical modeling), k_1' (adjusted based on LWD and resilient modulus tests), k_2' and k_3' (adjusted based on resilient modulus tests) to estimate the “extracted modulus.” This approach provides Level 5 ICMV. The extracted modulus can be layer-specific, providing better insights into the pavement layers' stiffness properties than the composite modulus measured by most field tests.

The second approach uses dynamic drum force at selected grids (with low variability) and LWD test results into the transfer function to estimate the “retrieved modulus.” This approach provides Level 4 ICMV. This report compares the UTEP extracted modulus (Level 5 ICMV), and UTEP retrieved modulus (Level 4 ICMV) with the LWD back-calculated modulus.

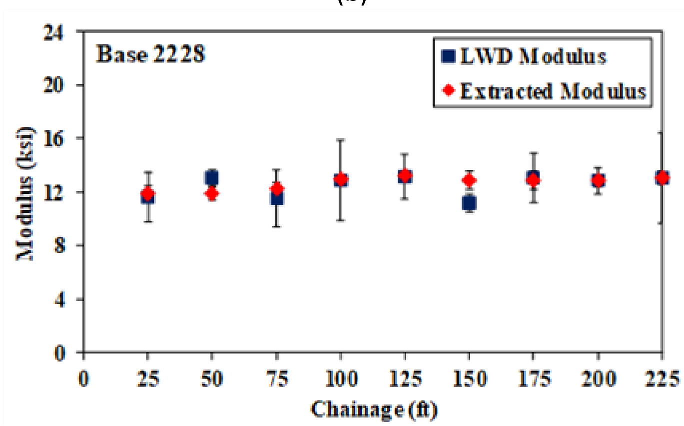
Figure 42 compares the extracted modulus from the UTEP system (Level 5 ICMV) and LWD back-calculated modulus for different pavement layers of Cell 2228. The data plotted for each chainage includes the two values. The error bars show the variations in the transverse direction, i.e., A, B, C, and D lines. A good correlation exists between the extracted modulus from Level 5 ICMV and the modulus back-calculated from LWD tests.



(a)



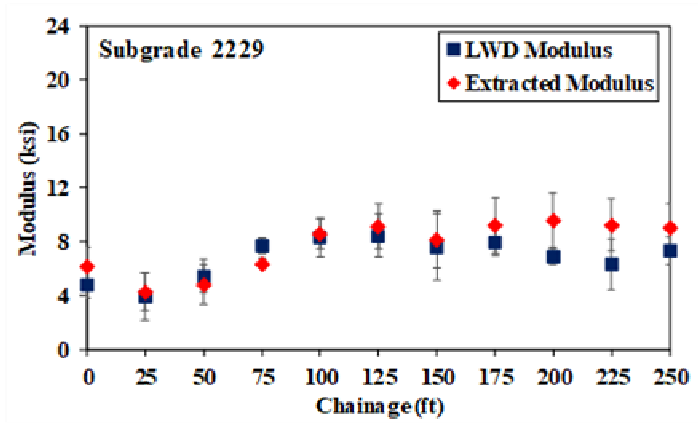
(b)



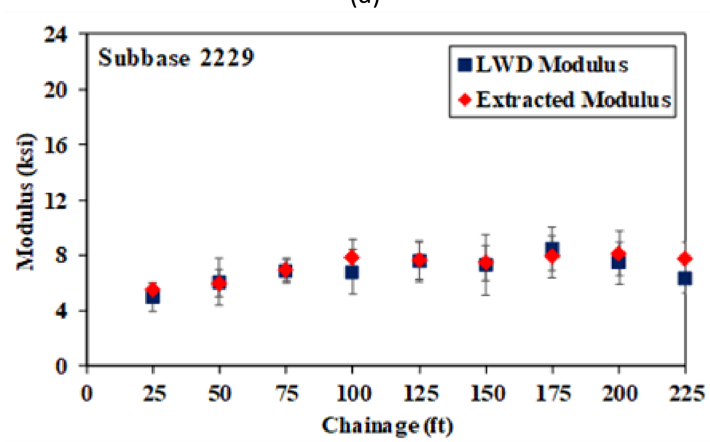
(c)

Figure 42. Comparison of UTEP extracted moduli (Level 5 ICMV) with LWD back-calculated modulus for (a) subgrade, (b) subbase, and (c) base of Cell 2228.

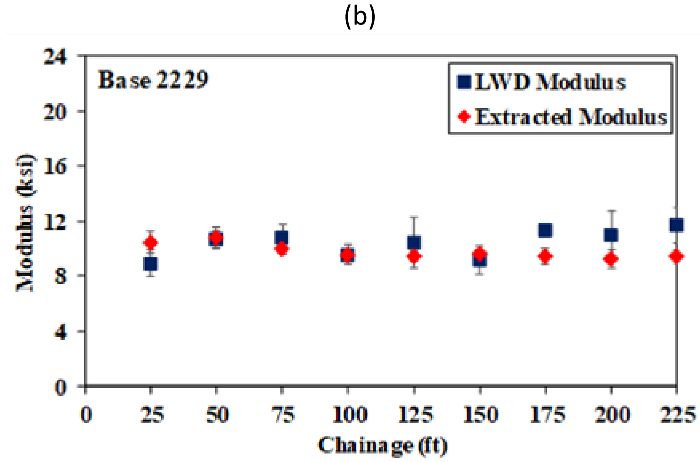
Figure 43 compares the extracted modulus from the UTEP system (Level 5 ICMV) and LWD back-calculated modulus for different pavement layers of Cell 2229. An excellent correlation exists between the extracted modulus from Level 5 ICMV and the modulus back-calculated from LWD tests.



(a)



(b)



(c)

Figure 43. Comparison of UTEP extracted moduli (Level 5 ICMV) with LWD back-calculated modulus for (a) subgrade, (b) subbase, and (c) base of Cell 2229.

Figure 44 through Figure 46 provides a visualization of the correlation between the UTEP system's extracted moduli (Level 5) and back-calculated LWD moduli. The error bars correspond to ±1 standard deviation for each chainage. Figure 44 shows a good correlation between UTEP-extracted moduli (Level 5 ICMV) and LWD moduli for the subgrade of both cells. All values of the extracted modulus (Level 5 ICMV) are within the ±25% error bounds.

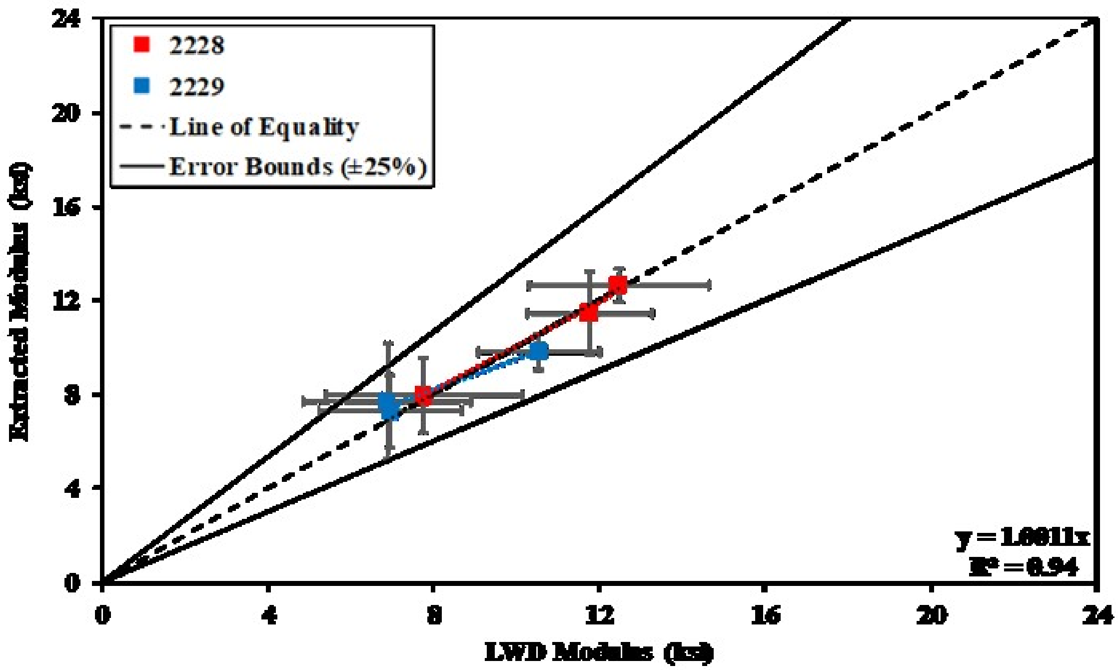


Figure 44. Correlation between UTEP extracted modulus (Level 5 ICMV) and LWD back-calculated modulus.

The variation of retrieved modulus (Level 4 ICMV) with the LWD back-calculated modulus is shown in Figure 45. Similar to extracted moduli (Level 5 ICMV), the retrieved moduli (Level 4 ICMV) correlate well with the LWD moduli. The results were also compared with the UTEP test results on similar subgrade at Cells 185-189 of MnROAD during the 2017 NCHRP 24-45 study. Fewer variations of moduli values were observed in 2022, indicating that the compacted sections were more uniform than those tested in 2017.

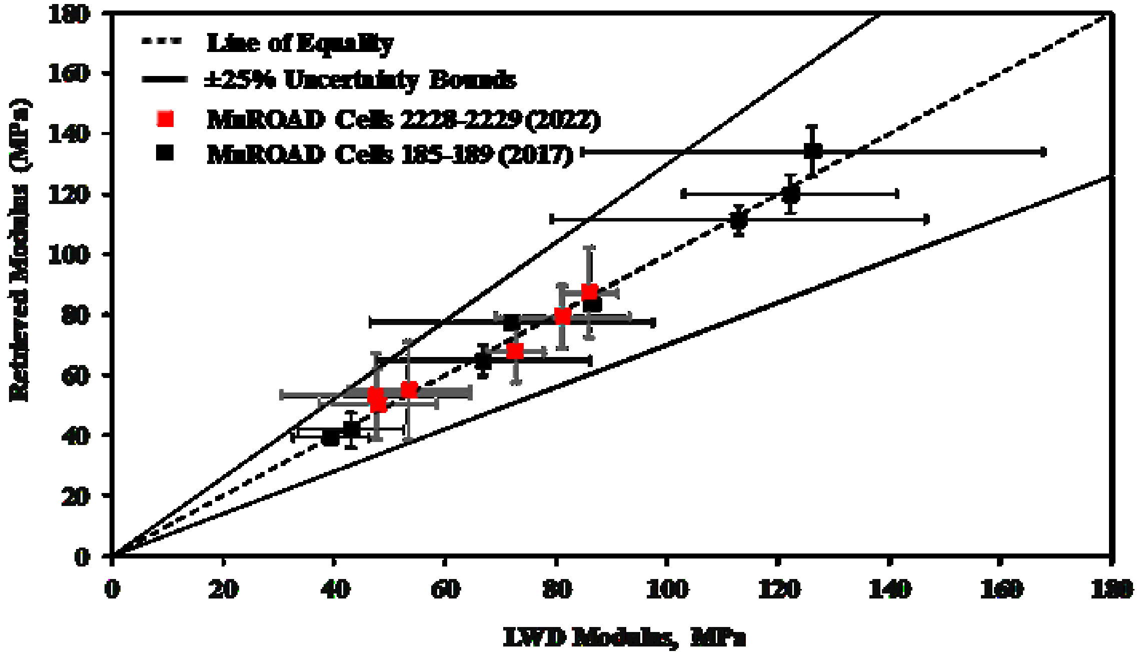


Figure 45. Correlation between UTEP retrieved modulus (Level 4 ICMV) and LWD back-calculated modulus.

One of the advantages of level 4-5 ICMVs is the ability to calculate layer-specific modulus. This feature improves the data QA process by identifying the less stiff areas in a specific pavement layer. Since the data from most in-situ tests provide composite properties of pavement layers, comparing layer-specific modulus and LWD modulus from tests conducted on each pavement layer provides a better insight into the compacted area properties. Figure 46 shows a good correlation between the moduli extracted per layer (from the displacement of specific layers) and the LWD back-calculated composite moduli. However, there is a slight deviation of each cell's trendlines of extracted modulus from the equality line. This deviation indicates that the LWD composite modulus may not strictly represent the layer stiffness. The high correlation observed in Figure 42 through Figure 46 shows that incorporating higher levels of ICMV can minimize the need for costly and time-consuming spot tests.

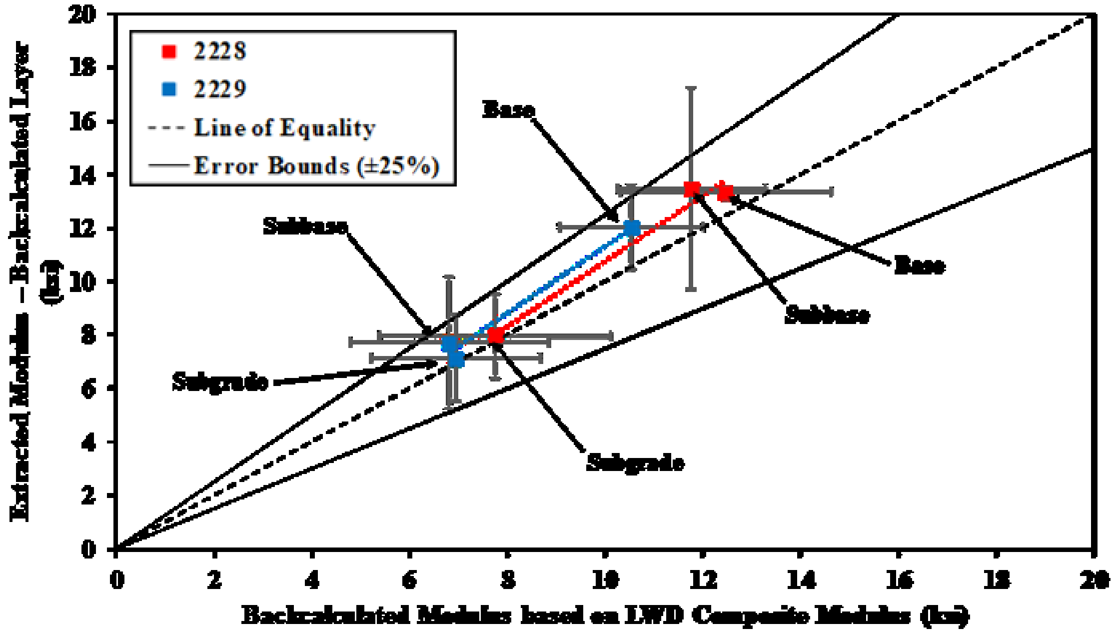


Figure 46. Correlation between UTEP extracted layer-specific modulus (Level 5 ICMV) and LWD back-calculated composite modulus.

CHAPTER 6: Framework for Future Soil, Subbase, And Base IC Certification

6.1 Introduction

This chapter describes the Task 4 efforts of the project, including the framework for certification of IC rollers for subgrade and subbase layers, the requirements for ICMV-spot test correlation, the uniformity metrics and their requirements for IC specification, and the proposed acceptance tests.

6.2 IC Certification Framework

A future IC certification program for soil and subbase compaction is needed before IC can be used as acceptance tests. There are well-developed and validated soil, subbase, and base IC specifications in Europe (CEN, 2016) and China (China Railway and Road, 2015; China Railway and Road, 2016). There are common and consistent contents among worldwide soil, subbase, and base IC specifications that can be used as the foundation of the soil, subbase, and base IC certification framework. The ICMV is also evolving and improving from Levels 1-2 to Levels 3, 4, and 5. Based on past soil, subbase, and base IC research and this study, the framework for soil, subbase, and base IC certification should include the ICMV requirements to be Level 3 and above (expressed in mechanical or physical properties), the minimum correlation between ICMV and spot test, and the minimum stability and uniformity of production ICMV.

6.3 Test Strip and Correlation Between ICMV and Spot Tests

To determine the minimum requirements for ICMV, a correlation between ICMV and spot tests should be established. For this purpose, a test strip representative of the actual pavement material and layers and construction method should be constructed. The test strip should:

- be constructed with the same roller pattern and equipment as the actual project,
- be constructed with the same material and layer thickness as the actual project,
- have a minimum length of 150 ft and minimum width of the road or embankment,
- be compacted within at least three different roller lanes with varying compaction efforts (low, medium, high) using the same roller settings, and
- be divided into grids at least 20 ft long and 6 ft wide (or roller drum width, whatever is smaller).

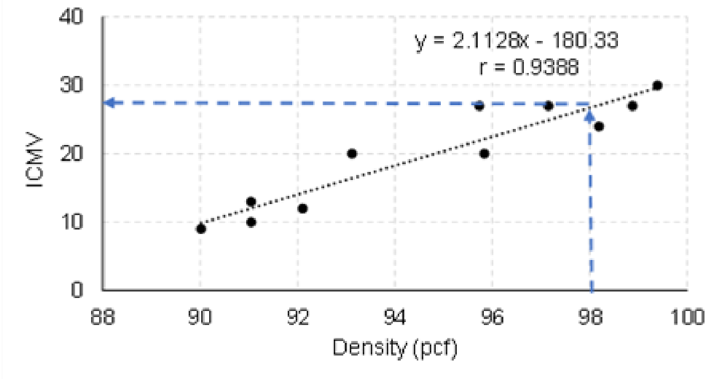
Once the test strip is established, the compacted material is mapped using an IC roller to identify the low, medium, and high areas. Then, the spot tests, including NDG density tests and LWD tests, are conducted on at least three spots (six are recommended) in the low, medium, and high ICMV areas. These spots are determined based on the lowest variation (COV less than 25%) in the color-coded maps of a particular spot test (if available) or at randomly selected spots along each compacted area category.

After collecting the IC and spot test data, the following correlations will be established:

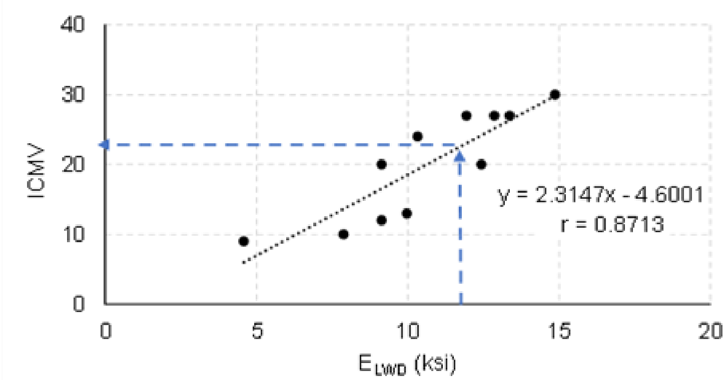
- Linear correlation between NDG density and average ICMV of the grid, and
- Linear correlation between back-calculated LWD modulus and average ICMV of the grid

Veta software may be used in establishing the above correlations. The regression analysis should result in a coefficient of determination R = 0.70 (i.e., $R^2 = 0.50$). If this criterion cannot be achieved, additional tests should be carried out. Such criteria can be raised as Level 3, 4, and 5 ICMVs are widely available.

Based on the findings of this project, there is a good correlation between LWD modulus and modulus computed from advanced methods (Level 4-5 ICMV). Therefore, a modulus requirement should be specified in the IC specification in addition to the density requirement. The density and LWD modulus requirements will be used to determine the minimum target ICMV using the correlations established above. The target ICMV must satisfy both density and modulus requirements (see Figure 47).

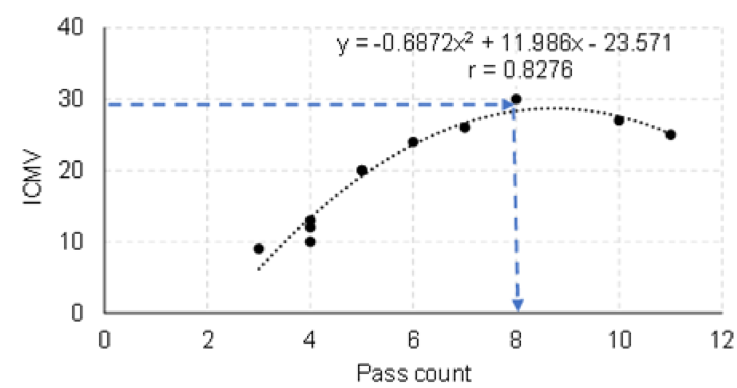


Example: Target density = 98%; then: Target ICMV = 27



Example: Target E_{LWD} = 12; then: Target ICMV = 23

Overall ICMV from spot tests: 27



Example: Maximum ICMV = 29; then: Optimum pass count = 8

Figure 47. Examples of correlations between ICMV and spot tests and pass count.

Furthermore, after establishing the target ICMV, the optimum pass count can be obtained using the third correlation established above for production compaction.

The IC test strip is not much different from the conventional test strip, but with the advantage of reducing spot tests during construction. The IC usage for the Istanbul Airport construction reduced a typical 1,000 conventional spot tests daily to about 70 spot tests, drastically reducing the spot test efforts and shortening the construction time.

6.4 ICMV Acceptance criteria for production compaction

The recommended acceptance criteria for an IC roller compacted geomaterial are summarized in the following items that are consistent with the EU standard (Sangioegi, 2016):

- Establish the minimum coefficient of determination for correlation between ICMV and spot test in a test strip. If this requirement is not met, the operation is not permitted.
- Determine the target ICMV based on the stiffness and density requirements in the specification.
- Calculate the mean and standard deviation of all ICMV data collected in the test section. and calculate the parameter c = mean – 1.28 x standard deviation (for 80% confidence level)
- If c ≥ target ICMV, the section passes the compaction quality requirement. Otherwise, improvements are needed to reach the required compaction level.

6.5 ICMV Uniformity Metrics

The ICMV measurements must be imported into standard analysis software (such as Veta). Then, the test grids as established in the previous section (e.g., 25 ft long by 6 ft wide) should be created. As shown in Chapter 5, one method of evaluating the uniformity of ICMV is to plot the maps of the coefficient of variation (COV) of the average ICMV within each grid from the average of the entire test section. The recommended threshold of COV of ICMV less than 25% for low variation and COV of ICMV greater than 35% for high variation can be established (recommended based on pilot tests in NCHRP project 24-45). If the COV of ICMV is above the maximum threshold, the section may not be rejected but need further improvement or a change of material properties (such as moisture).

As further IC studies for semi-variogram are advanced and validated in the future, the ICMV uniformity metrics may include both COV and geospatial semi-variogram.

6.6 ICMV Stability Metrics

To ensure consistent performance for ICMV systems, the roller's vibration frequency, amplitude, speed, and moving direction must be constant during the mapping runs. After the compaction is completed, the resulting ICMVs must be compared between two consecutive runs of the same test line. The point-by-point ICMV variation needs to be within 20%.

6.7 Recommended Spot Tests

The conventional acceptance tests for compacted geomaterials are mainly based on a measure of the degree of compaction, such as in-place density. For this purpose, NDG tests are typically conducted at certain intervals along the compacted area. With the increasing utilization of ICT, the costly and time-consuming spot tests such as NDG can be minimized, and more test coverage can be provided by ICT. Still, developing a correlation curve is necessary by performing a test strip to establish the target number of passes. In addition to reduced conventional spot tests such as NDG as a measure of the density of geomaterial, which may need further calibration with laboratory test results, other tests that are indicative of the compaction level of the pavement layers can be helpful.

According to the results of IC measurements and spot tests in Chapter 5, there is a good correlation between Level 3 and Level 4-5 ICMVs and LWD tests. In contrast, such a correlation was not observed between ICMVs and density in previous studies. The comparison between extracted modulus from Levels 3 to 5 ICMVs and back-calculated LWD modulus showed less than ±25% difference in most cases. Therefore, it is proposed to use the LWD test and the reduced NDG tests to measure the geomaterial's stiffness and density. This test should be repeated at least three times at each spot, and the average value should be used to minimize the uncertainties. The spot test data should be collected from low, medium, and high compaction areas. The number of spot tests in each test section and their spacing are site-specific. However, the results of this study (following NCHRP project 24-45) showed that the longitudinal spacing of 20-25 ft and transverse spacing of about the roller drum width could be a good test layout for establishing the acceptance criteria.

The approach recommended in this study considers both density and stiffness. As discussed above, minimum requirements for correlation between ICMV and spot tests and minimum requirement metrics for ICMV uniformity should be incorporated.

6.8 Proposed IC Reference Devices

Since spot tests have limited influence zones, it is proposed to use a continuous reference measurement device certification. Similar to the reference profilers used in high-speed inertial profiler certification, it is proposed to develop IC reference devices for ICMV certification: Continuous Compaction Reference Devices (CCRD). Such IC reference devices must have vertical vibration capability and Level 4-5 ICMV systems. Therefore, CCRD can be considered a moving plate load test (PLT) that produces the reference measurement to compare with a full-size IC roller’s ICMV. The cross-correlation method can be used for the comparison, similar to the inertial profiler certification. Future validation studies can establish the number of comparison runs and the acceptance criteria.

CHAPTER 7: Summary and Recommendations

7.1 Summary

This report documents the evaluation of Level 3-4 ICMV systems against Level 1 ICMV systems for soils, subbase, and base compaction to develop a blueprint for future certification procedures of IC. The study can be summarized as follows:

- Level 3-4 ICMV solutions were identified and compared with Level 1 solutions.
- A Caterpillar IC roller was used to measure the compaction meter value (CMV, Level 1 ICMV).
- The UTEP IC retrofit from the NCHRP Project 24-45 research was used to measure UTEP moduli (Level 4 and 5 ICMVs). The UTEP IC retrofit data were also used to emulate CMV (Level 1 ICMV), vibration modulus (E_{vib}, Level 3 ICV), and soil stiffness (K_s, Level 3 ICMV).
- The instrumentation of the Caterpillar IC roller with the UTEP IC retrofit system was successful.
- The field studies were conducted in two test cells at MnROAD during the 2022 reconstruction.
- IC mapping and spot tests were performed on the subgrade, subbase, and base of the two test cells. The spot tests included lightweight deflectometer (LWD) tests, nuclear density gauge (NDG), and GPS rover measurements. Soil samples were also taken for laboratory moisture content and resilient modulus tests.
- The field and laboratory test data were processed and compared. Statistical analysis of CMV was performed. The Level 1 CMV was compared with spot test results. The emulated Level 3 E_{vib}, Level 3 $K_{s,}$ and Level 1 CMV were compared. The comparison between UTEP moduli (Level 4 and 5 ICMVs) and spots showed the best correlation among all ICMVs.

7.2 Recommendations

Based on the findings of this project, the research team provides the following recommendations.

- A framework for future IC certification is recommended for future soils, subbase, and base IC compaction acceptance.
- The proposed framework includes the ICMV requirements to be Level 3 and above (expressed in mechanical or physical properties), the minimum correlation between ICMV and spot test, and the minimum stability and uniformity of production ICMV.
- The recommended spot tests are LWD and NDG tests (with the latter tests reduced) that most agencies use for compaction acceptance.
- Continuous compaction reference devices (CCRD) were recommended for future development as a certification reference device to follow the same high-speed inertial profiler certification path.

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Appendix A
Background of Level 1 to Level 5 Intelligent Compaction Measurement Values (ICMVs)

The following is the ICMV Level 1 to Level 5 background information (Xu, 2016; Xu and Chang, 2023).

Level 1 ICMV – Empirical Solutions based on Frequency Responses

The Level 1 ICMVs are empirical solutions based on frequency responses represented by harmonic ratios. These first-generation ICMVs are based on the reactive model for vibratory compaction or the reactive model for oscillation frequency reactive model. Examples of Level 1 ICMVs are Compaction Meter Value (CMV), Compaction Control Value (CCV), and HAMM Compaction Value (HMV). The details of CMV and CCV are described below.

Compaction Meter Value (CMV)

This Level 1 ICMV uses the harmonic ratio model, the most popular ICMV method in the industry. When the vibratory roller acts on soft material or the roller is suspended in the air, the waveform of the vibration drum response signal is sinusoidal (see Figure 4). Only the excitation frequency, f_0, is evident in the frequency-domain response. The waveform will be distorted when the vibratory roller acts on the relatively dense compacted materials. A second harmonic component, f_1, appears in the frequency-domain record in this situation. The ratio of these two frequency signals represents the degree of distortion of the waveform, a.k.a. Compaction Meter Value (CMV). The formula for CMV is shown in Eq. (1) by Thurner and Sandström in the 1980s. (Thurner and Sandström, 1980; Sandström, 2018)

$$\text{CMV} = C\frac{A(f_1)}{A(f_0)} \tag{2}$$

where $A(f_0)$ is the amplitude at the fundamental frequency; $A(f_1)$ is the amplitude at the first harmonic of the fundamental frequency; *C* is a constant. The harmonic ratio model uses CMV as the ICMV, and its change reflects the change in compaction quality. In Figure A.1, the compacted material is within a specific stiffness range as the number of rolling passes increases, and the packing state of the compacted materials transitions from loose to dense. Under such conditions, the CMV also increases (from Figure A.1 (a), Figure A.1 (b), to Figure A.1 (c)), reflecting the degree of compaction. However, when the compacted materials are very stiff, the changes in the frequency components of the vibration drum response signal appear at multiple frequencies that cannot be ignored (Figure A.1 (d)). Under such conditions, the CMV cannot correctly reflect the compaction quality information.

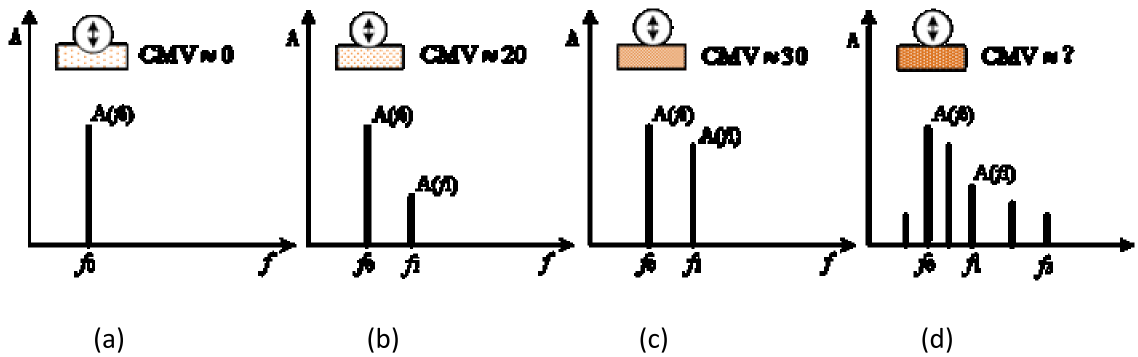


Figure A. 1. The CMV values reflect different compaction levels with frequency responses.

Compaction Control Value (CCV)

Several vendors use harmonic ratio models to address the multiple frequencies observed in Figure A.1. Examples are various Compaction Control Value (CCV) forms in Eq. (2).

$$\mathrm{CCV} = \frac{A(0.5f_0)+A(1.5f_0)+A(2f_0)+A(2.5f_0)+A(3f_0)}{A(0.5f_0)+A(f_0)}\times 100$$
$$\mathrm{CCV} = \frac{A(0.5f_0)+A(1.5f_0)+A(2.5f_0)+A(3f_0)}{A(2.5f_0)+A(3f_0)}\times 100 \quad (3)$$

Limitations of Level 1 ICMV

The harmonic ratio model cannot be applied universally. The field data have shown that the harmonic ratio method can only be applied to limited vibratory rollers compacting materials with specific packing structures. In addition, there is no theoretical proof of why harmonic ratios can be used to monitor changes in the compaction state. Therefore, CMV and CCV should be considered empirical indicators. As in many field studies, the limitations of the harmonic ratio method result in a poor correlation between CMV and conventional spot tests (Chang et al., 2014; Nazarian et al., 2015; Xu, 2016; Nazarian et al., 2020).

Level 2 ICMV – Energy and Rolling Resistance Solutions

The Level 2 ICMVs are energy and rolling resistance solutions. It is computed based on the reactive model with rolling resistance for static compaction. Examples of Level 2 ICMVs are OMEGA and MDP.

Energy Model (QMEGA)

The energy model is more scientific than the harmonic ratio model. It is based on the energy of the interaction between the vibratory roller and the compacted materials changes during the rolling process. The changes in energy at the end of compaction should be considered constant. The expression of the energy model that appeared in the 1990s is in Eq. (3).

$$\text{QMEGA} = \int_{2T} F(u)\dot{u} \qquad (4)$$

where *F(u)* is the resistance force of the compacted materials, $\dot{u}$ is the speed in the horizontal direction*, t* is the time*, and T* is the vibration period. This ICMV is called the OMEGA value. This formula is rarely used because this energy method is not directly related to the performance of the compacted materials and is not a parameter directly reflecting the compaction quality. Although the expression of the energy model seems scientific, it is still an empirical indicator based solely on the vibration drum response signals.

Rolling Resistance Model (MDP)

For static compaction, the compaction control can be performed by the phenomenon that "a certain quality static roller can only produce a certain compaction effect." Following this concept, a basic model for tracking the compaction process using a static roller is formed, which can also be considered a continuous compaction control method.

Static compaction can be considered as the rolling of a rigid drum along the surface of a deformed medium. The ratio of the roller's traction force, F (i.e., the relationship between the rolling resistance and the reaction force), and the acceleration of gravity, *G*, is defined as the rolling resistance coefficient, *f*. It has been shown in research and practices that each compacted material has a defined rolling resistance coefficient. During the compaction process, the rolling resistance coefficient changes with the densification of packing, which can be used as an indicator to evaluate the compaction effect (**Figure A.2**).

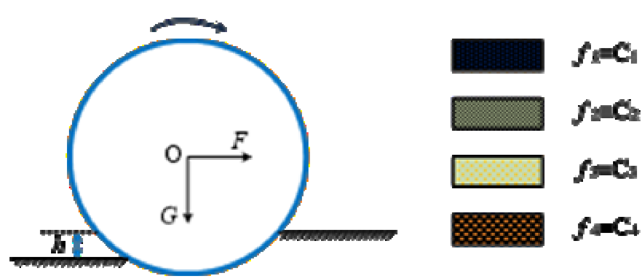


Figure A. 2. Rolling Resistance Model for static compaction.

In Figure A.2, the compression depth (i.e., deformation of the compacted materials) in the rolling process *h*, produced by the roller compaction of the roller drum, can be divided into two parts: elastic deformation, h_e, and plastic deformation, h_p. The resistance rolling coefficient, *f*, expression at the start of rolling (considering only plastic deformation, h_p) is as follows.

$$f = \frac{F}{G} = \frac{1}{(1+\mu c)(1-\mu c/3)}\sqrt{\frac{h}{D}} \quad (5)$$

where *F* is roller traction; *G* is the acceleration of the roller gravity; *D* is roller drum diameter; *h* is the depth of depression of the roller drum in compacted materials, where $h = h_e + h_p = h_p$, that is, the elastic deformation is not considered when starting the rolling; μc is material condition coefficient, for plastic clay and dry sand, $\mu c = 0.5$ Then, a heavier roller should be replaced to recompact it again.

The machine drive power (MDP) has been derived according to the above principle. The MDP uses the concept of rolling resistance and compressive deformation to determine the energy required to overcome rolling resistance, as expressed in Eq. (5).

$$\text{MDP} = P_g - WV\left(\sin\theta + \frac{a}{g}\right) - (mf \times V + bf) \quad (6)$$

where P_g is the total power required to drive the machine motion; *W* is the weight of the roller; *a* and *g* are the acceleration and gravitational acceleration of the machine; ϑ is the angle of the roller's forward movement; *V* is the speed of the roller, *mf,* and *bf* are the loss factors within the interior of the specific machine. *Θ*, *mf*, and *bf* must be calibrated before use. MDP requires the installation of multiple sensors and the calibration of some parameters, which needs the assistance of the roller manufacturer.

Limitations of Level 2 ICMVs

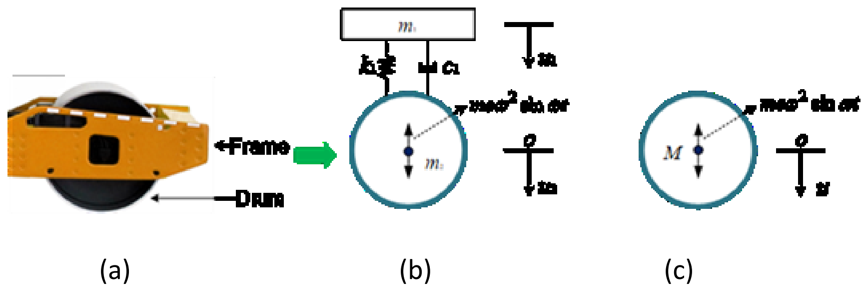
Due to its limitations of field performance, QMEGA is no longer used. Several studies of MDP have shown that MDP has a shallower influence depth than CMV (Chang et al., 2011). Some US DOTs had also observed the MDP's insensitivity to the soil stiffness variance.

Level 3 ICMV – Simplified Static Mechanistic Solutions

The Level 3 ICMVs are based on simplified static mechanistic solutions using either the discrete vibration, roller drum movement, or static continuum models. As described next, examples of Level 3 ICMVs include Ks (discrete vibration model) and E_{vib} (roller drum movement model).

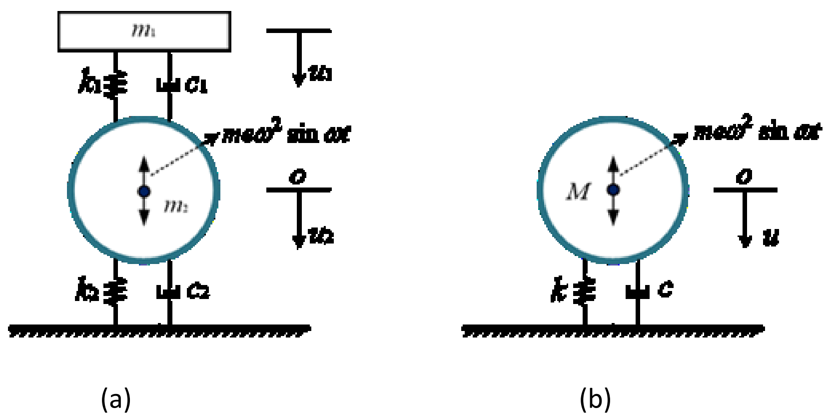
Soil Stiffness (K_s)

Soil Stiffness (K_s) is based on the lumped linear, mechanistic model to quantify the interaction between the roller drum and the compacted materials. The total force combines elastic and damping forces in the model (Anderegg, 2004). The two roller drum modes, A and B (**Figure A.3** (b) and Figure A.4 (c)), are applied to the discrete model. The masses of the compacted materials are omitted, resulting in the two linear discrete models: two degrees of freedom (**Figure A.4** (a)) and one degree of freedom (**Figure A.4** (b)). In **Figure A.4** (a), k_2 is the stiffness coefficient of the compacted materials; c_2 is the damping coefficient of the compacted materials. In **Figure A.4** (b), *k* is the stiffness coefficient of the compacted materials; *c* is the damping coefficient of the vibrating compacted materials. These parameters are unknown. The stiffness coefficient is particularly interesting since it can be used as an ICMV for compaction control.



Source: Xu and Chang (2022)

Figure A. 3. Simplified Roller Drum Model: (a) Roller frame and drum, (b) Mode A (middle), and (c) Mode B.



Source: Xu and Chang (2022)

Figure A. 4. Ks uses Linear Discrete Models: Mode A – two degrees of freedom (left) and Mode B – one degree of freedom (right).

The above model couples the roller drum with compacted materials, bonded with specific strength, and tightly coupled within a certain vibration intensity range. The model no longer applies when the decoupling happens or the bouncing range is exceeded. In addition, the mass of the compacted materials is not considered. Because the volume of the compacted materials changes during roller passes, the density is also changing. Therefore, the mass of the compacted materials cannot be determined. Therefore, the discrete model approximates the elastic state toward the end of compaction. However, the vibration balance point changes during plastic deformation, which causes difficulty in solving the ICMV.

Both Model A and Model B are considered classical steady-state vibrations (forced vibrations) models in vibration theory, which are relatively mature. The main concern for compaction quality control is determining the compacted materials' stiffness coefficient. Although these classic models can be solved, the solution for the stiffness coefficient of the compacted materials in the fields requires sophisticated techniques that are patented or trade secrets. Several stiffness solutions are provided next without discussing their derivation processes.

For the two-degree-of-freedom discrete model (Mode A), the expression of the stiffness coefficient, k_2, of the compacted materials can be obtained in Eq. (6):

$$k_2 = \omega^2\left(m_2 + \frac{me\cos\varphi}{u_2}\right) - \frac{m_1\ddot{u}_1}{u_2} \quad (7)$$

where φ is the phase lag between the excitation force and the displacement; m_1 is the roller frame mass; m_2 is the drum masses; m_e is the eccentric moment; ω is the vibration frequency, u_2 is the displacement; $\ddot{u}_1$ is the roller frame's acceleration. K_2 can be obtained when u_2, $\ddot{u}_1$, and φ are known. $\ddot{U}_1$, the roller frame's acceleration, can be measured with an accelerometer installed on the roller frame.

Two ways exist to solve the stiffness, k, of the compacted materials for the single-degree-of-freedom model (Mode B). In the first method, the roller drum's speed is assumed to be zero. Since the damping term is eliminated under this assumption, the expression of k is estimated using Eq. (7).

$$k = \omega^2\left(M + \frac{me\cos\varphi}{u}\right) \quad (8)$$

When the second method also considers the damping term, k is estimated using Eq. (8).

The

$$k = \omega^2\left[M + \sqrt{\left(\frac{me}{A}\right)^2 - \left(\frac{c}{\omega}\right)^2}\right] \quad (9)$$

In Eq. (9), c refers to the viscous damping coefficient, which can be determined in laboratories by a dynamic test. Roller manufacturers and field measurements can provide the remaining parameters. Ammann has implemented the ks, but it is rarely used in the US since 2008.

Vibratory modulus (E_{VIB})

The vibratory modulus (E_{VIB}) is calculated using the one-degree-of-freedom lumped parameter model and Lundberg's theoretical solution (Lundberg 1939) for a rigid cylinder on an elastic half-space. A detailed description of the E_{VIB} measurement technology is provided by Kröber et al. (2001). Previous studies (Krober 1998; Krober et al. 2001) reported that the E_{VIB} value relates to the modulus determined from a static plate load test. According to Eq. (10), using Lundberg's analytical solution, the drum force (F_s) and displacement (z_d) are related to E_{VIB}.

$$z_d = \frac{(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L} \cdot \frac{2}{\pi} \cdot \left(1.8864 + \ln\frac{L}{B}\right) \quad (10)$$

where, η = Poisson's ratio of the material, L = length of the drum, B = contact width of the drum, and R' = radius of the drum. According to Hertz (1895), the contact width (B) of a cylindrical drum can be calculated using the geometry of the drum, applied force, and the material properties, Eq. (10).

$$B = \sqrt{\frac{16}{\pi} \cdot \frac{R'(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L}} \quad (11)$$

The equations Eq. (11) and Eq. (12) can be solved to determine the E_{VIB} value. BOMAG and Dynapac have implemented the EVIB. BOMAG's E_{VIB} system uses two accelerometers pointing at 45° from the horizontal plane.

Limitations of Level 3 ICMVs

The Level 3 ICMVs provide the best field performance among commercially available ICMVs. However, there are still limitations of Level 3 ICMVs, such as not providing reliable measurements during double-jump, layer-specific measurement values, etc.

Level 4 ICMV – Hybrid Model with Dynamic Mechanistic Solutions

The Level 4 ICMVs are dynamic mechanistic solutions with a hybrid of impact, resistance identification, and modulus estimation models. The commercial versions of Level 4 ICMV are currently unavailable in the US. The followings are the backgrounds of Level 4 ICMV.

Impact Model (Decoupled system of a roller Drum and compacted materials)

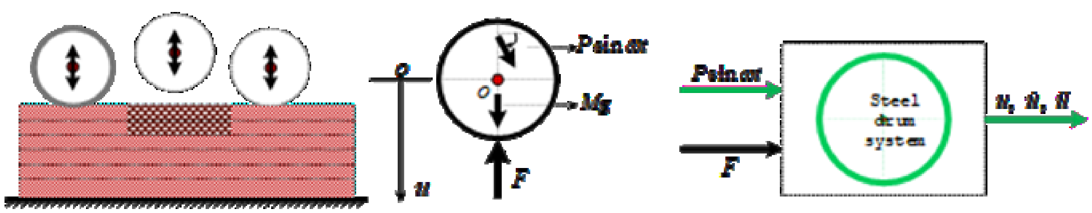
The above ICMV models require small elastic deformation, and the surface of the roller drum and the compacted materials must be in close contact and coupled. Otherwise, the models will no longer be valid. Under such a double jump (bouncing) condition, the models cannot provide accurate modulus or stiffness values. Whether the compacted materials are elastic, the roller drum and its surface are not fully coupled. Double jumps often occur during the later stage of compaction in the fields. Thus, it leads to a collision or impact problem. The cause for this bouncing phenomenon is that the rigidity of the compacted materials is inconsistent with the dynamic action of the roller drum. Whether the roller drum bounces is directly related to the modulus, E, of the compacted materials, the vibration mass, M, the excitation force, P, and the frequency, ω. However, it is difficult to determine those parameters theoretically in advance. (Xu and Chang, 2023)

If the roller drum bounces, the compacted materials will react to it as an indication of its enhanced resistance to deformation. For a roller with a specific vibration performance, the stiffer the compacted materials is, the stronger the reaction force on the roller drum will be. Therefore, it is more likely that the bounce will occur. The direct performance of the softness and hardness of the compacted materials (i.e., resistance to deformation) is the magnitude of the reaction force, i.e., the resistance force acting on the roller. It has been validated in the fields that the resistance force of compacted materials can also be used as a quality control index for compaction. The resistance force can always correctly reflect the change in the compaction state regardless of whether the roller drum bounces. The modulus and the stiffness coefficient are measures of the ability of the compacted materials to resist deformation, which is equivalent to the unit resistance. Resistance force applies to uncoupled collision/impact models and the coupled contact models mentioned above.

Resistance Identification Model

Due to intelligent compaction control's real-time and continuity requirements, it is impossible to embed sensors in compacted materials to measure their mechanical properties. Therefore, it is necessary to continuously measure the roller drum's dynamic response to identify the compacted materials' resistance force. Therefore, theoretical solutions and experimental calibration are needed to identify resistance forces (Xu and Chang, 2023).

To identify the resistance of the compacted materials through the roller drum, it is necessary to analyze the dynamic mode of the excitation of the roller drum during the compaction process. The resistance force can then be obtained by the system identification method. The movement mode of the roller drum is divided into two types: the coupling movement in close contact with the rolling surface; the collision movement without close contact with the rolling surface, as in Figure A.5 (a). Regardless of the mode, the effect of the compacted materials on the roller drum can be characterized by the resistance force, *F.* The force diagram of the steel wheel can be obtained in **Figure A.5** (b). The structural and performance parameters of the roller drum vibration system are known. Therefore, this collision/ impact model has two input parameters: the roller excitation force and the resistance of the compacted materials. The output is the dynamic response of the roller drum, as in Figure A.5 (c).



(a) (b) (c)

Source: FHWA (2017)

Figure A. 5. Collision/Impact Model: (a) roller compaction modes. (b) force diagram, and (c) system identification method.

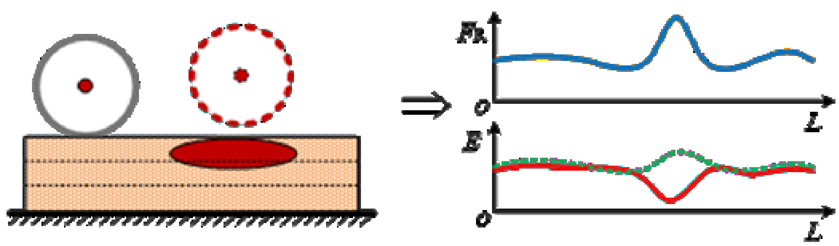
The eccentric force is generated from the roller drum's eccentric block rotation. The excitation force is the projection of the eccentric force in the vertical direction and is a known quantity related to the mechanical properties of the roller. The resistance force (*F)* is an unknown quantity as a function of the deformation and rolling. The change of *F* reflects the change in information of the resisting ability of the compacted materials. The resistance force is also the source of the sinusoidal motion of the roller drum. Measure the roller drum system's output is generally related to the type of sensor used. The commonly used output is the roller drum vibration's acceleration, speed, and displacement. Combined with the test technique and the motion pattern of the roller drum, a resistance identification model based on the system identification method can be formulated as follows.

$$F = Mg + \eta_1 me\omega^2 \sin \omega t - \eta_2 Mf(\ddot{}$$ (12)

Where η_1 is the dynamic correction coefficient of the excitation force; η_2 is the comprehensive correction coefficient of the dynamic response of the roller drum; φ is the phase difference between the excitation force input and the displacement output, which varies with the rolling pass counts. $f(\ddot{}$ is a function or time series related to roller drum's dynamic response ($\ddot{u}$), vibration frequency (ω), pthe hase difference (φ), and type of compacted materials. $f(\ddot{}$ needs to be determined based on the measured data in the fields. In practical applications, converting resistance, *F*, into resistance coefficient, F_R, will give better results.

modulus estimation model

During compaction, the resistance coefficient of the compacted materials obtained by the roller measurement is consistent with the modulus variation. When the roller drum encounters a stiffer area and bounces, the resistance coefficient can still be calculated correctly, increasing the value (see the solid blue line in Figure A.6. However, the computed modulus is erroneously small. As shown in **Figure A.6**, the erroneous moduli (solid red line) should be corrected by the impact model (the dotted green line).



Source: Xu and Chang (2023)

Figure A. 6. Resistance and modulus during double jumps

There are two approaches to estimating the moduli during double jumps.

Estimating the displacement of the compacted materials based on the dynamic response of the drum to identify the modulus

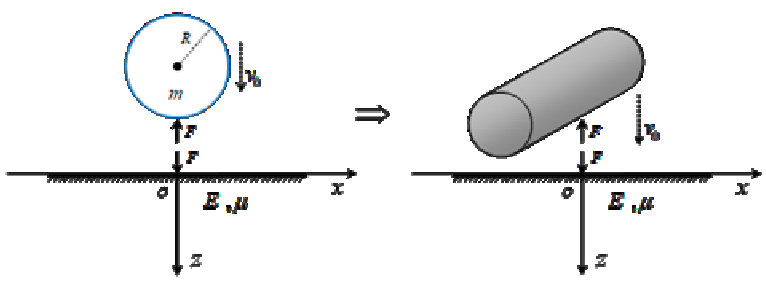
When the compacted materials are relatively stiff, the roller drum will bounce with its dynamic response closely related to the performance of the compacted materials. Although it cannot be obtained according to the roller drum response information, the displacement of the compacted materials can be estimated based on the roller drum reaction. The larger the roller drum response displacement, the smaller the compacted materials' displacement. The corresponding relationship between the two can be established through experiments. The displacement of the compacted materials can be estimated according to the roller drum's bouncing information, and the compacted materials' modulus can be computed using the unified theory, Eq. (24).

Estimate the modulus based on the collision time between the roller drum and the compacted materials

From collision dynamics, vibration compaction is the interaction of two objects: the roller drum and the compacted materials. Since the vibratory roller and the compacted materials are not entirely coupled, it can be regarded as a general object collision contact problem. Driven by the excitation force, the roller drum starts to contact the rolling surface at a certain speed, v_0, then impact, and a collision occurs. The compacted materials gradually produce compressive deformation until the speed of the roller drum becomes zero. As the compacted materials reach a specific elastic state, they start rebounding at a certain speed, and their elastic deformation will return to 0. Under such conditions, the roller drum will leave the rolling surface or bounce under the action of the eccentric force. Due to the plastic deformation and damping of the compacted materials, the speeds before and after the collision are generally different. A kinetic energy difference can be generated and absorbed by compacted materials.

During the collision process, the stiffness of the compacted materials is closely related to the collision contact time. The stiffer the compacted materials (i.e., large modulus), the greater the interaction force. The shorter the contact time, the greater the rebound speed. There is a connection between some parameters in the collision process and the modulus of the compacted materials.

The collision/impact model is assumed to be an elastic collision problem. The compacted materials are assumed to be an elastic half-space body, and the roller drum is rigid. The roller drum collision problem can be solved approximately by using the collision model of a steel ball and the elastic half-space Figure A.7.



Source: Xu and Chang (2023)

Figure A. 7. Collision/Impact Model: Steel ball and half-space compacted materials (left) and roller drum and half-space compacted materials.

The expression of the deformation and the collision contact time of the roller drum (contact velocity, *v*) in the compression phase of the elastic half-space body (i.e., compacted materials) can be obtained in Eq. (12) and Eq. (13), respectively.

$$u = \left[\frac{3\pi^{3/2} M (1-\mu^2)(v_0^2 - v^2)}{16LE} \right]^{1/2} \quad (13)$$

$$T_c = 2.944\left[\frac{3\pi^{3/2}M(1-\mu^2)}{16LE}\right]^{1/2} \qquad (14)$$

When the collision speed of the roller drum is constant, the larger the modulus of the compacted materials, the smaller the compressive deformation of the rolling drum on the rolling surface, and the larger the displacement of the rebound. Eq. (14) shows a compressive-recovery cycle among the contact time (T_c), the drum mass (*M*), the drum width (*L*), and the modulus of the compacted materials (*E*). Since the roller drum parameters (M and L) are known values, this reflects the relationship between the compacted materials' modulus and the roller drum's contact time.

It should be noted that the actual vibratory compaction problem is a mixture of forced vibration and collision impact. The contact time between the roller drum and the compacted surface includes the action time of the forced vibration and the collision impact time. Future study is warranted that would involve nonlinear dynamics.

Limitations of Level 4 ICMVs

Since there are no commercially available Level 4 ICMVs, the limitations of their field performance are unknown. Theoretically, Level 4 ICMVs should provide reliable measurements during double jumps and is one step closer to the ultimate Level 5 ICMVs that can provide layer-specific moduli and densities.

Level 5 ICMV – Dynamic Mechanistic and Artificial Intelligence Solutions

The Level 5 ICMVs combine dynamic mechanistic solutions and artificial intelligence solutions. The commercial versions of Level 5 ICMV are currently unavailable in the US or worldwide. The followings are the backgrounds of Level 5 ICMV.

Dynamic Model

The vibratory roller compaction operation can be characterized by vibration and movement while vibrating and rolling. Modeling such phenomena using dynamics is a natural choice. Based on the elastic half-space theory, the dynamic equilibrium (eq. 14), the geometric equation (eq. 15), the compatible equation (eq. 16), and the constitutive equation (eq. 17) can be established at any point inside the compacted materials.

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{yx}}{\partial y} + \dfrac{\partial \tau_{zx}}{\partial z} = \rho \dfrac{\partial^2 u}{\partial t^2} \\ \dfrac{\partial \tau_{xy}}{\partial x} + \dfrac{\partial \sigma_y}{\partial y} + \dfrac{\partial \tau_{zy}}{\partial z} = \rho \dfrac{\partial^2 v}{\partial t^2} \\ \dfrac{\partial \tau_{xz}}{\partial x} + \dfrac{\partial \tau_{yz}}{\partial y} + \dfrac{\partial \sigma_z}{\partial z} = \rho \dfrac{\partial^2 w}{\partial t^2} \end{cases} \qquad (15)$$

$$\varepsilon_x = \frac{\partial u}{\partial x} \quad , \quad \varepsilon_y = \frac{\partial v}{\partial y} \quad , \quad \varepsilon_z = \frac{\partial w}{\partial z}$$
$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}, \quad \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}, \quad \gamma_{zx} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \tag{16}$$

$$\begin{aligned}
&\frac{\partial^2 \varepsilon_y}{\partial x^2} + \frac{\partial^2 \varepsilon_x}{\partial y^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y} \qquad \frac{\partial}{\partial x}\left(\frac{\partial \gamma_{zx}}{\partial y} + \frac{\partial \gamma_{xy}}{\partial z} - \frac{\partial \gamma_{yz}}{\partial x}\right) = 2\frac{\partial^2 \varepsilon_x}{\partial y \partial z} \\
&\frac{\partial^2 \varepsilon_z}{\partial y^2} + \frac{\partial^2 \varepsilon_y}{\partial z^2} = \frac{\partial^2 \gamma_{yz}}{\partial y \partial z} \qquad \frac{\partial}{\partial y}\left(\frac{\partial \gamma_{xy}}{\partial z} + \frac{\partial \gamma_{yz}}{\partial x} - \frac{\partial \gamma_{zx}}{\partial y}\right) = 2\frac{\partial^2 \varepsilon_y}{\partial z \partial x} \\
&\frac{\partial^2 \varepsilon_x}{\partial z^2} + \frac{\partial^2 \varepsilon_z}{\partial x^2} = \frac{\partial^2 \gamma_{zx}}{\partial z \partial x} \qquad \frac{\partial}{\partial z}\left(\frac{\partial \gamma_{yz}}{\partial x} + \frac{\partial \gamma_{zx}}{\partial y} - \frac{\partial \gamma_{xy}}{\partial z}\right) = 2\frac{\partial^2 \varepsilon_z}{\partial x \partial y}
\end{aligned} \tag{17}$$

$$\begin{aligned}
\varepsilon_x &= \frac{1}{E}[\sigma_x - \mu(\sigma_y + \sigma_z)] \quad , \quad \gamma_{xy} = \frac{1}{G}\tau_{xy} \\
\varepsilon_y &= \frac{1}{E}[\sigma_y - \mu(\sigma_z + \sigma_x)] \quad , \quad \gamma_{yz} = \frac{1}{G}\tau_{yz} \\
\varepsilon_z &= \frac{1}{E}[\sigma_z - \mu(\sigma_x + \sigma_y)] \quad , \quad \gamma_{zx} = \frac{1}{G}\tau_{zx}
\end{aligned} \tag{18}$$

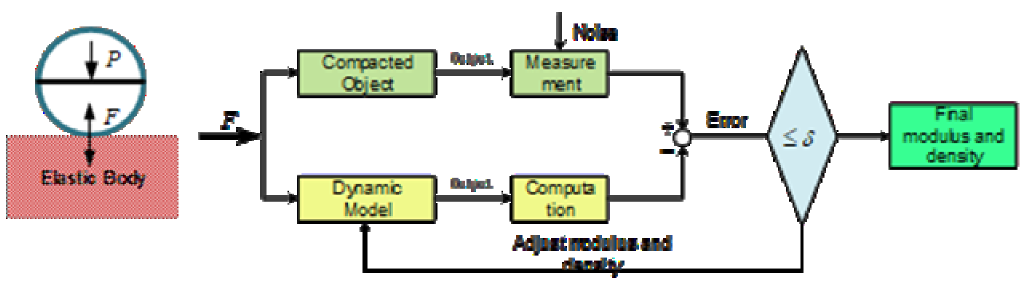
where *u*, *v*, and *w* are the displacement components in the *x*, *y*, and *z* directions, respectively; $\sigma(x, y, z)$ and $\tau(x, y, z)$ are the normal stress and the shear stress, respectively; $\varepsilon(x, y, z)$ and $\gamma(x, y, z)$ are normal strain and shear strain, respectively; *G* is the shear modulus, *E* is the elastic modulus, and *μ* is the Poisson's ratio, and the following relationship exists between the three.

$$G = \frac{E}{2(1+\mu)} \tag{19}$$

Eq. (14) to Eq. (18) describe the characteristics of the inner part of the elastic half-space body under stress. They are also the fundamental equations of the elastic half-space theory with the boundary conditions, such as the dynamic compaction force at the surface, the stress, strain, and displacement in the infinite depth are all zero. The above constitutes a complete dynamic model through the movement of the vibratory roller. While it is not difficult to build a model based on the theory of elasticity, the difficulty lies in solving it analytically.

Three critical parameters characterize the properties of the compacted materials, i.e., elastic modulus, *E*, density, *ρ*, and Poisson's ratio, *μ* — representing physical parameters of elastic half-spaces. For compaction quality control, modulus and density are key control indicators. These three parameters represent the mechanical and physical properties of the compacted materials as the conventional spot tests for compaction control. One of the goals pursued by CCC/IC researchers is to obtain continuous and real-time changes in modulus and density during the compaction process to control the compaction quality better.

During compaction, modulus and density are unknown parameters in the dynamic model. Solving these parameters is an inverse problem. System identification with known input and output can solve the system's unknown parameters. The basic principle is to provide a set of initial values of modulus and density to the kinetic model according to a particular method. Then, the known input (i.e., compaction force) is simultaneously applied to the compacted materials and the dynamic model, and the compacted materials' output response (such as displacement) is obtained. While the output response of the model is calculated, the measured output and the calculated output are compared. If the accuracy, *δ*, requirement is not met, the modulus and density values are adjusted according to a specific rule until the error satisfies the accuracy, *δ*, requirement. The final modulus and density values obtained are the final solutions (Figure A.8 where *P* is the excitation force. *F* is the compaction force).



Source: Xu and Chang (2023)

Figure A. 8. Flow chart to obtain modulus and density values with the system identification method.

Modulus and density are determined using a system identification method, with the premise that the input and output of the model are known, and the solution of the model is also known (as a positive problem). The difficulties currently encountered come from the following aspects:

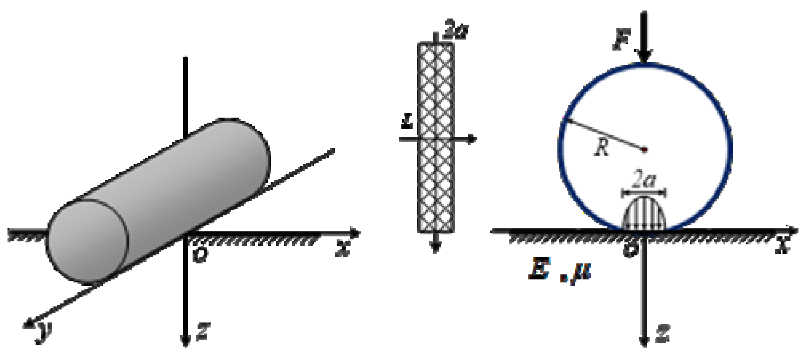
1. Under the action of a vibratory roller, the input of the compacted materials (i.e., dynamic compaction force) and output (i.e., displacement) cannot be directly measured. These two can only be estimated based on the dynamic response information of the roller drum, with the combination of theories and field correction.
2. The analytical solution of the current dynamic model has not been found, and only numerical solutions are available. If numerical solutions are used, their slow calculation speed makes it challenging to meet the needs of real-time display and control on site.
3. Parameter identification is an inverse problem with an ill-posed solution that is not unique. Determining the adequately identified parameters requires an extensive database of field data and cannot be solved by theories alone.

Although the continuous dynamics model and the associated ICMV are ideal, this approach cannot be applied to on-site quality control. More research is needed before it can be applied to the fields. Therefore, one could simplify the approach using a static model described in the next section.

Static Model

The static model is a particular case of the dynamic model. When the acceleration is zero, the dynamics model degenerates into a static one. Currently, the density parameter no longer appears in the model. Only the two parameters of modulus and Poisson's ratio, the critical compaction control index, modulus, still exist. (Xu and Chang, 2023)

The basic equations of the static model are based on Eq. (15) to Eq. (19), where the accelerations in the three directions, *u*, *v*, and *w,* are all 0, and the boundary conditions at the surface. However, the compaction force is not the gravitational force of the roller drum, but rather the dynamic compaction force is regarded as static. Therefore, the static model is equivalent to a quasi-dynamic model, a dynamic and static force mixture. The static mode of interaction between the roller drum and the elastic half-space body (compacted materials) is shown in Figure A.9, where *F* is the compaction force, *Lr* is the drum width, and *R* is the radius.



Source: Xu and Chang (2023)

Figure A. 9. Static model for a roller drum and half-space compacted materials.

The force between the roller drum and the elastic half-space compacted materials is the compaction force, *F*, and its distribution can be expressed by a general Hertz approximation formula (Hertz 1881).

$$p(x,y)=\frac{2F}{\pi aL}(1-\frac{x^2}{a^2})^{1/2} \qquad (20)$$

The projection of the above compaction force on the surface of the elastic half-space compacted materials (i.e., the contact area) is a narrow rectangle, as shown in Figure A.9. The length and width of the contact area are *Ls* and *2a*. The width, *2a*, is the compressive stress distribution width, not the actual contact width of the roller drum and the compacted materials. The roller drum's compressive stress distribution width is expressed in Eq. (20).

$$2a=\sqrt{\frac{16RF(1-\mu^2)}{\pi LE}} \qquad (21)$$

The basic equations from (16) to (20) of the static model, the boundary conditions at the surface (z = 0), and the boundary conditions at the infinite depth ($z = \infty$) together form the static model. Solving this model requires mathematical tools like elliptic integrals, Hankel transforms, etc. At present, the deformation at the surface of the elastic half-space compacted materials under the center of the roller drum (i.e., x = 0, y =0, z = 0) can be obtained as follows (Eq. 21):

$$w(0,0,0) = \frac{2F(1-\mu^2)}{\pi LE}[\ln(\frac{L}{2a})+1.886] \quad (22)$$

For the known roller drum and elastic half-space compacted materials, it is necessary to substitute the roller drum radius, R, the length, L, the elastic modulus, E, of the elastic half-space compacted materials, the Poisson's ratio, μ, and the force, F, into Eq. (22), and calculate the compressive stress. The width of the stress distribution is 2a, which is then substituted into Eq. (23) to calculate the deformation, w, at the center point. This is the typical positive mechanics problem with known force (input), object parameters, and solved displacement (output).

The solution of CCC is an inverse problem of mechanics. The properties of the elastic half-space compacted materials are unknown, and the magnitude of the force is not directly given. Only the roller drum parameters and the roller drum's dynamic response are known. Using this limited information to solve the parameters of the compacted materials and identify the modulus requires some techniques that involve patents and confidential technologies but are not in the public domain.

The above solution assumes that the compressive stress conforms to the Hertz distribution. Although it is an analytical solution, it is incomplete and only approximate. The deformations derived for other locations along the y-axis are different, with the following expression.

$$w(0,y,0) \approx w(0,0,0) - \frac{F(1-\mu^2)}{\pi LE}\ln[1-(2y/L)^2] \quad (23)$$

However, the displacement of the compacted materials along the y-axis of the roller drum (0, y, 0) is the same in the field. Therefore, there is a contradiction between the above solution and field measurements. Therefore, finding such realistic answers still requires further research.

The relationship between the compaction force and the deformation of the compacted material is a complex problem. If the compacted material is an elastoplastic material, especially when the plastic deformation is large (such as the initial compaction stage), the relationship between the two is very complicated. Currently, there is no ideal solution but various semi-empirical formulas, such as the unified form in Eq. (23).

$$F = \beta E w^n \quad (24)$$

Where E is the deformation modulus; n is the deformation index of the compacted materials, which is related to the nature and load type of the compacted materials and can take decimals; β is the dynamic correction (impact) factor that is related to the geometry and pressure distribution form of the loading, and the nature of the compacted materials, that can be theoretically derived or determined according to experiments. For example, the β expression in Eq. (23) (i.e., deformation under the center of the roller drum) is in Eq. (24), and the β expression under the action of a rigid plate load with radius, *ar*, is in Eq. (25).

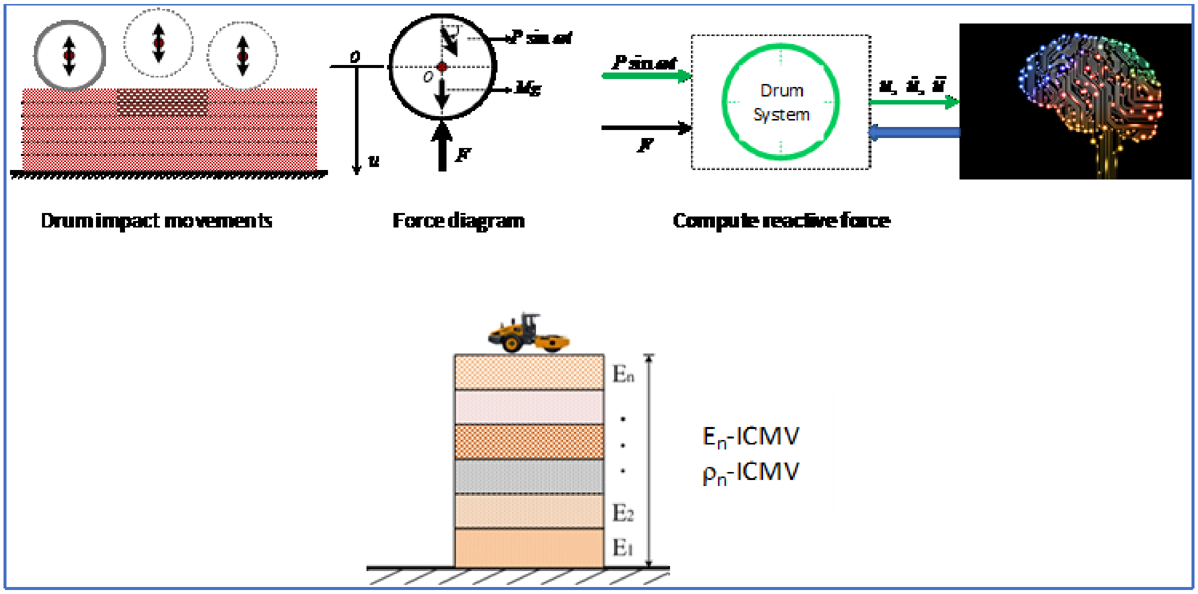
$$\beta = \frac{\pi L}{2(1-\mu^2)}[ln(\frac{L}{2\times ar}) + 1.886]^{-1} \quad (25)$$

$$\beta = \frac{2\times ar}{(1-\mu^2)} \quad (26)$$

AI-Enhanced Model

The ultimate ICMV is the Dynamic Model enhanced by Artificial Intelligence (AI). The AI model uses Artificial Neural Network (ANN) and Genetic Algorithm (GA). The key to success is to use sufficient and accurate roller parameters, field measurements of reactive forces, and compacted material properties to train the AI model. The training methods may include Hebbian, Delta rule, and Least Mean Squared (LMS). The quality of the training data should be stressed to develop a reliable AI model.

The Level 5 ICMVs can provide layer-specific moduli and density measurements. Layer-Specific Modulus ICMV (E_n-ICMV) and Density ICMV (r_n-ICMV) are based on a combination of the Dynamic Impact Model for Decoupled Drum and Layer Systems and Artificial Intelligence Method. Though still under development, it is envisioned that both models can be fused, and field measurement methods can include layer-by-layer mapping to measure E_n-ICMV and r_n-ICMV. A true real-time auto-feedback system can then be deployed to optimize compaction without human intervention. Then, an autonomous intelligent compaction machine can be realized.

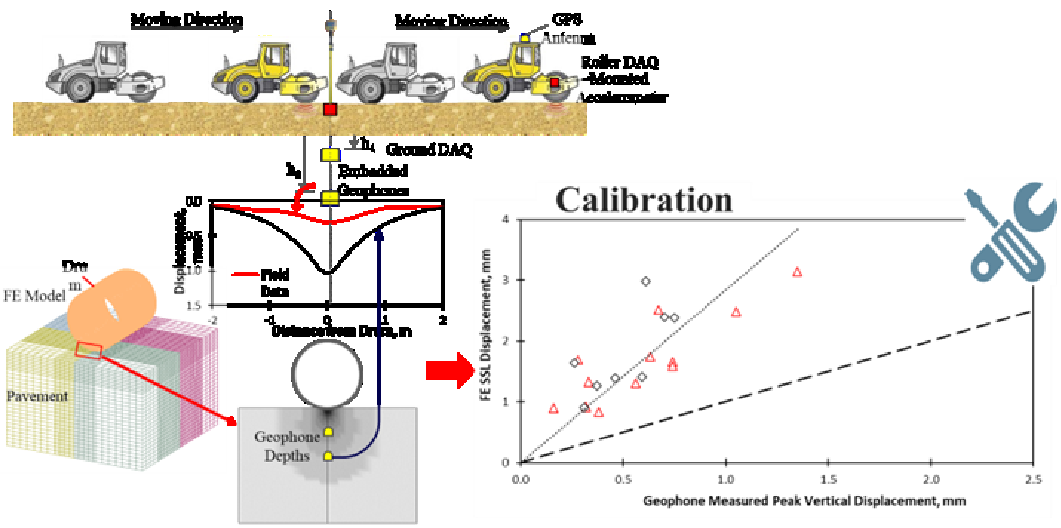


Source: FHWA (2017)

Figure A. 10. Level 5 Layer-Specific Modulus ICMV (E_n-ICMV) and Density ICMV (ρ_n-ICMV) and Its Computation Method

Level 4 and 5 ICMVs – UTEP ICMV System

The UTEP moduli ICMV system, a research product instead of a commercial one, produced both Level 4 and Level 5 ICMVs. The UTEP moduli ICMV approach was developed after conducting many finite elements (FE) simulations of roller compactions. The FE model was calibrated using geophone measurements embedded in various field test sites. The calibrated FE simulation results were used to develop and validate an Artificial Neural Network (ANN) surrogate model (Figure A.11). (Nazarian et al., 2020).



Source: Nazarian et al. (2020)

Figure A. 11. Calibration of the UTEP FE IC model.

The resilient modulus test can be conducted on the samples of the compacted materials to extract the nonlinear input parameters $k_i^{'}$ values for the ANN model, which are the regression parameters in Eq. (26).

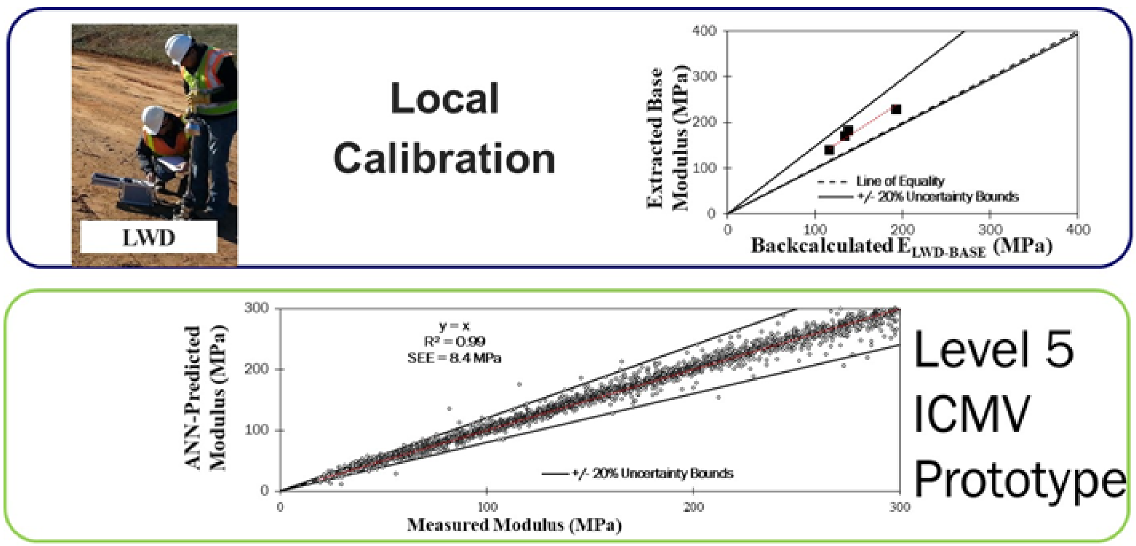
$$MR_{opt} = k_1^{'} P_a \left[\frac{\theta}{P_a} + 1\right]^{k_2^{'}} \left[\frac{\tau_{oct}}{P_a} + 1\right]^{k_3^{'}} \quad (27)$$

where θ = bulk stress, τ_{oct} = octahedral shear stress, P_a = atmospheric pressure (101.3 MPa, 14.7 psi), and $k_i^{'}$ = nonlinear regression parameters.

There are several ways of obtaining k_i', as described in NCHRP project 24-45. The nonlinear parameters, k_i', can be directly calculated from Eq. (27) or converted from regression parameters of resilient modulus relationship from the Pavement ME Design.

Nazarian et al. (2020) proposed two approaches for estimating the modulus of pavement layers. The first approach is to use an ANN inverse solver that utilizes the displacement (calibrated from numerical modeling), k_1' (adjusted based on LWD and resilient modulus tests), k_2' and k_3' (adjusted based on resilient modulus tests) to estimate the “extracted modulus.” This approach provides Level 5 ICMV. The extracted modulus can be layer-specific, providing better insights into the pavement layers' stiffness properties than the composite modulus measured by most field tests. (**Figure A.12**)

The second approach uses dynamic drum force at selected grids (with low variability) and LWD test results into the transfer function to estimate the “retrieved modulus.” This approach provides Level 4 ICMV.



Source: Nazarian et al. (2020)

Figure A. 12. Local Calibration of the UTEP ICMV model.

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