Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials

Final Report

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16. Abstract

Intelligent compaction (IC) is an emerging technology, and for some applications it is mature enough for implementation in field compaction of pavement materials. The intent of this project is to realize the blueprint in the FHWA IC strategic plan. This study was under the Transportation Pooled Fund project, TPF-5(128), which includes 12 participating state department of transportation: Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, New York, North Dakota, Pennsylvania, Texas, Virginia, Wisconsin.

This document is the final report for this pooled fund IC project.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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Executive Summary

The FHWA/Transportation Pooled Fund (TPF) project, TPF-5(128), "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials" demonstrated tried-and-true Intelligent Compaction (IC) technologies through sixteen (16) field projects and open house activities (Figure 1) , numerous meetings and training for TPF State personnel and local earthwork/paving contractors, and assistance on the development of State IC specifications.

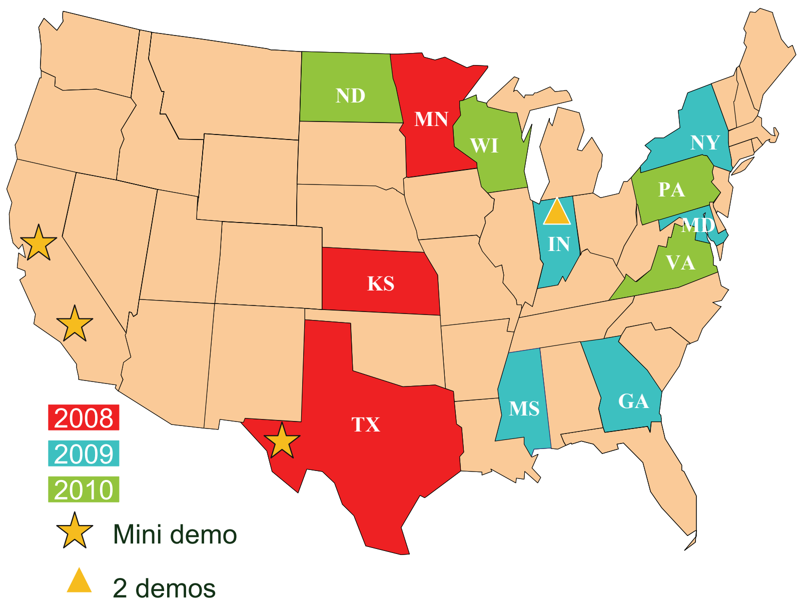

Figure 1. Participating TPF State DOTs and schedule for field demonstrations.

The key for the success of this three-year project is the seamless cooperation of the Technical Working Group (TWG) formed dynamically with knowledgeable and passionate representatives from FHWA, the IC project team, the TPF pooled fund states, earthwork/paving contractors and many IC roller and component vendors. Twelve (12) State departments of transportation (DOTs) participate in the TWG: Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, North Dakota, New York, Pennsylvania, Texas, Virginia, and Wisconsin. Most importantly, support from major IC roller and component vendors, as a part of the TWG, has made these efforts possible by providing IC machines and technical support: Ammann/Case, Bomag America, Caterpillar, Dynapac, Sakai America, TopCon, Trimble, and Volvo.

The goals of this project include:

1. Demonstration of soils/subbase and Hot Mix Asphalt (HMA) IC technologies to department of transportation (DOT) personnel, contractors, etc.,
2. Develop an experienced and knowledgeable IC expertise base within DOT,
3. Assisting DOT in the development of IC quality control (QC) specifications for the subgrade, subbase, and HMA pavement materials, and
4. Identification and prioritization of needed improvements and further research for IC equipment and data analysis.

Goal No. 1 was accomplished by demonstrating the abilities of the IC system such as: tracking roller passes, HMA surface temperatures, and intelligent compaction measurement values (ICMV).

Goal No. 2 was accomplished by building the IC knowledge base with extensive field experiences, data, and analysis/reports from diverse demonstration projects.

Goal No. 3 was accomplished by training DOT personnel and earthwork/paving contractors on the IC technologies via field demonstrations and open house activities. Continuous support was provided to the TPF State DOTs for the development of local, customized IC specifications during the project period.

Goal No. 4 was accomplished by compiling a comprehensive list of recommendations for the IC roller vendors to further improve their systems for widespread use of the technologies. Various IC systems were reviewed in-depth and gaps were identified for future research and engineering practices.

Major Findings

Benefits of IC Technology

The immediate benefits of IC technologies common to both the earthwork and paving industries include:

- IC mapping of existing support layers is effective in identifying weak support areas for corrective actions prior to the compaction of the upper layers.
- With HMA IC, tracking roller passes and HMA surface temperatures provide necessary means to maintain a consistent rolling pattern within optimal ranges of temperatures for 100 percent coverage of a construction area.
- IC technologies can be especially beneficial to maintain consistent rolling patterns under lower visibility conditions such as night paving operations.
- IC technology will have profound influence on the responsibilities of various stages of pavement constructions and will eventually help produce better and more consistent pavement products.

Soils IC

The major findings regarding soils and subbase IC include:

- Influence on measurements depths associated with various devices and in-situ moisture conditions are the main factors for correlation between ICMV and other in-situ point test devices. Other factors include different target material properties such as stiffness and density.
- A linear correlation was shown between ICMV and back-calculated layer stiffness from deflections measurements, e.g., light-weight deflectometer (LWD) and falling weight-deflectometer (FWD) tests.
- A less desirable correlation was found between ICMV and plate-loading-test-based stiffness, and between ICMV and California bearing ratio (CBR) values from dynamic cone penetrometer (DCP) tests.
- The least desirable correlation was found between ICMV and nuclear/non-nuclear density gauge measurements.

- ICMV is also influenced by factors such as machine settings (frequency, amplitude). Therefore, it is recommended that all measurements at calibration areas and production areas during QA should be obtained at a constant amplitude setting to avoid complication in data analysis and interpretation.
- Multi-linear correlation has revealed the significant influences of multiple factors on the ICMVs such as soils moisture contents and vibration amplitudes.
- Using the compaction curves of IC data on a test strip, optimal roller passes can be determined to prevent over/under compaction as long as the supports are relatively uniform.
- Semivariograms of IC data can be used to evaluate the compaction uniformity that can be crucial for long-lasting support and bearing capacity.

HMA IC

The major findings regarding HMA IC include:

- Mapping existing support materials using IC rollers prior to subsequent HMA paving is proved to be effective on identifying weak locations. Evidences from the IC field demonstration have shown that the desired densities of the HMA materials would be difficult to achieve at weak support locations and even premature failure may occur under construction traffic.
- Mapping has been successfully demonstrated on granular subbase, stabilized subbase, and milled asphalt surfaces with IC roller settings at low vibration amplitudes and low frequencies.
- The correlation between ICMV and HMA core densities is inconsistent due to factors such as limited spot tests and the different nature of measured properties (e.g., mechanical property vs. material proportioning).
- The correlation between ICMV and FWD/LWD-based deflections or moduli indicates a relatively higher linear correlation than that between ICMV and HMA core densities.
- The relatively low correlation between ICMV and nuclear/non-nuclear density gauge (NG/NNG) measurements can be due to: a) ICMV reflects the stiffness of the entire pavement structure and the underlying support while NG/NNG only measure the top 6” of HMA layers; b) ICMVs do not yet factor in the temperature effects in the measurements while NG/NNG measurements are independent of HMA temperatures.
- Using mutli-linear regression has improved the correlation analysis between ICMVs and in-situ spot tests. These analyses indicated the influences of multiple factors on ICMVs including the machine settings (i.e. amplitude, vibration frequency), conditions of underlying layers (i.e. ICMV), and HMA temperatures.
- IC data can be used to build a compaction curve for a specific material of a specific project. The compaction curve can then be used to identify the optimal roller pass so that over/under compaction can be prevented.
- IC data can be used to produce semivariograms that serve as the metrics for compaction uniformity. Generally, compaction uniformity increases for subsequent lifts.

Recommendations for Future Research

- An improved (or even better, universal) ICMV model is recommended to decouple stiffness for each pavement layer, so that correlation of ICMV and in-situ spot measurements can be improved.

- For soil/subbase compaction, real time moisture mapping is recommended and an improved ICMV model would be needed to account for the effect of moisture.
- For HMA compaction, an improved ICMV model is recommended to account for HMA temperatures, and ICMVs are recommended to be reported with respect to a reference temperature (e.g., 68 °F).
- Multivariate technique is recommended to characterize each vendor's ICMV in order to better understand the effects of machines and operation settings.
- A standardized IC data management and analysis tool is recommended to help speed up the acceptance of IC technologies by agencies.
- Long term pavement performance monitoring is recommended in order to identify performance trends that may relate to ICMV values and uniformity metrics.

Intelligent Compaction (IC) Road Map

An IC Road Map (Figure 2) was developed under this FHWA/TPF project to provide practical guidelines for IC implementation via the following four main tracks:

- Track 1 — Equipment and Technologies
- Track 2 — Data Management and Integration
- Track 3 — Specifications
- Track 4 — Technology Transfer and Training

While the IC is still evolving and improving, this report provides a wealth of state-of-the-art IC knowledge for agencies and the industry to accelerate implementation of IC technologies.

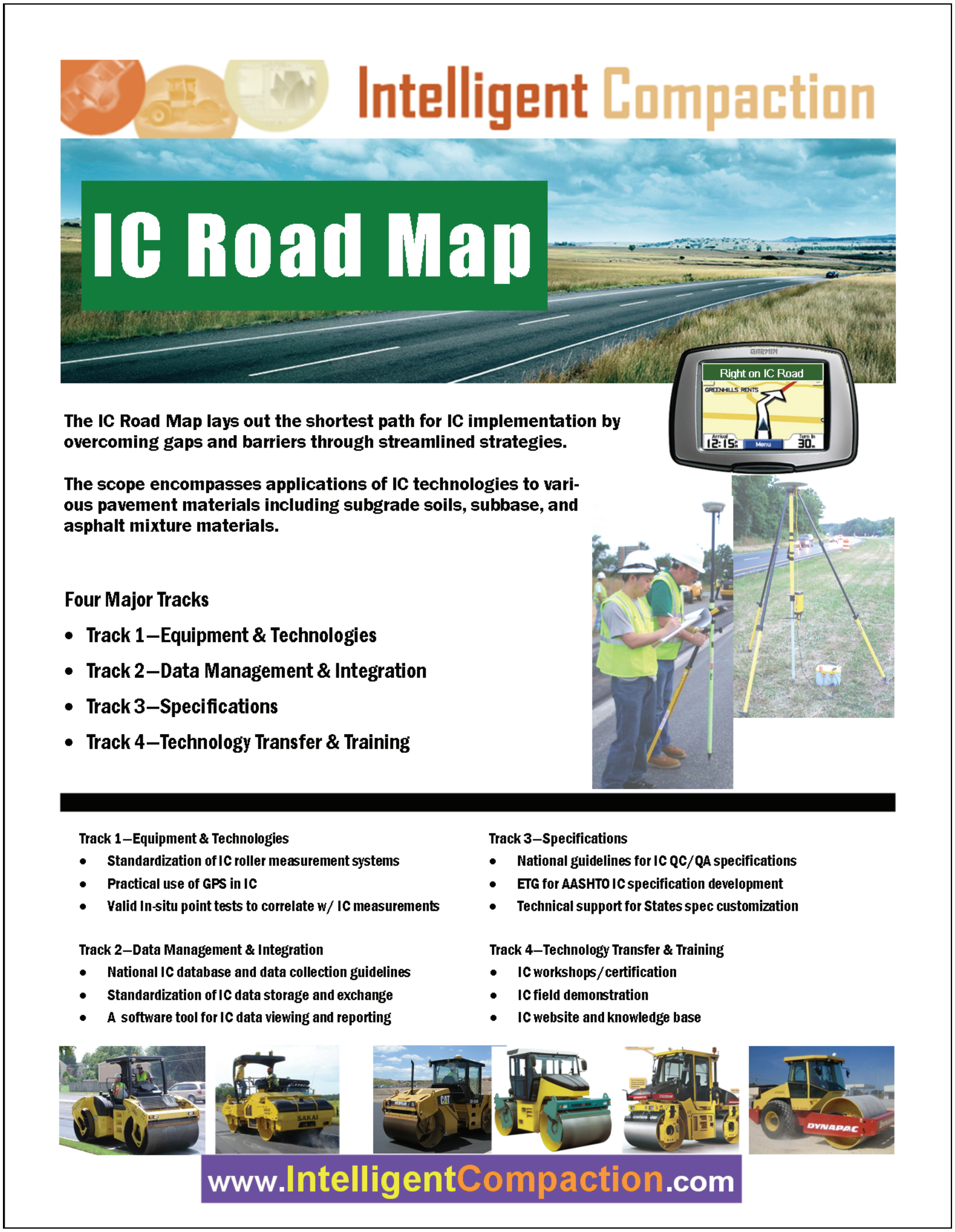

Figure 2. IC Road Map.

Acknowledgement

This IC project is not possible if not for the funding and assistance from FHWA and the TPF State departments of transportation, IC roller vendors, GPS vendors, and earthwork/paving contractors of the seventeen demonstration projects. The list is too long to fit in this limited space, so that only a partial list is presented below.

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Dave Dennison of Bomag Americas, Inc.
Hans-Josef Kloubert of Bomag
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Jeff Drake of Trimble

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Luke Magnuson of Trimble

Symbols and Terminology

a	Theoretical vibration amplitude (eccentric moment divided by the drum mass)
A_{Ω}	Acceleration at fundamental frequency
a*	Actual measured vibration amplitude (double integral of acceleration data)
A’	Machine acceleration
AFC	Automatic feedback control
$A_{X\Omega}$	Acceleration at X-order harmonic
B	Contact width of the drum
b	machine internal loss coefficient used in MDP calculation
b0	Intercept in a linear regression equation
b1, b2, b3	Regression coefficients
BCD	Briaud compaction device
C	Semivariogram scale
C+C0	Semivariogram sill
C0	Semivariogram nugget
CBR	California bearing ratio
CBR_{300}	Weighted average CBR to a depth of 300 mm
CBR_{Base}	Weighted average CBR to a depth equal to the depth of the base material
CCC	Continuous compaction control
CCV	compaction control value (by Sakai)
CMV	Compaction meter value
COV	Coefficient of variation (calculated as the ratio of mean and standard deviation)
d0	measured settlement under plate
D_{10}	Particle size corresponding to 10% passing
D_{30}	Particle size corresponding to 30% passing
D_{60}	Particle size corresponding to 60% passing
DPI	Dynamic cone penetration index
E	Elastic modulus
E_{BCD}	Modulus determined from Briaud Compaction Device (BCD)
E_{FWD-K3}	Elastic modulus determined from 300-mm plate KUAB falling weight deflectometer
E_{LWD-Z2}	Elastic modulus determined from 200-mm plate Zorn light weight deflectometer
E_{LWD-Z3}	Elastic modulus determined from 300-mm plate Zorn light weight deflectometer

E_{V1}	Initial modulus from 300-mm diameter static plate load test
E_{V2}	Reload modulus from 300-mm diameter static plate load test
E_{VIB}	Vibratory modulus determined from the roller (by Bomag)
F	Shape factor
f	Vibration frequency
Fs	Drum force
FWD	Falling weight deflectometer
g	Acceleration of gravity
GPS	Global positioning system
Gs	Specific gravity
h	Separation distance
ICMV	Intelligent compaction measurement value
ks	Roller-integrated stiffness (also expressed as kb, by Ammann/Case)
LL	Liquid limit
LWD	Light weight deflectometer
m	Machine internal loss coefficient used in MDP calculation
m_d	drum mass
MDP	Machine drive power (by Caterpillar)
MDP_{40}	See description in text
MDP_{80}	See description in text
m_{ere}	Eccentric moment of the unbalanced mass
n	Number of test measurements
p	Number of regression parameters
Pg	Gross power needed to move the machine
PI	Plasticity index
PL	Plastic limit
PLT	Static Plate Load Test
r	Radius of the plate
R	Semivariogram range
R’	Radius of the roller drum
R^2	Coefficient of determination
R^2(adjusted)	Adjusted coefficient of determination (adjusted for number of parameters in multiple regression analysis)
v	Roller velocity
W	Roller weight

$w_{(H)}$	Moisture content determined from Humboldt nuclear gauge
$w_{(SDG)}$	Moisture content determined from Transtech's Soil Density Gauge (SDG)
$w_{(T)}$	Moisture content determined from Troxler nuclear gauge
w_{opt}	Optimum moisture content
zd	Drum displacement
α	Slope angle (roller pitch from a sensor)
η	Poisson's ratio
ϕ	Phase angle
$\gamma_{d(H)}$	Dry unit weight determined from Humboldt nuclear gauge (NG)
$\gamma_{d(SDG)}$	Dry unit weight determined from Transtech's Soil Density Gauge (SDG)
$\gamma_{d(T)}$	Dry unit weight determined from Troxler nuclear gauge (NG)
γ_{dmax}	Maximum dry unit weight
μ	Statistical mean
σ	Statistical standard deviation

Chapter 1 Introduction

Background

Compaction is one of the most important processes in roadway construction. It is needed to achieve high quality and uniformity of pavement materials, which in turn better ensure long-lasting performance. Pavement materials often possess optimum densities that ensure adequate support, stability, and strength. Achieving the uniformity is a key for successful compaction. Generally, in-situ spot tests (with nuclear or non-nuclear gauge density devices) or cores tests are required for the quality control (QC) and/or quality assurance (QA). However, there are many issues associated with this conventional density control method, including but not limited to: 1) In-situ spot tests or cores are limited and often conducted at random locations, and thus those tests are not necessarily representative for the entire pavement area; 2) there may be weak or unqualified compaction areas unidentified by the limited spot tests; and 3) the measured density of top bound layer is limited to indicate the structural capacity of the entire pavement layers. As a result, non-uniform and unsatisfactory compaction may be outcomes, leading to premature failure and worse long-term life performance. Therefore, intelligent compaction (IC) has been developed to address these issues.

IC is a compaction technology used for materials including soils, aggregates, and asphalt mixtures, by using vibratory rollers equipped with the real-time kinematic (RTK) Global Positioning System (GPS), roller-integrated measurement system (normally accelerometer-based), feedback controls, and onboard real-time display of all IC measurements. IC rollers maintain a continuous record of measurements that include the number of roller passes, roller-integrated measurement value (ICMV), GPS locations of the roller, roller vibration amplitudes/frequencies, and HMA surface temperatures, etc. Based on the real time onboard color-coded display of the above measurements, roller operators can either manually or allow the IC rollers to automatically adjust the machine settings for optimum compaction. ICMV, while different from one vendor to another, is used to evaluate the level of compaction. With 100 percent coverage on the compacted area, the IC technology can be used to produce uniformly compacted pavement products that perform better and last longer.

While being implemented in Europe and Japan for years, the IC technologies have been introduced to the US recently (White et al. 2007). Therefore, there is still a lack of experiences, knowledge, and availability of IC equipment in the US. Meanwhile, the IC technology is still evolving, especially for the HMA compaction (Scherocman et al. 2007). This combination has resulted in difficulty in implementing IC by State Departments of Transportation (DOTs) and paving contractors.

With the above needs in mind, the Federal Highway Administration (FHWA) and transportation pooled fund (TPF) project, (TPF-5(128)), "Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, And Asphalt Pavement Materials" was initiated in 2007 to realize the FHWA's IC strategic plan. This report includes the study for the FHWA/TPF IC demonstration projects conducted in 12 states: Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, North Dakota, New York, Pennsylvania, Texas, Virginia, and Wisconsin. The purpose of this project is to accelerate the understanding and implementation of IC technology. This will be accomplished through a coordinated effort by both IC roller manufacturers and government agencies on various construction projects around the country.

IC is applicable to virtually all materials that require compaction during construction. In this project, the following material types are covered:

- Type I – Granular, non-cohesive subgrade soils
- Type II – Fine-grained, cohesive subgrade soils
- Type III – Aggregate base material
- Type IV – Asphalt pavement material
- Type V – Stabilized subbase material

The objectives of this project were short-term goals for introducing soil/subbase and HMA IC technology to DOTs and contractors who may not have prior experience with IC. The project was intended to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of HMA pavement and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Report Structure

This report is structured as follows:

- Chapter 1 - Introduction: It provides an overview of this report.
- Chapter 2 - IC Roller Systems: It contains a detailed description of IC roller systems (including single drum and double drum rollers), GPS requirements, IC measurement types and associated correlation studies, verification of various IC models, and a proposed new IC model.
- Chapter 3 – Field Spot Tests for IC Implementation: It describes field spot tests recommended as verification tests for IC implementation for both soils/subbase and HMA.
- Chapter 4 - IC Analysis and Report: It tackles one of the critical steps for implementing IC by providing detailed guidelines for IC data storage/exchange, viewing of IC data, basic statistics and geostatistics analyses, developing compaction curves and performing univariate/multivariate correlation analyses.
- Chapter 5 - Demonstration Projects Overview: Field demonstration projects are the major work under the FHWA/TPF IC study. This chapter provides an overview for the field demonstration projects including demonstration activities (location, test bed, roller system, in-situ tests, etc.), and recommendations.
- Chapter 6 - Demonstration Projects for Soils IC: It contains the summary of soils/subbase field demonstration projects on diverse materials/structures/road types conducted under the FHWA/TPF IC project that serves as a rich knowledge base for soil IC implementation.
- Chapter 7 - Demonstration Projects for HMA IC: It contains the summary of hot mixture asphalt field demonstration projects on diverse materials/structures/road types conducted under the FHWA/TPF IC project that serves as a valuable knowledge base for HMA IC implementation.
- Chapter 8 - Guidelines for IC Implementation: It consists of a concise, clear road map for IC implementation, and guidelines for developing IC implementation plans, performing IC data management, developing IC specifications for both soils/subbase and HMA, and conducting IC training and workshops.
- Chapter 9 -Conclusions and Recommendations: It contains key conclusions from this IC

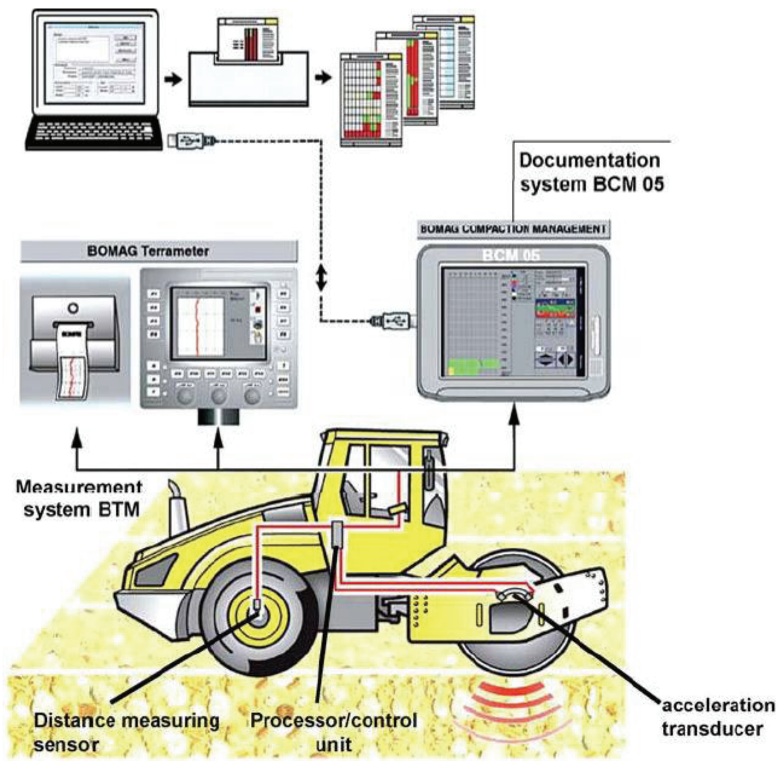
study and recommendations for future IC improvements and research.

- References
- Appendix A - Understand Semivariogram
- Appendix B - Understand GPS
- Appendix C - How to Setup GPS for IC
- Appendix D - Generic Soils IC Specifications
- Appendix E - Generic HMA IC Specifications
- Appendix F - Generic Subbase IC Specifications

Chapter 2 IC Roller Systems

IC Rollers

Intelligent Compaction refers to the compaction of road materials, such as soils, aggregate bases, or asphalt pavement materials, using modern vibratory rollers equipped with an in-situ measurement system and feedback control. Global Positioning System (GPS) based mapping is included, as well as software that automates documentation of the results. By integrating measurement, documentation, and control systems, the IC rollers allow for real-time monitoring and correction of the compaction process. IC rollers also maintain a continuous record of (nominally) color-coded plots that indicate the number of roller passes, roller-generated material stiffness measurements, and precise location of the roller. An example of such IC roller system is illustrated in Figure 3.

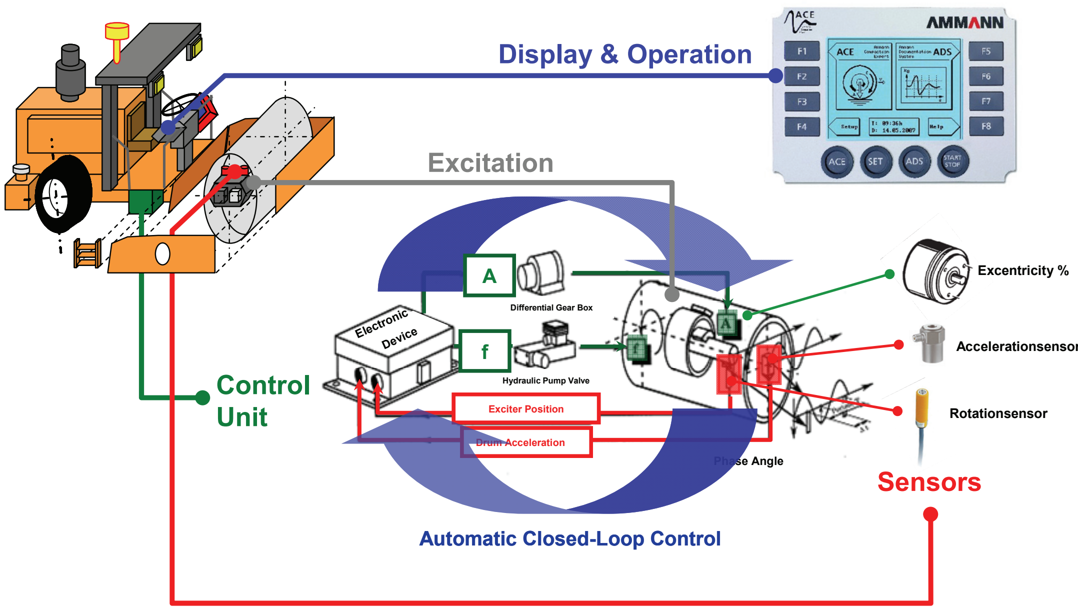


(Courtesy of Bomag)

Figure 3. Bomag VarioControl System

How IC Rollers Work

IC rollers utilize the framework of a vibratory roller. IC rollers, if come with auto-feedback systems, are equipped with instrumentation which feeds information documentation and feedback control systems which process the data in real time for the roller operator to monitor. An example of such IC feedback system is illustrated in Figure 4.



(Courtesy of Case/Ammann)

Figure 4. Case/Ammann auto-feedback control (AFC) system.

The precise location of the roller, speed, and number of passes over a given location are mapped using GPS. These systems are commonly used to establish grade and to control other pieces of equipment.

Compaction meters or accelerometers are mounted in or about the drum to monitor applied compaction effort, frequency, and response from the material being compacted. The readings from this instrumentation determine the effectiveness of the compaction process. The methodology to calculate material response to compaction is often proprietary, resulting in various types of intelligent compaction measurement values (ICMV).

A calibration procedure is often used to correlate the ICMV to a material modulus or density measured by other (in-situ) test devices. Compaction curves from ICMVs and in-situ test results can be established to indicate the target ICMV and optimum roller passes (see an example in Figure 5).

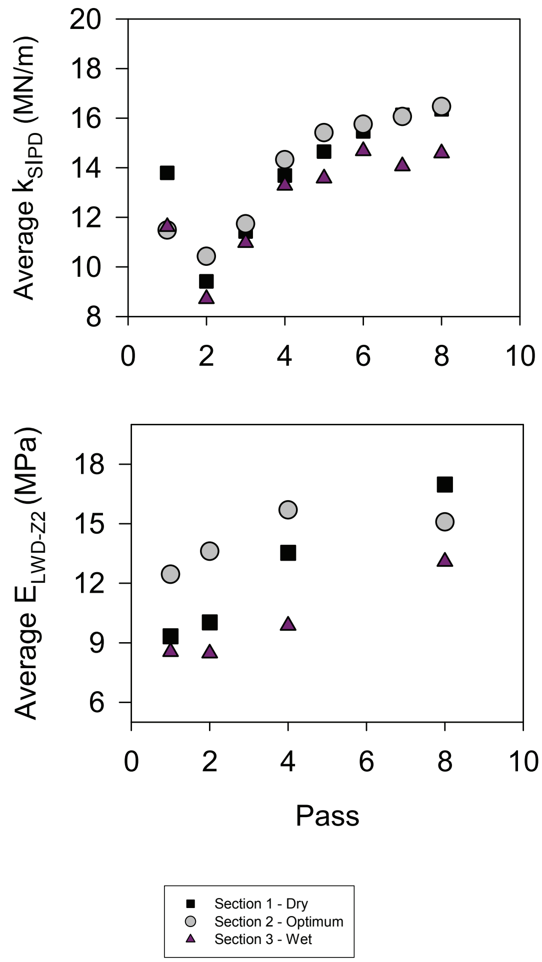


Figure 5. Calibration test – with compaction growth curves for Case/Ammann ICMV (k_{SIPD}) and in-situ point measurements (ICPF TXDOT demo).

For asphalt IC rollers, additional temperature instrumentation is used to monitor the surface temperature of the asphalt pavement material. This is critical as vibratory compaction within certain temperature ranges (such as too-cold-to-compact temperatures or tender zones for Superpave mixtures) can have adverse effects. An example of IC temperature instrumentation is illustrated in Figure 6 to measure asphalt surface temperatures by using an infrared sensor. There are on-going researches on measurement of asphalt internal temperature using embedded measure devices or "tags". However, those devices are available for widespread use at this time.

Figure 6. Infra-red temperature sensor on a Sakai IC roller.

Single Drum IC Rollers

IC rollers used to compact natural subgrade and aggregate materials use a single drum, as shown in Figure 7 for the participating vendors under this study. The drums can be smooth or fitted with a padfoot shell kit. The Sakai single drum IC roller system, instead, is a padfoot with smooth drum shell kit. Being a more straightforward form of IC, there is currently more experience, available rollers, and construction history with soil and aggregate IC.

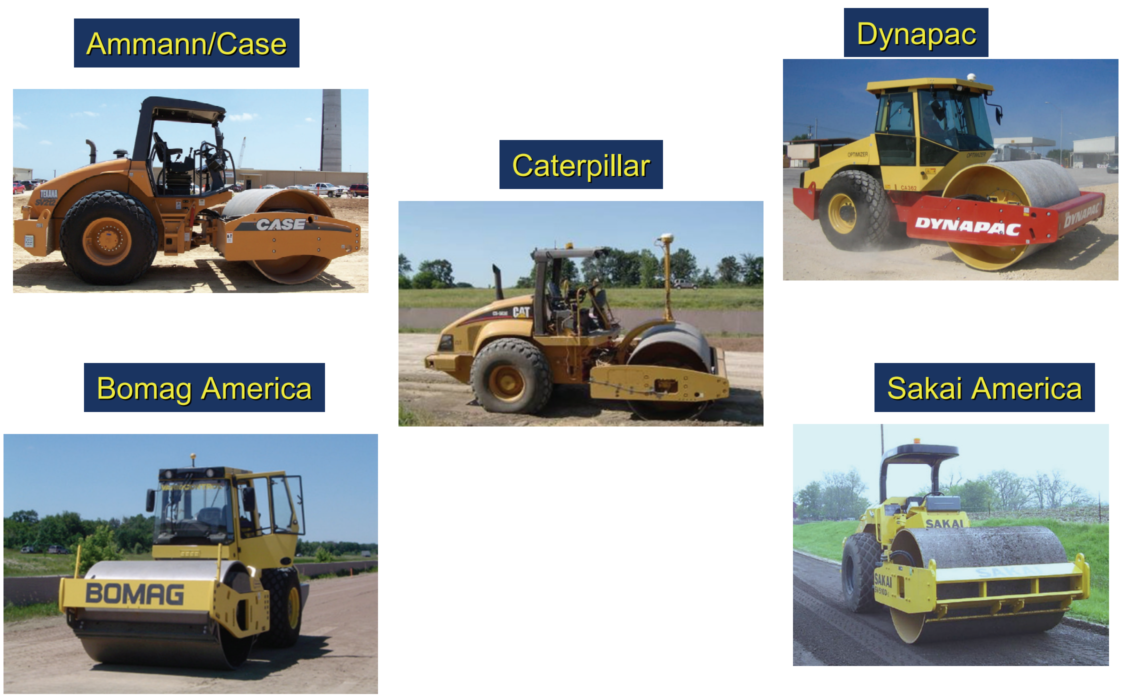


Figure 7. Single smooth drum IC rollers.

A summary of available IC rollers for soil materials is presented below in Table 1:

Table 1. Summary for Single Drum IC Rollers

Vendor	Ammann/Case	Bomag	Caterpillar	Dynapac	Sakai
Model	ACEplus	VarioControl	NA	DCA-S (GPS)	CIS
Model Number	SV	BW213-4BVC	NA	CA 152–702	SV505/SV510
Auto-Feedback	Y	Y	Y	Y	N
With measurement System	Y	Y	Y	Y	Y
Measurement Value	Kb	Evib	CMV	CMV	CCV
Measurement Unit	MN/m	MN/m^2	Unitless	Unitless	Unitless
GPS Capability	Yes	Y	Y	Y	Y
Documentation System	ACEPlus	BCM 05 Office and Mobile	AccuGrade	DCA	AithonMT-R
Development Status	In production	In production	In production	In production	In production
Availability	Current	Current	Current	Current	Current

- ACEplus: Ammann Compaction Expert-Plus
- DCA-S (GPS): Dynamic Compaction Analyzer for Soil with GPS
- Kb: Stiffness or ground bearing capacity (as related to the plate loading tests)
- Evib: Vibration modulus
- CMV: Compaction Meter Value
- CIS: Sakai Compaction Information System
- CCV: Sakai Compaction Control Value
- Availability: Refers to the availability in the US

Double Drum IC Rollers

IC rollers used to compact asphalt pavement materials use a dual-drum configuration, as shown in Figure 8 for the participating vendors under this study. Monitoring and automating feedback controls for two vibratory drums add complexity to the IC process for asphalt pavement materials. In addition, timing of rolling and mat temperature are critical when compacting asphalt pavement materials. For this reason, additional instrumentation and considerations are necessary when utilizing IC technology for these materials.

Figure 8. Double drum IC rollers.

A summary of IC rollers for asphalt materials is presented below in Table 2:

Table 2. Summary for Asphalt IC Rollers

Vendor	Ammann/Case	Bomag	Caterpillar	Dynapac	Sakai
Model	NA	Asphalt Manager	AccuGrade Compaction	DCA-A	CIS
Model Number	NA	BW190AD-4AM	CB534D,CB534D-XW,CB564D	CC 224 etc	SW850/SW880 /SW890
Auto-Feedback	NA	Y	N	N	N
With measurement System	NA	Y	Temperature and Pass Count	N	Y
Measurement Value	NA	Evib	Temperature	NA	CCV
Measurement Unit	NA	MN/m^2	°C	NA	Unitless
GPS Capability	NA	Y	Y	Y	Y
Documentation System	NA	BCM 05 Office and Mobile	AccuGrade	DCA	AithonMT-A
Development Status	Under development	In production	Available as special order	In production	In production
Availability	Future	Current	special order	Future	Current

- Evib: Vibration modulus
- CMV: Compaction Meter Value
- CCV: Compaction Control Value
- DCA-A: Dynamic Compaction Analyzer for Asphalt

- Dynapac CC 224 Etc.: The models include: CC 224-624, PTR's, CP 224, and 274.
- Availability: Refers to the availability in the US

GPS Requirements and Setup

It cannot be stressed enough for the GPS data collection in IC implementation. To ensure accurate and consistent data collection, the following capabilities for the roller GPS systems are required:

- RTK GPS (Real-Time Kinematic GPS) systems on IC rollers (see Figure 9 for the GPS receiver setup on a Sakai roller),
- System reports and records values in Northing and Easting and vertical position in meters in UTM coordinates (though State coordinates and county coordinates are commonly used in the US) for the project site, and
- If an offset is necessary between GPS antenna and center of front drum it must have been input and validated.

Technical assistance by roller vendors or GPS equipment manufacturers is often recommended:

- On-site staff with sufficient technical knowledge to set up roller-mounted GPS equipment and provide input for equipment operation during the first day of the field operation.
- Contact information for personnel with sufficient technical knowledge to assist the research team with technical questions during field testing when on-site technical assistance is not available.

Use of a GPS base station radio operating at 900MHz is recommended (see Figure 13) from vendors such as Trimble, TopCon, Leica, etc. In addition to setting up GPS base stations, there can also be other options such as virtual reference station (VRS) and internet-based correction signals. Prior to the beginning of IC data collection during the compaction operation, the GPS setup must be validated using a survey grade handheld GPS "rover" (e.g., placed on top of the roller-mounted GPS receiver, see Figure 14) unit to ensure that the roller-mounted GPS is providing accurate positioning data.

Figure 9. RTK GPS receiver and antenna on a Sakai roller (ICPF MnDOT demo).

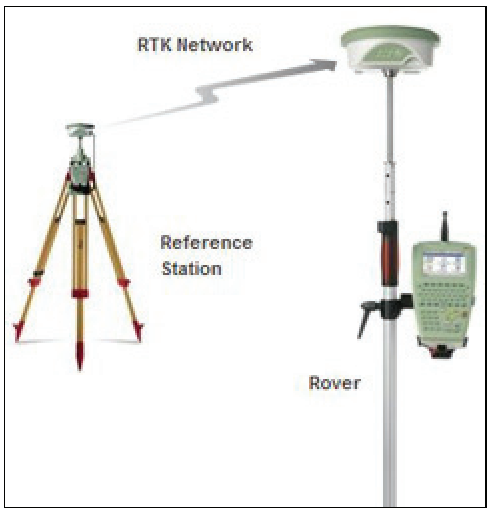
GPS Precision

There are four types of GPS position data with various precisions: Autonomous (10 to 15 m horizontal); DGPS (0.5 to 4 m horizontal); Float (1 meter to sub-meter); and Fixed (1 to 3 cm), where the fixed GPS is recommended to be used with IC.

Real-time kinematic (RTK) GPS system, a "fixed" type of GPS, is recommended for use on moving IC rollers or hand-held rovers to measure locations in real time with high accuracy (within 1 to 3 cm). This high level of precision is achieved by receiving correction signals transmitting from one (single station RTK) or multiple (network RTK) onsite GPS base stations or virtual reference stations (VRS).

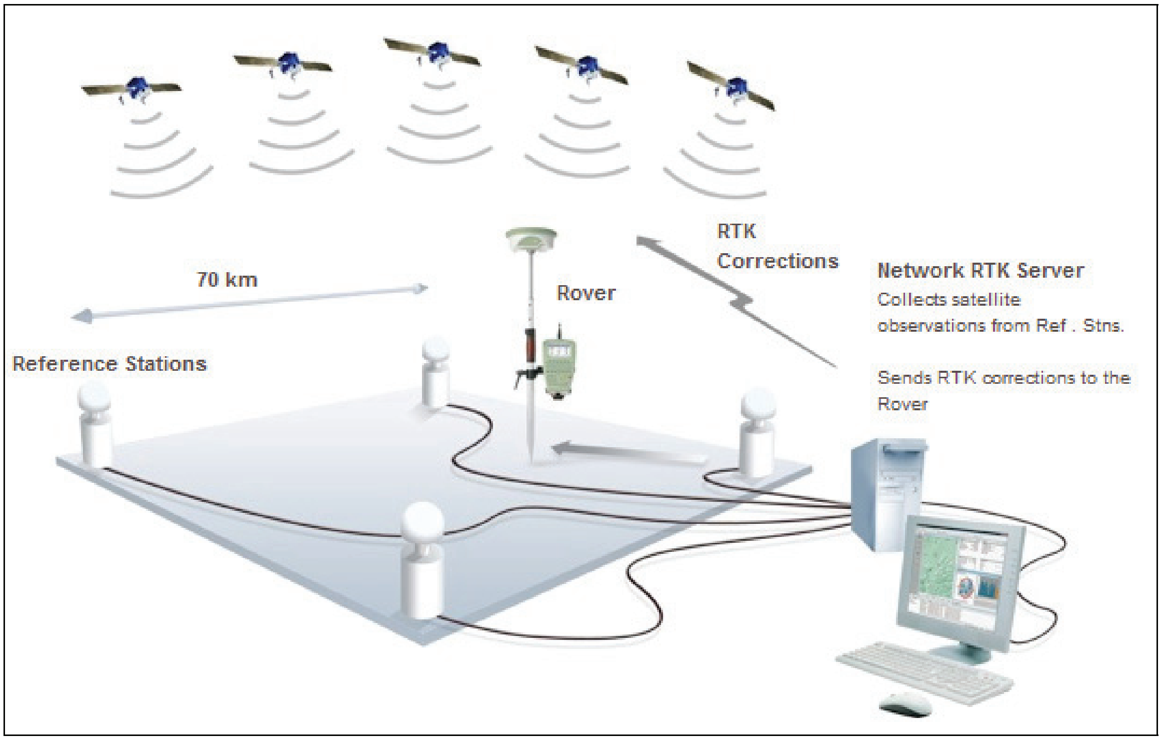
The effective range of a GPS station, depending on position of setup and its antenna, can be approximately 2 miles in radius. Currently, only the horizontal precision is of major interest for the IC application. However, vertical precision is crucial for applications such as intelligent construction using systems such as the Trimble Total Station system.

Even with GPS base stations or VRS, the GPS precision on an IC roller may degrade to "float" or even "autonomous" when the radio line of sight between the base station and the GPS receivers is blocked by obstacles such as hills, horizontal/vertical curves, trees, etc.



(courtesy of Laica)

Figure 10. RTK using a Handheld rover/receiver with a single base/reference station.



(courtesy of Laica)

Figure 11. RTK using a Handheld rover/receiver with a reference network.

Datum Coordinate System

Different GPS coordinate references may be used in the construction, including the geographic (degree-minute-second), the state plane, the county plane, and UTM (east and north, meter/feet). The UTM zone system is recommended to be used in the IC systems.

The UTM (Universal Transverse Mercator) coordinate system zone is designated when the UTM grids are produced based on the geodetic GPS data, longitudes and latitudes. The conversion is based on The World Geodetic System 84 (WGS84) and North American Datum of 1983 (NAD83). See Figure 12 for the UTM zones in the US. Users can normally select the desired UTM zone in the settings of a vendor's IC field software program.

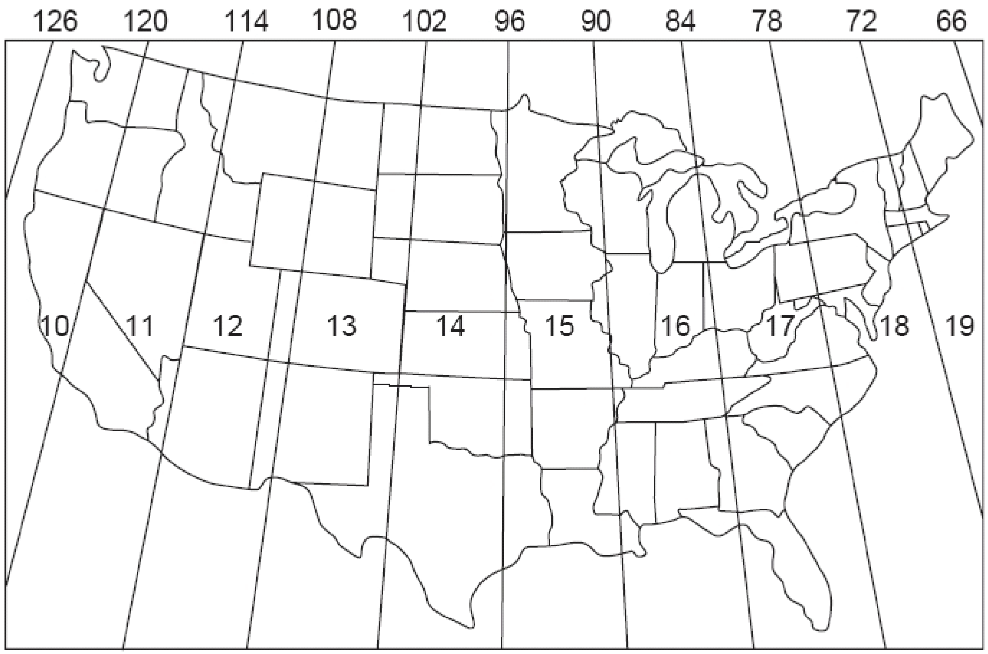


Figure 12. UTM Zones in the US.

GPS Equipment Setup for IC

The Real-Time Kinematic (RTK) Global Position Systems (GPS) can be used for IC rollers. The GPS receiver and radio/antenna are installed on the top of the IC machine which may or may not position to the center of the front or rear drums (if not, an offset needs to be applied). The GPS receiver collects signals from both the GPS base station and satellites. With the connection to the GPS station, the GPS position is the "fixed" mode which may result in 1-3 cm precision. Otherwise, it is in a "float" mode with a precision of meter or sub-meter. The precise roller position for recording the GPS coordinates (e.g. geographic and UTM) and roller pass data are recorded to the computer system.

To establish an RTK fix in a state plane, UTM, or a local coordinate system, the base station must be started on a known position with established NEZ coordinates. A typical setup procedure is as follows (courtesy of TopCon):

- Use a network rover and dial up a specific State reference station network. Set up GPS software and apply the desired datum (e.g., UTM) for a projection. Set up a tripod, and install the receiver on top of the tripod. Measure the point using a 2-minute occupation time and save it as the base station location.
- Set up the GPS geodetic receiver on the tripod and start the base station using the measured coordinates to broadcast the NEZ coordinates of the selected datum (e.g., UTM) for that location. If the NEZ values are not being broadcasted from the base, the GPS data can have a horizontal error up to 12 to 15 feet. This is called an autonomous start, which only broadcasts the Latitude and Longitude of the base station and does not apply the datum (e.g., UTM) correction.

- Caution: If one base station is started autonomously and then restarted with the UTM correction applied, the measurement of the same point will have different NEZ values, depending on the UTM grid factor that is applied by the software.
- While the use of an autonomous start provides relative reference points, the use of a state plane or UTM base station start is strongly recommended to ensure GPS measurements at any time (e.g., after the project is complete) can be at the exact locations.

Figure 13. A Trimble GPS base station (ICPF MnDOT demo).

Figure 14. Validation of roller mounted GPS with a hand-held rover.

IC Measurement Types

Introduction

Development and evaluation of continuous compaction control (CCC) measurement technologies was initiated over three decades ago in Europe for use on vibratory rollers compacting granular soils (Forssblad 1980 and Thurner and Sandström 1980). Since its inception, the concept has been expanded to different measurement technologies and materials and is available commercially for different roller configurations. For vibratory roller configurations, CCC involves measurement and analysis of output from an accelerometer mounted to the roller drum and can provide a spatial record of compaction quality when linked to position measurements and a documentation system.

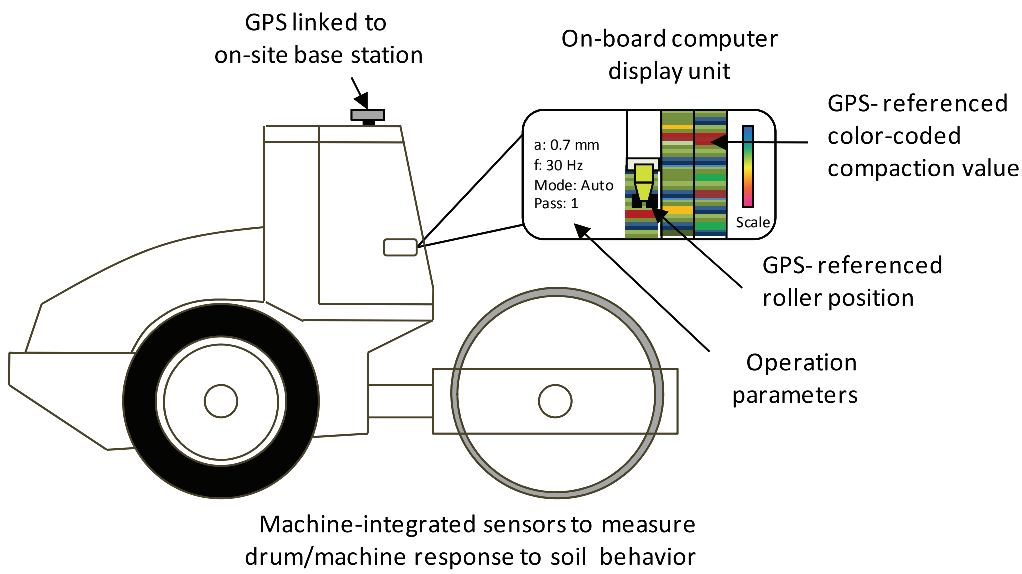


Figure 15. Overview of ICMV compaction monitoring systems.

When the measurement system provides automatic feedback control (AFC) for roller vibration amplitude and/or frequency, it is referred to as "intelligent" compaction (IC). Roller measurement values calculated based on accelerometer measurements use one of two different approaches:

- calculate a ratio of selected frequency harmonics for a set time interval, or
- calculate ground stiffness or elastic modulus based on a drum-ground interaction model and some assumptions.

An alternative to accelerometer-based vibratory measurements is the measurement of rolling resistance/machine drive power which can be applied to both vibratory and non-vibratory roller operations. Regardless of the technology, the premise of ICMV is that the measurement values are related to traditional compaction measurements and will be useful as part of effective earthwork or pavement compaction operations and QC/QA practices. The purpose of this section is to provide an overview of the literature in areas of:

- Developmental history of ICMV;
- ICMV technologies, manufacturers, and documentation systems;

- Factors influencing the ICMV measurements;
- Field correlation studies and factors influencing the correlations; and
- Specification attributes and concepts.

Model testing, discussions of disadvantages of existing models, and recommendation for future model development will also be presented.

Development of IC Measurements

The concept of ICMV was first investigated by Dr. Heinz Thurner of the Swedish Road Administration in 1974 by relating drum harmonics to soil compaction properties. Field trials were conducted by Dr. Thurner by instrumenting Dynapac vibratory smooth drum rollers using accelerometers on granular soils. Results from these field trials provided evidence that the ratio of the acceleration amplitude of the first harmonic and the acceleration amplitude of the fundamental frequency of the vibrating drum was an indicator of soil stiffness/modulus. In 1975, Dr. Thurner partnered with Åke Sandström and founded Geodynamik to continue research and development on ICMV. In 1976, Compactometer™ Compaction Meter Value (CMV) measurement was developed by Geodynamik in cooperation with the Dynapac Research Department. In 1980, five technical articles were presented on the CMV measurement technology and its applications (Thurner 1980, Thurner and Sandström 1980, Forssblad 1980, Hansbo and Pramborg 1980, and Machet 1980) at the First International Conference on Compaction held in Paris.

In 1983, Geodynamik introduced the Oscillometer Value (OMV) for oscillatory rollers which is a dimensionless value obtained from the amplitude of the horizontal acceleration of the drum. HAMM AG adopted the OMV measurement technology (Thurner and Sandström 2000) for use on their smooth drum oscillatory rollers, but virtually no published information is available in the English literature on OMV relationships with soil properties.

In the early 1980s, BOMAG developed the Terrameter® system measuring the Omega value (BTM 1983). The Omega value provides a measure of the compaction energy transmitted to the soil using accelerometer data. Hoover (1985) published a research report from a field study evaluating the Omega value on three different types of granular soils which showed encouraging results. Later in 2000, BOMAG replaced the Omega value by introducing the Vibratory Modulus (E_{VIB}) value which uses acceleration data to determine drum displacement, an estimated applied force, and a dynamic roller-soil model (Kröber et al. 2001).

In the late 1990s, Ammann introduced the roller-integrated stiffness (k_b) measurement value, which provides a measure of quasi-static stiffness using the measured drum displacement, estimated applied force, and a spring-dashpot model representing roller-soil interaction (Anderegg and Kauffmann 2004).

Currently, Dynapac, Trimble, and Caterpillar use the CMV measurement technology as part of their ICMV systems by linking CMV data with GPS measurements for on-board real time display. Trimble offers a retrofit CCC system for smooth drum vibratory rollers (White and Vennapusa 2009). In 2004, Sakai introduced Compaction Control Value (CCV) which is also a dimensionless parameter similar to CMV (Scherocman et al. 2007), but considers both the fundamental and sub-harmonic frequencies for determining CCV.

In 2003, a research collaboration project between the Iowa Department of Transportation, Federal Highway Administration (FHWA), and Caterpillar was initiated to evaluate Caterpillar's Machine Drive Power (MDP) system for use on granular and cohesive soils. The MDP system is based on the principle of rolling resistance due to drum sinkage, and the approach works in both the vibratory and static modes. The measurement system has been investigated in field trials since 2003 (Tehrani and Meehan 2009, White et al. 2004, 2005, White and Thompson 2008, Thompson and White 2008) and has recently been used on a full-scale earthwork compaction project in Minnesota (White et al. 2009a, b).

Currently, Bomag, Ammann, and Dynapac offer AFC/IC systems, wherein the vibration amplitude, and/or frequency are automatically adjusted when drum jumping is determined or when a preset threshold roller measurement value is reached. Some of the potential advantages cited in the literature (e.g., Adam and Kopf 2004) for using AFC for soil compaction are increased chance of more rapid compaction (i.e., less passes) and improved uniformity of soil properties. Based on this literature review, these benefits are not well quantified in the technical literature.

IC Measurement Types

Currently, at least six manufacturers (Ammann, Bomag, Case/Ammann, Caterpillar, Dynapac, and Sakai) offer ICMV on their machines (note that Case uses Ammann ICMV technology on their rollers). All the manufacturers employ proprietary data filtering, recording, and display methods using proprietary software. A summary of key features from each manufacturer is presented in Table 3. Figure 16 to Figure 21 show different roller configurations and display software by different manufacturers.

Table 3. Key features of different ICMV systems

Feature	Ammann/ Case	Bomag	Caterpillar	Dynapac	Sakai	Trimble
ICMV Value	ks (MN/m)	EVIB (MPa)	MDP40 (shown as CCV in the output) and CMV	CMV	CCV	CMV
Single Drum Configuration	Padfoot, Smooth Drum	Smooth Drum	Padfoot and Smooth Drum	Padfoot and Smooth Drum	Smooth Drum	(Retrofit) Smooth Drum
Display Software	ACE-Plus ®	BCM05 ®	AccuGrade®	DCA®	Aithon MT®	AccuGrade®
Output Documentation	Date/Time, Location (Latitude/ Longitude/ Elevation), Machine length/width, Direction (forward/ backward), Vibration (On/Off), Stiffness (ks), Amplitude (actual), Speed, Frequency	Date/Time, Location (Northing / Easting/ Elevation at center of the roller drum), EVIB, Frequency, Amplitude (actual), Speed, Jump	Date/Time, Location (Northing/Easting/ Elevation of left and right ends of the roller drum), Speed, CCV, CMV, ICMV, Frequency, Amplitude, Direction (forward/ backward), Vibration (On/Off)	Location (Latitude / Longitude/ Elevation), Direction (forward/ backward), CMV, Bouncing, Frequency, Speed, Amplitude	Date/Time, Location (Northing/ Easting/ Elevation), CCV, Temperature, Frequency, Direction (forward/ backward), Vibration (On/Off), GPS Quality	Date/Time, Location (Northing/Easting/ Elevation of left and right ends of the roller drum), Speed, CCV, CMV, ICMV, Frequency, Amplitude, Direction (forward/ backward), Vibration (On/Off)
Output Export File	*.txt	*.csv	*.csv	*.txt	*.csv	*.csv
Automatic Feedback Control (AFC)	Yes	Yes	No	Yes	No	No

Figure 16. Ammann and Case rollers (padfoot and smooth drum) equipped with roller-integrated k_s measurement system on-board display units with ACE-Plus® software.

Figure 17. A single-drum Bomag roller equipped with roller-integrated E_{VIB} measurement system on-board display units with BCM-05® software.

Figure 18. Caterpillar rollers (padfoot and smooth drum) equipped with roller-integrated MDP and CMV measurement systems on-board display unit with AcuGrade® software.

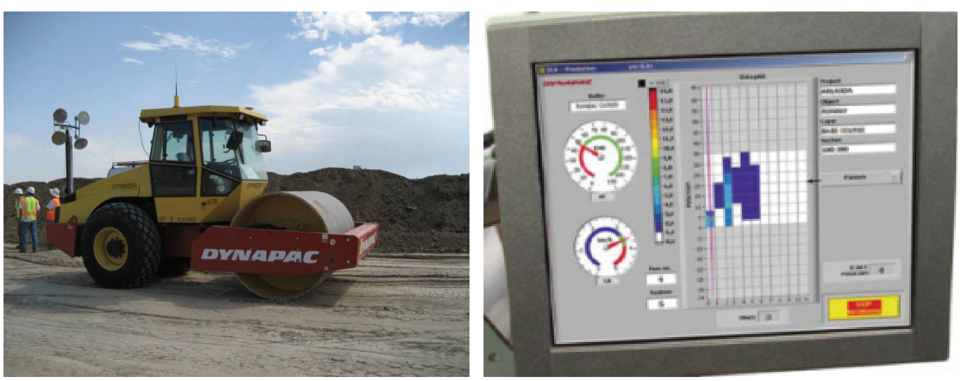


Figure 19. A single-drum Dynapac roller equipped with roller-integrated CMV measurement system and on-board display unit with DCA® software.

Figure 20. Sakai rollers (padfoot and smooth drum) equipped with roller-integrated CCV measurement system and on-board display unit with Aithon-MT® software.

Figure 21. Trimble CB430 on-board display unit with roller-integrated CMV measurement system.

The commonly used IC measurement values (ICMV) in the US are summarized in Table 4. These measurements are either based on vibration frequency analysis or mechanical modeling. More details on those IC measurements are described in the following sections.

Table 4 Summary of IC Measurements

IC Measurements	Units	IC Systems	Model Definition
Compaction Meter Value - CMV	None	Caterpillar, Dynapac	$\mathrm{CMV} = C\frac{A_{2\Omega}}{A_{\Omega}}$
Machine Drive Power - MDP	None	Caterpillar	$\mathrm{MDP} = \mathrm{P_g} - \mathrm{Wv}\left(\mathrm{Sin}\alpha + \frac{\mathrm{A'}}{\mathrm{g}}\right) - (\mathrm{mv} + \mathrm{b})$
Compaction Control values - CCV	None	Sakai	$\mathrm{CCV} = \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] \times 100$
Stiffness - K_b	MN/m	Ammann/Case	$\mathrm{k}_b = \omega^2\left[m_d + \frac{m_0 e_0 \cos(\phi)}{z_d}\right]$
Vibration Modulus - E_{vib}	MN/m^2	Bomag	$\frac{\Delta F}{\Delta z_1} = \frac{E_{vib} \cdot 2 \cdot a \cdot \pi}{2 \cdot (1-\nu^2) \cdot \left(2{,}14 + 0{,}5 \cdot \ln(\frac{\pi \cdot (2 \cdot a)^3 \cdot E_{vib}}{(1-\nu^2) \cdot 16 \cdot (m_b + m_e + m_r) \cdot g \cdot (d/2)})\right)}$

Compaction Meter Value (CMV)

Compaction meter value (CMV) is a dimensionless compaction parameter developed by Geodynamik that depends on roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed), and is determined using the dynamic roller response (Sandström 1994). The concept of development of different harmonic components of drum vibration with increasing ground stiffness is illustrated in (Figure 22). CMV is calculated using Equation 1, where C is a constant (i.e. 300), $A_{2\Omega}$ = the acceleration of the first harmonic component of the vibration, and A_{Ω} = the acceleration of the fundamental component of the vibration (Sandström and Pettersson 2004).

$$\mathrm{CMV} = \mathrm{C} \cdot \frac{\mathrm{A}_{2\Omega}}{\mathrm{A}_{\Omega}} \quad (1)$$

The Geodynamik system also measures the resonant meter value (ICMV) which provides an indication of the drum behavior (e.g. continuous contact, partial uplift, double jump, rocking motion, and chaotic motion) and is calculated using Equation 2, where $A_{0.5\Omega}$ = subharmonic acceleration amplitude caused by jumping (the drum skips every other cycle). Dynapac reports the value as bouncing value (BV). It is important to note that the drum behavior affects the CMV measurements (Brandl and Adam 1997) and therefore must be interpreted in conjunction with the ICMV or BV measurements (Vennapusa et al. 2010).

$$\mathrm{RMV\ or\ BV} = \mathrm{C} \cdot \frac{\mathrm{A}_{0.5\Omega}}{\mathrm{A}_{\Omega}} \quad (2)$$

Dynapac uses a preselected threshold BV as an indicator of roller jumping to adjust the amplitude in AFC mode compaction. Similarly, Caterpillar uses ICMV to adjust amplitude on a smooth drum vibratory roller used on a project (White et al. 2008b).

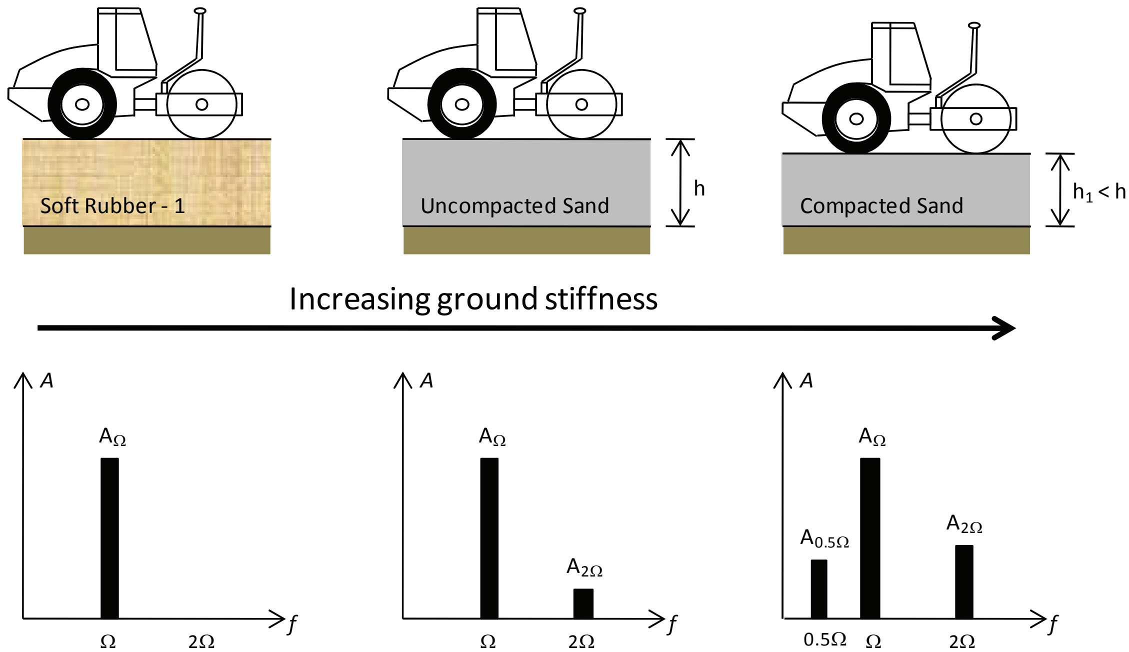


Figure 22. Illustration of changes in drum harmonics with increasing ground stiffness (modified from Thurner and Sandström 1980).

It was found that CMV increases monotonously with the stiffness of soil. Caterpillar, Dynapac, and Volvo/Ingersoll Rand IC systems have made use of the Geodynamic CMV.

Machine Drive Power (MDP)

Machine drive power (MDP) technology relates mechanical performance of the roller during compaction to the properties of the compacted soil. MDP is calculated as follows:

$$MDP = P_g - Wv\left(\text{Sin}\alpha + \frac{A'}{g}\right) - (mv + b) \quad (3)$$

where MDP = machine drive power (kJ/s), P_g = gross power needed to move the machine (kJ/s), W = roller weight (kN), A' = machine acceleration (m/s^2), g = acceleration of gravity (m/s^2), α = slope angle (roller pitch from a sensor), v = roller velocity (m/s), and m (kJ/m) and b (kJ/s) = machine internal loss coefficients specific to a particular machine (White et al. 2005). MDP is a relative value referencing the material properties of the calibration surface, which is generally a hard compacted surface (MDP = 0 kJ/s). Positive MDP values therefore indicate material that is less compact than the calibration surface, while negative MDP values indicate material that is more compacted than the calibration surface (i.e. less roller drum sinkage).

In a recent field study documented by White et al. (2009b) and field studies conducted as part of this pooled fund research project (Kansas and Mississippi field project from this research study), the MDP values are referred to as MDP_{80} or MDP_{40} depending on the modified settings. These modified values were recalculated to range between 1 and 150 as follows:

$$MDP_{80} = 150 - 1.37(MDP) \quad (4)$$

$$\mathrm{MDP}_{40} = 150 - 2.75(\mathrm{MDP}) \quad (5)$$

For MDP_{80} calculation, the calibration surface with MDP = 0 kJ/s was scaled to MDP_{80} = 150, and a soft surface with MDP = 108.47 kJ/s (80000 lb-ft/s) was scaled to MDP_{80} = 1. For MDP_{40} calculation, the calibration surface with MDP = 0 kJ/s was scaled to MDP_{40} = 150 and a soft surface with MDP = 54.23 kJ/s (40000 lb-ft/s) was scaled to MDP_{40} = 1.

Compaction Control Value (CCV)

The Sakai CCV is a relative stiffness index determined from the measured acceleration data based on the harmonic frequency. Sakai IC rollers make use of an accelerometer mounted to the roller drum to create a record of machine-ground interaction data. The concept behind the CCV is that as the ground stiffness increases, the roller drum starts to enter into a "jumping" motion which results in vibration accelerations at various frequency components, as illustrated in Figure 23. The CCV is computed based on the equation below.

$$\mathrm{CCV} = \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] \times 100 \quad (6)$$

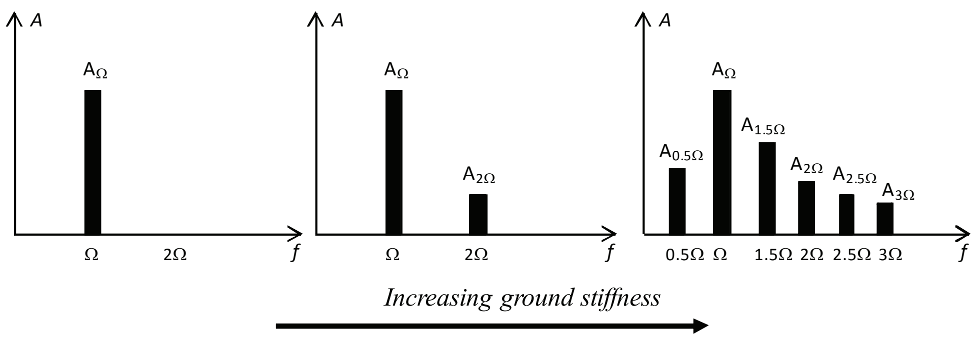


Figure 23. Changes in amplitude spectrum with increasing ground stiffness (modified from Scherocman et al. 2007).

Roller-Integrated Stiffness (k_b)

The stiffness of soil, k_b (or ks), is determined from a one-dimensional nonlinear mechanical model based on the theory of chaotic vibration (Anderegg et al. 2006, Anderegg and Kaufmann 2004). Figure 24 shows the force-displacement relationship for the roller-soil interaction.

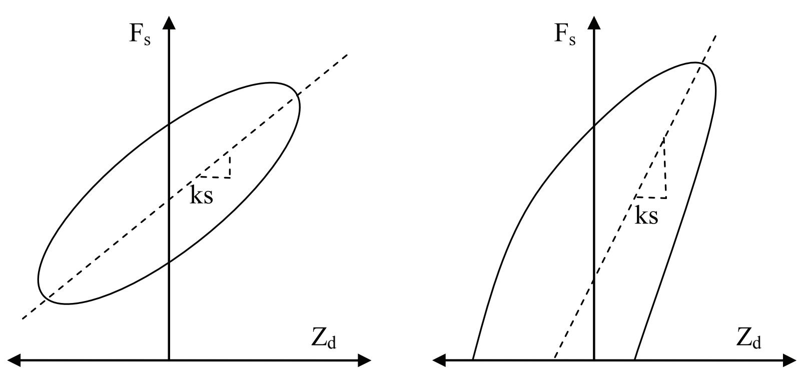


Figure 24. Force-displacement diagram for k_b.

In this model, the soil is simulated as an elastic-plastic material. Both the loading and unloading procedures are considered, and the latter induces partial unrecoverable deformation. The plastic deformation of the soil is simulated in the compaction zone (Sandstrom 1994).

The elastic stiffness of k_b value can be derived from the slope of the unloading curve as shown in Figure 24 A simple model consists of two mechanical parts: one part for the roller which is simulated as a rigid body with acceleration toward the soil; another part is for the soil foundation which is simulated with one spring and one damping dashpot in parallel. The machine above the roller may also be considered to consist of three parts together with the roller and soil foundation, as shown in Figure 25.

Some other research has also considered the damping effect of the roller system, such as the simulation done by Tawfik (2006). The force balance equations were established for both the rigid roller and the soil body. The roller-soil interaction force can be derived from the acceleration data such as vibration frequencies and displacement amplitudes, and then the soil stiffness is back-calculated.

In this model the drum displacement is expressed as a cosine function. Similar to Figure 23, the vibration frequency has a series that is dependent on the roller vibration modes at different stages including: (1) permanent drum-ground contact, when i =1Ω (i.e., natural frequency); (2) periodic loss of contact when roller lifts off the ground, when i=1Ω, 2Ω, 3Ω; and (3) bouncing/rocking during the subharmonic stage, when i=1/2Ω, 1Ω, 3/2Ω, 2Ω, 5/2Ω, and 3Ω.

This model has been implemented in the Ammann IC machines, and has been primarily used for the soil/base compaction projects including the Transportation Pooled Funding (TPF) intelligent compaction study in the USA.

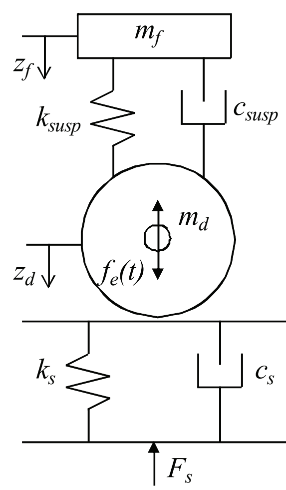


Figure 25. Lumped parameter two-degree-of-freedom spring dashpot model representing vibratory compactor and soil behavior (reproduced from Yoo and Selig 1980).

The k_b value is determined using Equation 7, where f is the excitation frequency, m_d is the drum mass, $m_e r_e$ is the eccentric moment of the unbalanced mass, ϕ is the phase angle, and a is vibration amplitude. The k_b value represents a quasi-static stiffness value and is reportedly independent of the excitation frequency between 25 to 40 Hz (Anderegg and Kaufmann 2004).

$$k_b = 4\pi^2 f^2 \left[\frac{m_d + m_e r_e \cos\phi}{a} \right] \quad (7)$$

The k_b measurement system has the capability to perform compaction in a manual mode and in an automatic feedback control (AFC) mode. The AFC operations in the Case roller are controlled by the Ammann Compaction Expert (ACE) plus system. Three AFC operation settings are possible using the ACE plus system (Anderegg et al. 2006):

- Low performance setting: Maximum applied force = 14 kN with vibration amplitude (a*) varying from 0.4 to 1.5 mm.
- Medium performance setting: Maximum applied force = 20 kN with vibration amplitude (a*) varying from 1.0 to 2.0 mm.
- High performance setting: Maximum applied force > 25 kN with vibration amplitude (a*) varying from 2.0 to 3.0 mm.

When operated in AFC mode, as sub-harmonic vibrations occur, the roller automatically adjusts the eccentric mass moment to adjust the vibration amplitude and excitation frequency (Anderegg et al. 2006). Correlation studies relating k_s to soil dry unit weight, strength, and stiffness are documented in the literature (Anderegg and Kaufmann 2004).

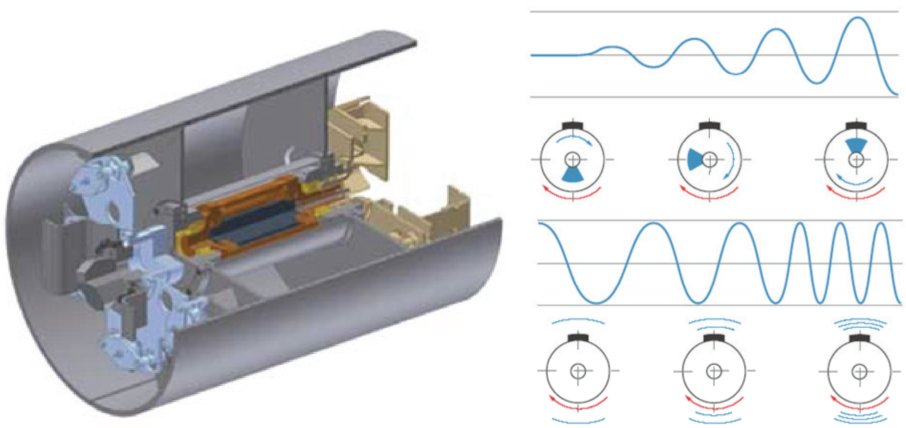


Figure 26. Ammann two-piece eccentric mass assembly and AFC of vibration amplitude and frequency (picture courtesy of Ammann).

Vibratory Modulus (E_{VIB})

The vibratory modulus (E_{VIB}) value is calculated using the one-degree-of-freedom lumped parameter model and Lundeberg'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 and Krober et al. 2001) reported that the E_{VIB} value is related to the modulus determined from a static plate load test. The drum force (F_s) and displacement (z_d) behavior is related to E_{VIB} (see Equation 8) using Lundberg's analytical solution. According to Hertz (1895), the contact width of a cylindrical drum (B) can be calculated using the geometry of the drum, applied force, and the material properties (see Equation 9). The two equations (Equations 8 and 9) are numerically solved to determine the E_{VIB} value.

$$z_d = \frac{\left(1-\eta^2\right)}{E_{VIB}} \cdot \frac{F_s}{L} \cdot \frac{2}{\pi} \cdot \left(1.8864 + \ln\frac{L}{B}\right) \quad (8)$$

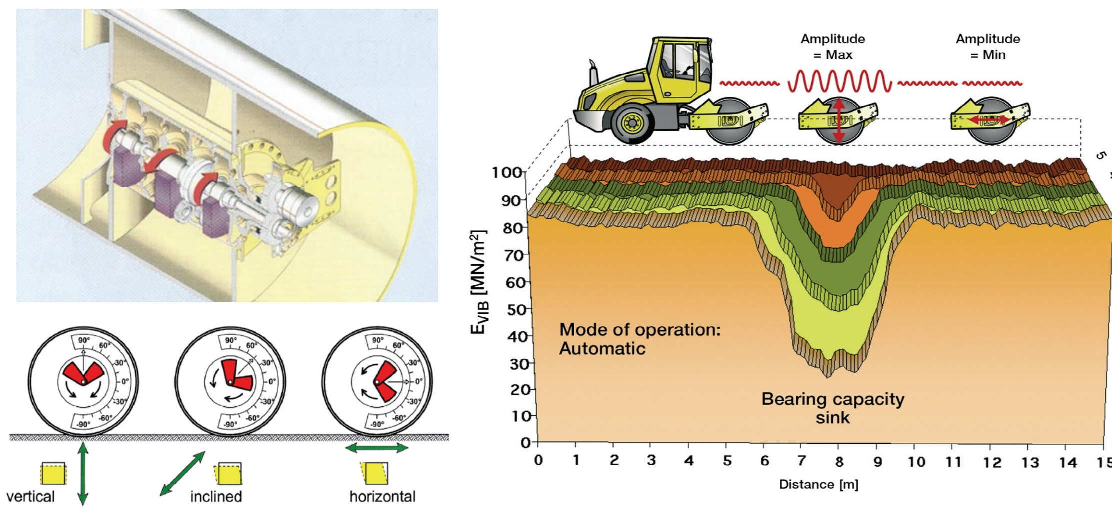
$$\text{where } B = \sqrt{\frac{16}{\pi} \cdot \frac{R'(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L}} \quad (9)$$

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.

The automatic feedback control (AFC) system developed by Bomag uses a concept of counter-rotating eccentric mass assembly that is directionally vectored to vary the vertical excitation force on the soil (see Figure 27). If the counter-rotating masses are opposite each other in their rotation cycles, the eccentric force is zero. On the other hand, when the counter-rotating masses pass each other, the eccentric force is at maximum. The AFC system automatically adjusts the amplitude (by adjusting the vectors) depending on the pre-selected settings or the drum behavior (see Figure 27). Two different AFC settings are available as described below.

Pre-selected target EVIB and a maximum amplitude a_{max} value: In this setting, the vibration amplitude is reduced below the a_{max} value when $E_{VIB} \geq$ target E_{VIB}, and the amplitude is at the a_{max} value when $E_{VIB} <$ target E_{VIB}.

Pre-selected vibration amplitude a_{max} value: In this setting, the vibration amplitude is controlled based on the drum double jump behavior (described in more detail below) as measured by the jump value. When the jump value increases above 0, the amplitude is lowered to 0.6 mm.



(courtesy of Bomag)

Figure 27. Bomag roller eccentric mass assembly and vectoring to vary the vertical excitation force (left) and principle of Bomag's automatic feedback control (AFC) system (right).

Review of Field Correlation Studies

Correlation studies relating different ICMV measurements to soil dry unit weight, strength, and stiffness/modulus properties in-situ are documented in the technical literature. A variety of in-situ test QC/QA devices have been used in the documented correlation studies (Figure 28):

- Density and moisture content — nuclear gauge (Figure 28a), electrical density gauge (Figure 28b), water balloon method, sand cone replacement method, radio isotope method, and drive core method.
- Stiffness or Modulus — light weight deflectometer (LWD) (Figure 28c), soil stiffness gauge (SSG) (Figure 28d), static plate load test (PLT) (Figure 28e), falling weight deflectometer (FWD) (Figure 28f), Briaud compaction device (Figure 28g), dynamic seismic pavement analyzer (D-SPA) (Figure 28h), Clegg hammer (Figure 28i), pressure meter, and screw plate.
- Strength or California bearing ratio — shelby tube sampling and laboratory testing (Figure 28j), dynamic cone penetrometer (DCP) (Figure 28k), cone penetration testing (CPT) (Figure 28l), rut depth measurements under heavy test rolling (Figure 28m).
- Other — surface settlement monitoring under compaction passes using GPS or total station surveying, etc.

A summary of field correlation studies documented in the literature is provided in Table 4.

A comprehensive correlation study involving field evaluation of five different ICMV technologies on 17 different soil types from multiple project sites is documented in NCHRP 21-09 (2010). A list of factors that commonly affected the correlations between ICMV and in-situ test measurements identified from that study are as follows:

- Heterogeneity in underlying layer support conditions
- High moisture content variation
- Narrow range of measurements
- Machine operation setting variation (e.g., amplitude, frequency, speed) and roller "jumping"
- Non-uniform drum/soil contact conditions
- Uncertainty in spatial pairing of point measurements and ICMV
- Limited number of measurements
- Not enough information to interpret the results
- Intrinsic measurement errors associated with the ICMV and in-situ point measurements

Of all the factors above, heterogeneity in support conditions of layers underlying the compaction layer is identified as the major factor that affects the correlations (NCHRP 21-09 2010). This is largely due to differences in measurement influence depths between the roller and the in-situ point-MVs (see Figure 29). An approach of using the underlying layer ICMV measurements and in-situ point-MV information, and incorporating those into multiple regression analysis is described in NCHRP 21-09 (2010).

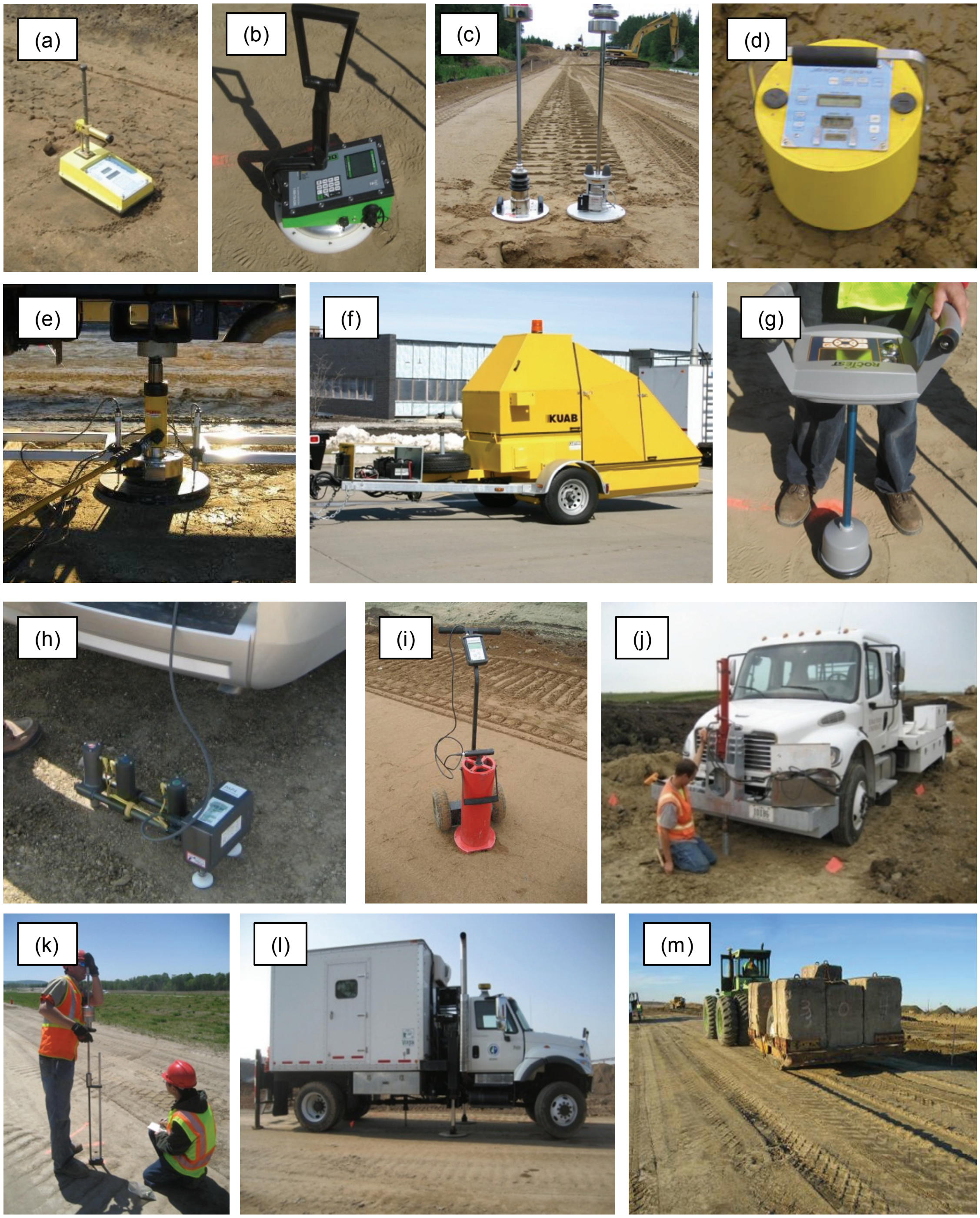


Figure 28. Various in-situ QC/QA test measurements: (a) nuclear moisture-density gauge; (b) electrical density gauge; (c) light weight deflectometers; (d) soil stiffness gauge; (e) static plate load test; (f) falling weight deflectometer; (g) Briaud compaction device; (h) seismic pavement analyzer; (i) Clegg hammer; (j) shelby tube sampling; (k) dynamic cone penetrometer; (l) static cone penetrometer; and (m) heavy test rolling.

Table 5. Summary of field correlation studies

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
Forssblad (1980)	Sweden	Dynapac SD; CMV	Morainic soil, fine rock fill, and coarse rock fill	Water balloon volumeter (for density), PLT, FWD, and surface settlement	Linear correlations have been observed between CMV and Point-MVs. Moisture content should be considered in correlations for fine grained soils. Roller results in a composite value in layered soil condition. CMV measurements are affected by roller speed (higher speeds result in lower CMV).
Hansbo and Pramborg (1980)	Stockholm, Sweden	Dynapac SD; CMV	Gravelly sand, silty sand, and fine sand	Sand cone (for moisture and density), pressuremeter, PLT, screw-plate, CPT, and DCP	Compaction growth curves showed improvement in CMV and other mechanical properties (i.e., modulus and cone resistance) with increasing pass. Relative compaction measurement was not sensitive to changes in compaction.
Floss et al. (1983)	Munich II airport, Munich, Germany	Dynapac Dual SD; CMV	Sandy to silty gravel fill	Bentonite displacement, water balloon method, and sand cone (for moisture and density), PLT, and DCP	Correlations generally showed increasing CMV with increasing density, modulus, and DCP penetration blows (per 0.6 m penetration). Correlations with modulus and penetration blows were generally better than density. CMV measurements are dependent on speed, vibration frequency and amplitude, type of soil, grain composition, water content, and strength of subsoil.
Brandl and Adam (1997)	—	BOMAG SD; CMV	—	PLT	Correlation between CMV and PLT modulus (initial) showed different regression trends for partial uplift and double jump operating conditions. Regressions in partial uplift and double jump conditions yielded R^2 = 0.9 and 0.6, respectively.
Nohse et al. (1999)	2nd Tomei Exp. way, Japan	Sakai SD; CMV	Clayey gravel	Radio-isotope (for density)	On calibration test strips, average dry density and CMV increased with increasing roller passes. Linear regression relationships with $R^2 >$ 0.9 were observed for correlations between dry density and CMV.
Kröber et al. (2001)	—	BOMAG SD; EVIB	Silty gravel	PLT	Correlations from calibration test strips between E_{VIB} and PLT initial and reload modulus (E_{V1} and E_{V2}) showed strong correlation with $R^2 >$ 0.9.

Table 4. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
Gorman and Mooney (2003); Mooney et al. (2003)	Oklahoma	Ingersoll Rand SD; Total harmonic distortion (THD)	Well-graded sand	DCP	Trends in relationship between THD and DPI generally showed decreasing penetration resistance with increasing THD. Strength of the correlations improve significantly if the sub-lift material was stiffer.
Preisig et al. (2003); Anderegg and Kaufmann (2004)	Bern, Switzerland	Ammann dual SD; ks	Eight project sites with sandy gravel materials	PLT	Correlations between ks and PLT initial and reload (E_{V1} and E_{V2}) modulus showed R^2 = 0.68 and 0.56, respectively. If only data points with E_{V2}/E_{V1} ratio < 3.5 (i.e., areas with less plastic deformation during reloading) are considered, the R^2 values improve to about 0.80.
White et al. (2004, 2005)	Edwards, Illinois	Caterpillar PD; MDP	Lean clay	NG, Drive core, DCP, and Clegg hammer	Correlations between MDP and in-situ test measurements using simple and multiple regression analyses are presented. MDP correlated relatively better with dry unit weight (R^2 = 0.86) than with DCP (R^2 = 0.38) or CIV (R^2 = 0.46). Including moisture content via multiple regression analysis greatly improves the R^2 values for DCP and CIV (R^2 > 0.9). These results were developed by averaging data over 20m long strip per pass.
Camargo et al. (2006)	Atwater test site, Minnesota	BOMAG SD; EVIB	Select granular subbase	LWD, DCP, and SSG	No statistically significant correlation between Point-MVs and E_{VIB} values, however, the COV observed in LWD and SSG measurements were similar to COV in E_{VIB} measurements. Narrow range of measurements contributed to weak correlations.
Hossain et al. (2006)	US65 and I-70, Kansas	BOMAG SD; EVIB	Well-graded silty sand	NG and DCP	E_{VIB} measurements are sensitive to soil moisture content. Weak correlation was observed between E_{VIB} and CBR determined from DCP, and NG. (E_{VIB} measurements obtained in AFC mode which are influenced by changing amplitude).
Peterson et al. (2006)	MnRoad, Albertville, Minnesota	BOMAG SD; EVIB	Silty sand, railroad ballast, and well-graded granite	DCP, SSG, LWD, PLT, FWD, NG, and sand cone (for moisture and density)	Influence of applied stress on soil modulus determined by different test methods, and influence of measurement influence depth and differences between different test methods are discussed in this paper.

Table 1. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
Petersen and Peterson (2006)	TH53, Duluth, Minnesota	Caterpillar SD; CMV and MDP	NA	LWD, DCP and SSG	Weak correlations were obtained on a point-by-point basis comparison between in-situ test measurements and roller measurements, likely due to the depth and stress dependency of soil modulus, and the heterogeneity of the soils. Good correlations were obtained between CMV values and DCP measurements for depths between 200 and 40 mm depth.
White et al. (2006a, b)	Edwards, Illinois	Caterpillar PD; MDP	Well-graded silty sand	NG and DCP	Average machine power values showed a decreasing (logarithmic) trend, dry unit weight values showed an asymptotic increase, and DCP index showed an asymptotic decrease with increasing roller pass. Correlations between MDP and Point-MVs showed good correlations (R2 = 0.5 to 0.9). Incorporating moisture content into analysis is critical to improve correlations for dry unit weight.
White et al. (2006b); Thompson and White (2008)	Edwards, Illinois	Caterpillar PD; MDP	Silt and lean clay	NG, DCP, Clegg Hammer, and LWD	Correlations between MDP and Point-MVs are presented using simple and multiple regression analysis. Averaging the data along the full length of the test strip (per pass) improved the regressions. Multiple regression analysis by incorporating moisture content as a regression parameter further improved the correlations.
Thompson et al. (2008) and White et al. (2007a)	US14, Janesville, Minnesota	Ammann SD; ks	Sandy lean clay subgrade, and poorly graded sand base layer	LWD, PLT, DCP, Clegg Hammer, and NG	k_s correlated well with PLT with R^2 = 0.80 and the R^2 values with other measurements ranged from 0.30 to 0.61 on subgrade. Poor R^2 values were observed on the base layer due to narrow range of measurements.

Table 4. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2007a); White et al. (2008b)	TH64, Ackley, MN	Caterpillar SD, CMV	Poorly graded sand and well-graded sand with silt	LWD, DCP, and NG	Project scale correlations by averaging data from different areas on the project are presented, which showed R^2 values ranging from 0.52 for density and 0.79 for DPI. Correlations with LWD showed poor correlations due to the effect of loose surficial material. The COV observed in the CMV data was similar to DCP and LWD measurements but not to density measurements.
White et al. (2007b); White and Thompson (2008)	Edwards, Illinois	Caterpillar SD; MDP and CMV	Reclaimed asphalt, clayey gravel, silty gravel, poorly graded gravel, and silt	NG, DCP, Clegg hammer, and LWD	Averaging the data along the full length of the test strip (per pass) improved the correlations between MDP, CMV, and Point-MVs. The relationships were independent of soil type. Compaction curves of MDP, CMV, and Point-MVs showed improvement in soil compaction with increasing roller pass. CMV measurements reflected the properties of the underlying subgrade layer.
White et al. (2007b)	Edwards, Illinois	Caterpillar PD; MDP	Sandy lean clay	NG and DCP	Based on average measurements over the length of the test strip (~20 m); correlations between MDP and Point-MVs (R^2 = 0.87 for density and 0.96 for DCP)
White et al. (2008c); Vennapusa et al. (2009)	Edwards, Illinois	Caterpillar PD; MDP	Crushed gravel base	DCP and LWD	Correlations were obtained on a test bed with multiple lifts placed on a concrete base and a soft subgrade base. Correlations between MDP and Point-MVs yielded R^2 = 0.66 to 0.85 for spatially nearest point data, and R^2 = 0.74 to 0.92 for averaged data (over the length of concrete or soft subgrade).

Table 4. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2009a, b)	TH60, Bigelow, Minnesota	Caterpillar PD; MDP80 and Caterpillar SD; CMV	Sandy lean clay to lean clay with sand	Heavy test roller, DCP, LWD, and PLT	Correlations were obtained on multiple calibration test strips and production areas from the project. MDP_{80} and LWD modulus correlation showed two different trends (R2 = 0.35 and 0.65) over the range of measurements as the MDP_{80} reached an asymptotic value of about 150 which is the maximum value on the calibration hard surface. CMV correlation with LWD modulus produced R^2 = 0.70, and with rut depth produced R^2 = 0.64.
White et al. (2009b)	TH36, North St. Paul, Minnesota	Caterpillar SD; CMV	Granular subbase and select granular base	DCP, SSG, Clegg Hammer, LWD, PLT, FWD, and CPT	Correlations between CMV and Point-MVs from calibration and production test areas based on spatially nearest point data are presented. Positive trends are generally observed with $R^2 > 0.5$ (for LWD, FWD, PLT, SSG, and Clegg) with exception of one test bed (FWD, LWD, and CPT) with limited/narrow range of measurements.
White et al. (2009b)	US10, Staples, Minnesota	Caterpillar SD; CMV	Poorly graded sand with silt to silty sand	LWD, PLT, and DCP	Correlations between CMV and Point-MVs from calibration and production test areas based on spatially nearest point data are presented. Correlations between CMV and Point-MVs showed R2 value ranging from 0.2 to 0.9. The primary factors contributing to scatter are attributed to differences in measurement influence depths, applied stresses, and the loose surface of the sandy soils on the project. Correlations between CMV and LWD or DCP measurements improved using measurements at about 150-mm below the compaction surface.

Table 4. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
White et al. (2009b)	CSAH 2, Olmsted County, Minnesota	Caterpillar PD; MDP80	Sandy lean clay	LWD	MDP80 values were influenced by the travel direction of the roller due to localized slope changes and roller speed. Correlations between MDP80 and LWD generally showed R2 > 0.6 (with exception of one case) when regressions were performed by separating data sets with different travel directions and speed. Data was combined by performing multiple regression analysis incorporating travel speed and direction which showed correlations with R2 = 0.93.

Table 4. Summary of field correlation studies (continued)

Reference	Project location	Roller Type; ICMV	Soil type(s)	QC/QA Point-MVs	Key findings/ Comments
NCHRP 21-09 (2010)	Minnesota, Colorado, North Carolina, Florida, and Maryland	Caterpillar (PD and SD; MDP and CMV), Dynapac (PD and SD; CMV), Sakai (SD, CCV), BOMAG (PD, SD, EVIB), Case/ Ammann (SD, ks)	Two types of cohesive subgrade materials, five types of granular subgrades, and six types of granular base materiasl	NG, DCP, LWD, FWD, PLT, Clegg hammer, SSG	Simple linear correlations between ICMV and compaction layer point-MVs are possible for a compaction layer underlain by relatively homogenous and stiff/stable supporting layer. Heterogeneous conditions in the underlying layers, however, can adversely affect the relationships. A multiple regression analysis approach is described that includes parameter values to represent underlying layer conditions to improve correlations. Modulus measurements generally capture the variation in ICMV values better than traditional dry unit weight measurements. DCP tests are effective in detecting deeper "weak" areas (at depths > 300 mm) that are commonly identified by ICMV values and not by compaction layer point-MVs. High variability in soil properties across the drum width and soil moisture content contribute to scatter in relationships. Averaging measurements across the drum width, and incorporating moisture content into multiple regression analysis, when statistically significant, can help mitigate the scatter to some extent. Relatively constant machine operation settings are critical for calibration strips (i.e., constant amplitude, frequency, and speed) and correlations are generally better for low amplitude settings (e.g., 0.7 to 1.1 mm).

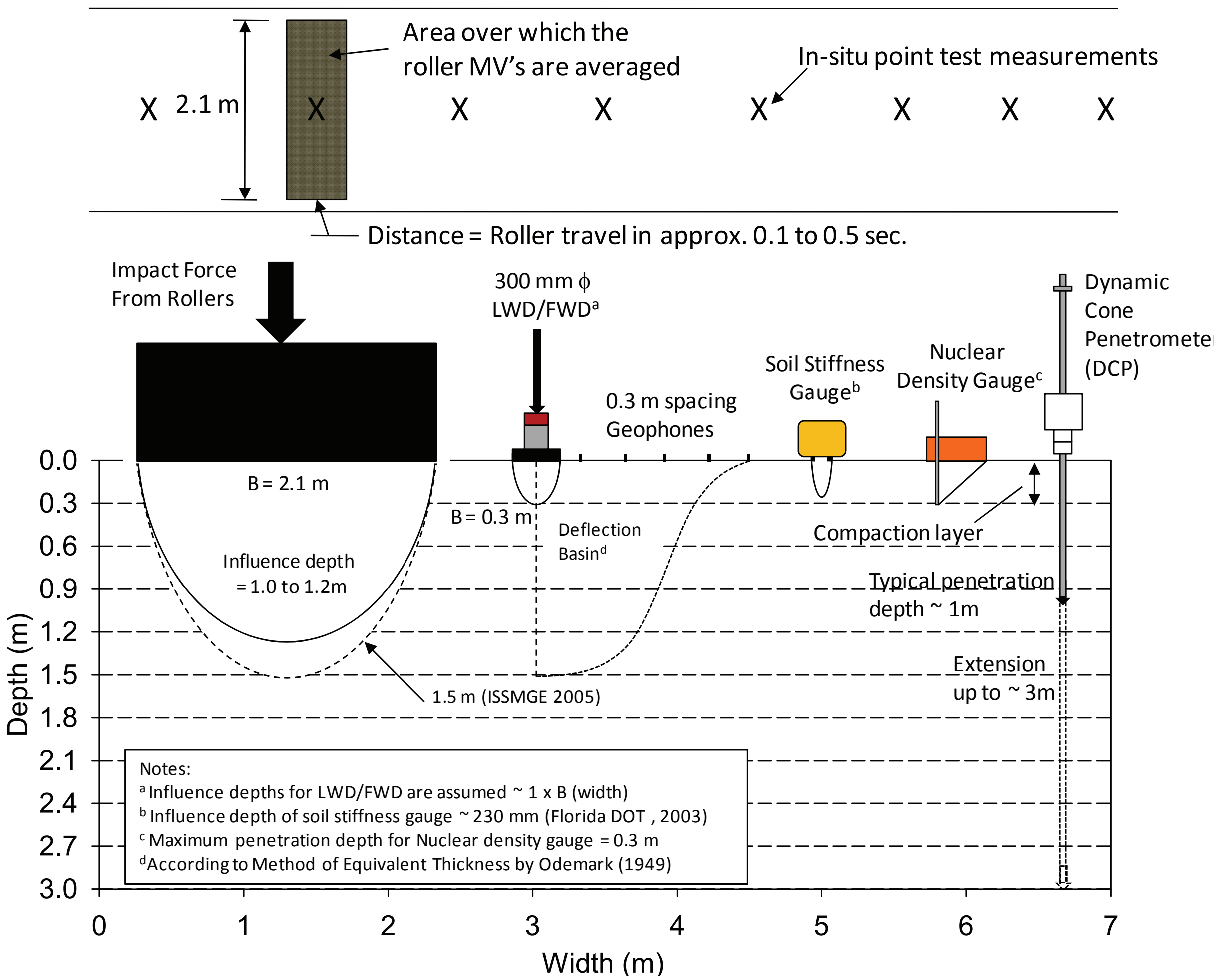


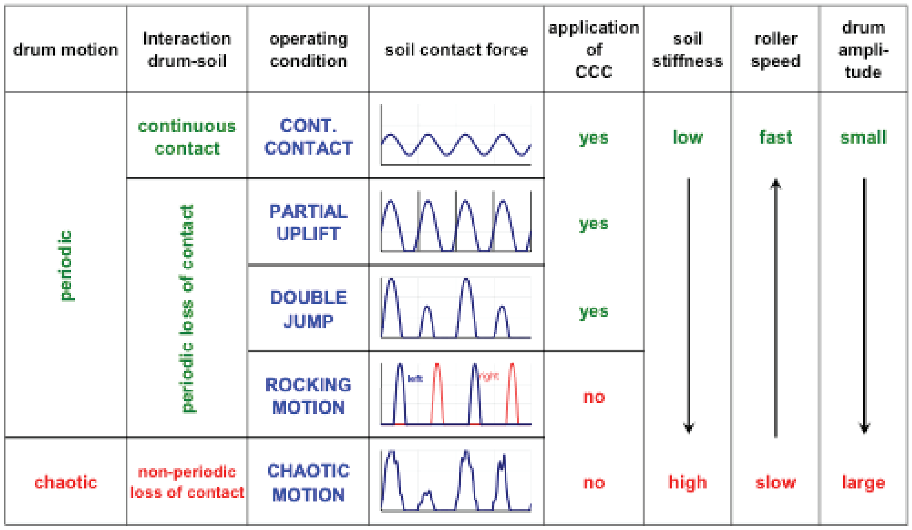
Figure 29. Illustration of differences in measurement influence depths for different measurements (modified from White 2008).

Examine IC Measurements and Correlation Analysis

Influence of Drum Behavior on ICMVs

Previous experimental and numerical investigations (e.g., Adam and Kopf 2004) on roller drum-soil interaction identified five different drum behavior modes which are dependent on the soil stiffness and roller operational settings (i.e., amplitude, frequency, and speed). These five modes include: continuous contact, partial uplift, double jump, rocking motion, and chaotic motion (see Figure 30). The column "application of CCC" means whether continuous compaction control is applicable. The accelerometer-based ICMV values (i.e., CMV, ICMV, Omega, E_{VIB}, and k_s) are influenced by these different drum modes (see Figure 31).

For CMV measurement technology the drum jump behavior is assessed using the ICMV or BV measurements. According to Adam and Kopf (2004), ICMV or BV = 0 indicates that the drum is in a continuous contact or partial uplift mode. For ICMV or BV > 0, the drum enters double jump mode and transitions into rocking and chaotic modes with increasing soil stiffness. Based on numerical studies, Adam and Kopf (2004) demonstrated the change in CMV relative to soil stiffness and drum behavior as shown in Figure 31. For E_{VIB} measurement technology, the drum behavior is assessed using Jump value. Jump = 0 indicates the drum is in continuous contact or partial uplift mode and Jump > 0 (1 or 2) indicates the drum is in either in double jump, rocking, or chaotic mode. AFC systems should help control the drum behavior to prevent the drum jumping by automatically adjusting the vibration amplitude and/or frequency.



drum motion	Interaction drum-soil	operating condition	soil contact force	application of CCC	soil stiffness	roller speed	drum ampli-tude
periodic	continuous contact	CONT. CONTACT		yes	low	fast	small
	periodic loss of contact	PARTIAL UPLIFT		yes	↓	↑	↓
		DOUBLE JUMP		yes			
		ROCKING MOTION	left right	no			
chaotic	non-periodic loss of contact	CHAOTIC MOTION		no	high	slow	large

Figure 30. Influence of soil modulus and drum behavior on ICMVs (from Adam and Kopf 2004).

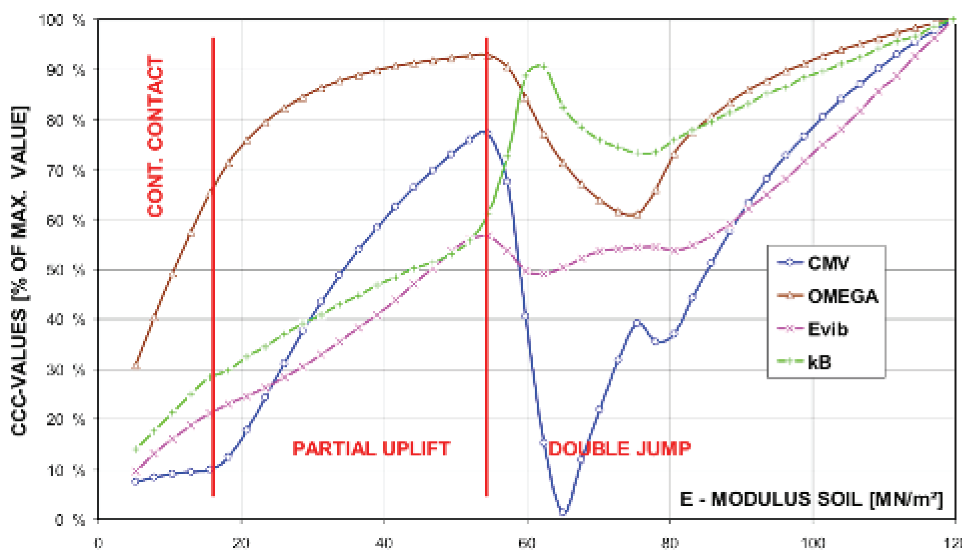


Figure 31. Influence of drum behavior on ICMVs relative to soil modulus (based on numerical simulations from Adam and Kopf 2004) (Note $k_B = k_s$).

Correlation between in-situ point tests and IC indices

At different time series and rolling points during compaction, the moisture of soil and temperature of HMA may be different from that of the in-situ spot tests. However, the existing ICMV models are unable to convert the ICMVs to that at a uniform moisture or temperature condition due to the technical challenges. Meanwhile, the existing ICMV models are based on a multilayered pavement system or a single soil foundation with a certain influence depth, thus they are unable to capture the stiffness of a specific pavement layer. As a result, these two issues may raise problems when correlating the ICMV to the in-situ measurements of a respective soil or pavement layer.

Auto-feedback Control (AFC) mode

AFC mode was used for the soil/subbase compaction with Case/Ammann and Bomag IC rollers for the Texas, Mississippi, and New York demonstration projects, and conclusions are as follows:

- AFC system is expected to help control the drum behavior to prevent the drum jumping by automatically adjusting the vibration amplitude and/or frequency. However, results show that AFC mode does not necessarily prevent roller jumping (e.g. the Texas demonstration using Ammann/Case, and the New York demonstration using Bomag).
- Under AFC mode machine amplitude/frequency adjusts dependent on the settings. E.g. 1: when operated in high performance setting, the vibration amplitude was decreased and the excitation frequency was increased with increase in k_s (Mississippi demonstration using Case/Ammann); E.g. 2: when E_{VIB} < target E_{VIB}, the amplitude is at the a_{max}, and when E_{VIB} > target E_{VIB} the amplitude is effectively reduced to 0.60 mm (Bomag Evib in New York demonstration).
- No consistent proof shows that AFC mode will improve the ICMVs. E.g. the New York soil compaction (TB5) shows that AFC mode (with a_{max} = 1.10mm, and target E_{VIB}=150MPa) results in higher E_{VIB} at the first pass, but similar results after eight passes compared to the manual model with a constant amplitude setting (with a = 0.70mm).
- No proof shows significant difference of in-situ measurements (e.g. dry density, modulus, and CBR) after a certain pass count between the AFC mode and manual mode.
- No consistent proof shows that AFC mode has improved the compaction uniformity based on the semivariogram parameters (e.g. the New York soil compaction using the Bomag IC roller).

Correlation among Different IC Measurements

Mostly, more than one IC vendor is used for the same highway project in these demonstrations. For some of the same test strips, more than one IC vendor is used (e.g. both are used for mapping, one is used as breakdown roller and another one is used as intermediate roller, etc.). Results indicate that generally different ICMV models may result in similar trends in the same compaction area (e.g. the mapping of existing HMA layer using both Sakai and Bomag resulted in similar trends for the Maryland HMA IC demonstration). All rollers can identify the weak or strong compaction areas. However, the issues of different ICMV models include:

- There is no consistent linear relationship between different ICMVs of different IC vendors due to their different computation algorithm and definition, e.g. the harmonicfrequency-based unitless CMV or CCV vs. the roller-soil interaction based mechanical models of E_{VIB} (MN/m^2) or k_b (kN/m);
- Inconsistent ICMV definition could be one of the main obstacles for the industry standardization; and thus
- A harmonized model or more standardized definition of ICMV model may help industry standardization, better evaluation, and more broad application of IC technology.

Verification of the IC models

In this research a prototype is developed to verify the ICMV models from different IC vendors for a test purpose. Readers can also refer to similar work in the NCHRP soils IC report (Mooney, et al., 2011).

Methodologies

The simulation is based on the model algorithms for different vendors as discussed above. Fortran® was used for the core computation and Excel Visual Basic Application® (VBA) was used for the interface user inputs/outputs (Figure 32). Different IC models can be simulated, including the Case/Ammann K_b, Bomag E_{vib}, Sakai CCV, and Caterpillar CMV.

Four signal types are defined, including the "Harmonic excitation" (pavement stress/displacement follows a sinusoidal format), "Measurement" (use the measured roller acceleration data if available), "Free generation" (free generated signals), and "Constant" (pavement stress/displacement is assumed constant). The general model parameters are defined for all IC vendors, e.g. "Debug" (debug or not), "Time point" (time series length), "Time interval", "Max Ite. No." (maximum allowed iteration number for numerical solution), and "Tolerance" (computation error for solution such as for E_{vib}). Roller parameters are also essential information for computation of ICMV, such as the "Drum weight" and "Add. mass weight" (the additional mass for roller vibration), etc.

Inputs

ICMV Simulation

General Model Parameters

Debug	1	1: Yes;2: No
File path of IC data	C:_DOC\207012 - Intelligent Co	
Time point	200	times
Time interval	0.033	s
Max Ite. No.	500	times
Tolerance	0.10%	

IC Model Type: Case/Ammann Kb

Signal type: Harmonic excitatior

Roller Parameters

	Bomag	Case/Ammann	Caterpillar CMV	Sakai CCV	Unit
Frame weight	100000	100000			kg
Drum weight	2000	2000			kg
Add. mass weight	100	100			rad/s
Drum width	2	2.2			m
Drum Diameter	1	0.75			m
Add. mass radius	0.25	0.25			m
Vibration frequency	2100	2100			vpm
Force Amp.	146000	146000			N
Deflection Amp.	0.0007	0.0007			m
Phase lag	0	0			rad
Mat. Poisson's ratio	0.35	0.35			N/A

Figure 32. Interface for ICMV simulation.

Verification Results

Figure 33 shows the simulation results of Case/Ammann k_b for a time period of 200 minutes (12000 seconds). Figure 34 shows the simulation results vs. measurements, which show some discrepancies and even reverse trends at some time periods. This discrepancy could be due to the reasons summarized as follows:

- The IC exported data (measurements) has only limited information with limited time points (e.g. sampling rate of 60 seconds) which cannot be directly used to re-produce the results through simulation;
- Some information, e.g. deflection of soils and soil-roller interaction force, are unknown to the simulation test, which can only be guessed or assumed in the simulation.

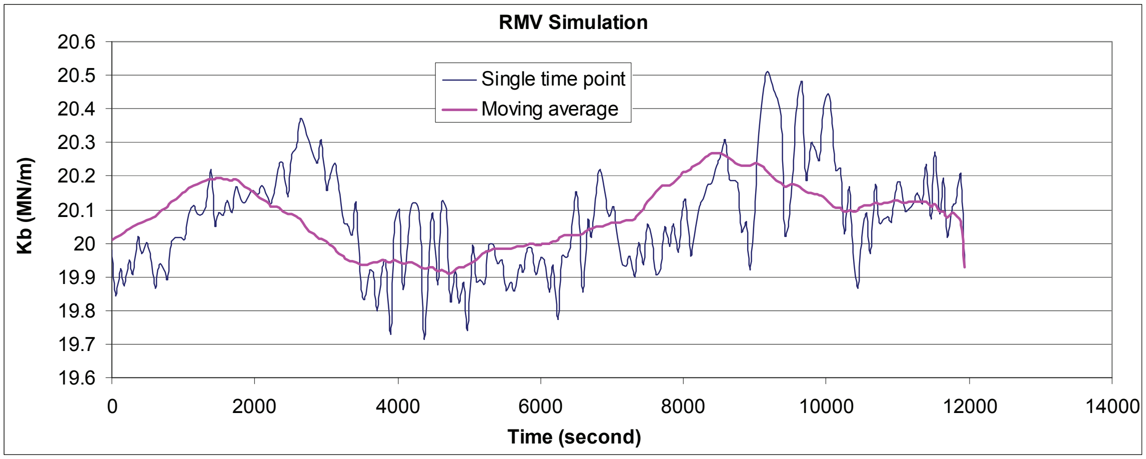


Figure 33. Simulated Case/Ammann K_b.

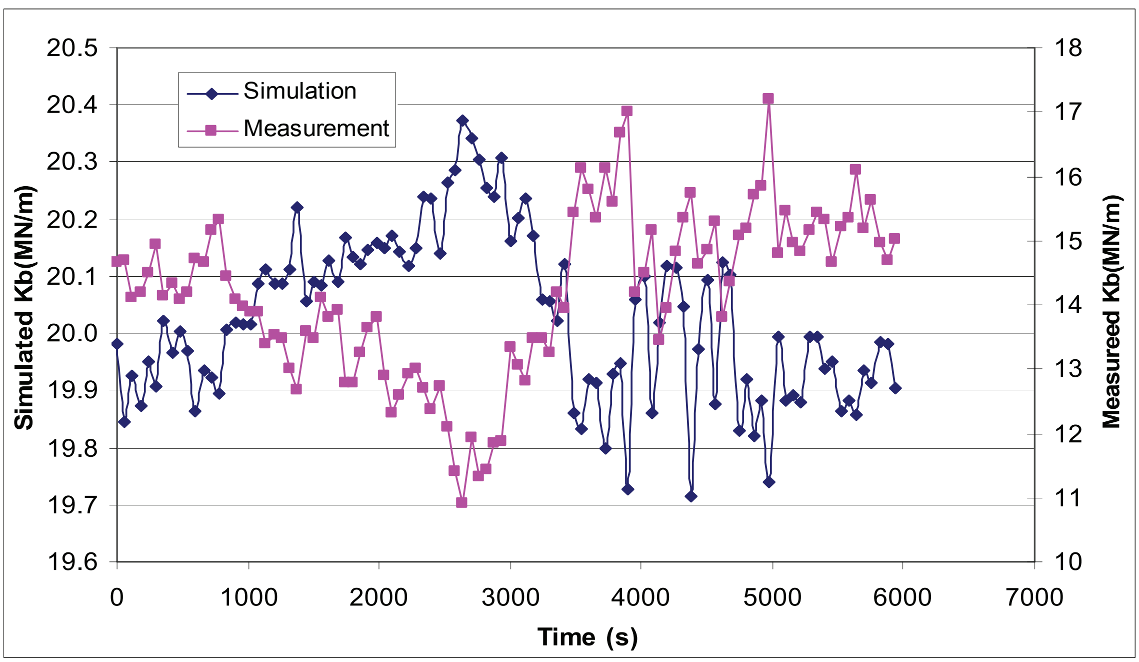


Figure 34. Simulated vs. measured Case/Ammann K_b.

Figure 35 shows the simulated Bomag E_{vib} under the signal type of Harmonic excitation, in which the deflection and soil-roller interaction force are assumed to follow the sinusoidal function. As results, the simulated E_{vib} also roughly follows a harmonic format. It should be noted that this result may not represent the IC exported results from field compaction since the deflection/force may not exactly follow the harmonic function. Meanwhile in real production, sampling will be used to “smoothen” the data (e.g. using the average smooth). These may explain the discrepancy between the simulation results and measurements from IC vendors.

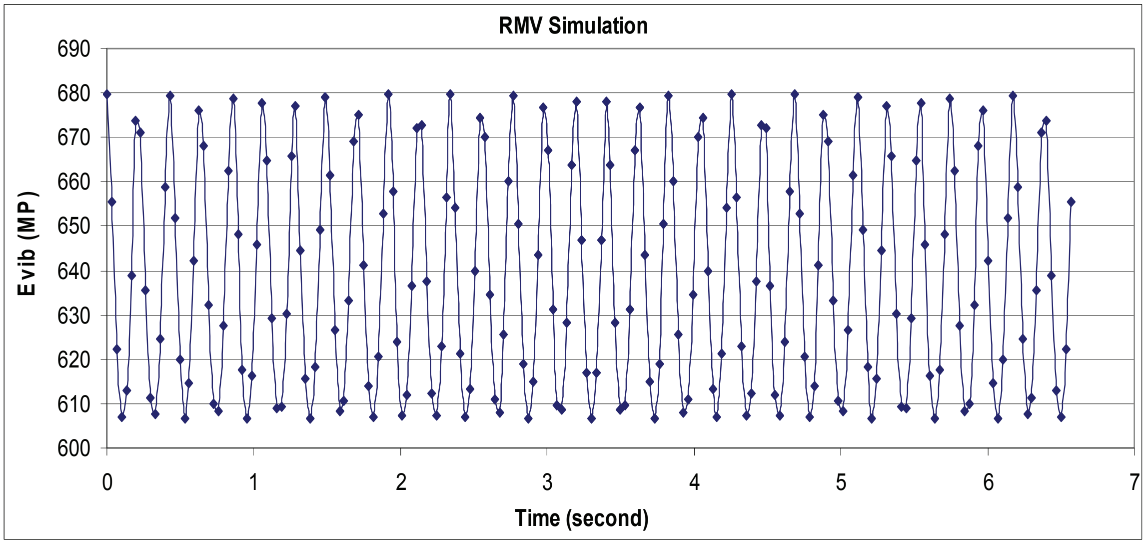


Figure 35. Simulated Bomag E_{vib}.

The simulation intends to check the possibility of harmonizing the IC models for the uniform industry standards. As shown here one of the main obstacles may be from the available but insufficient data/information offered by the production of roller vendors.

A Proposed New IC Model

As discussed before there are some key issues with existing IC models, including that the ICMV is not considering each respective pavement layer, and it is not converted to that at a reference temperature of HMA. Thus, a more advanced IC model is needed to address these issues. Here a new IC model was proposed as a future research. This new IC model will account for the following characteristics to address the main issues of existing IC models:

- Decoupled stiffness of each pavement layer, including that of asphalt mixture, base/subbase, and soil, respectively;
- The viscoelastic property of asphalt mixture and temperature;
- This proposed model is a mechanical model based on the roller-pavement dynamic interaction as shown in Figure 36.

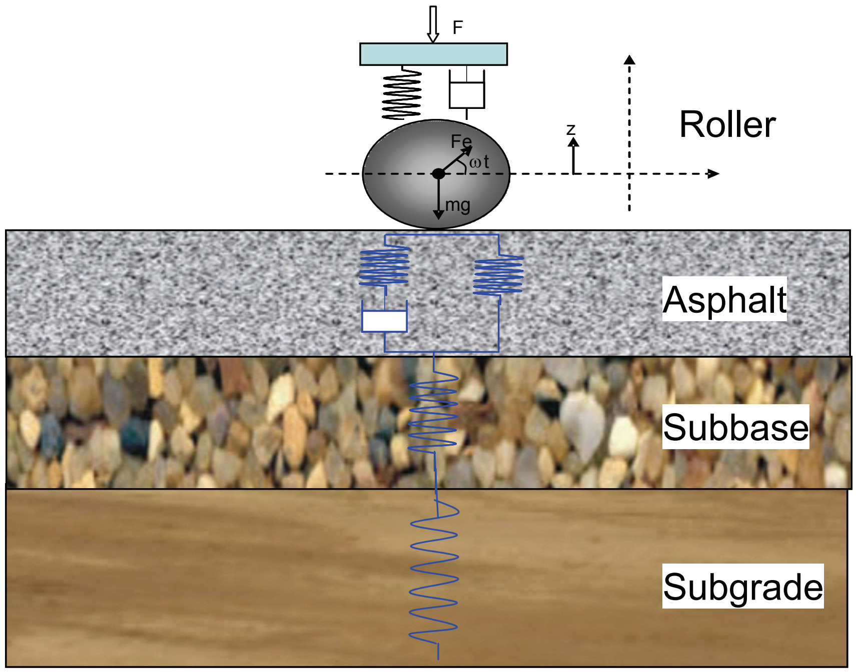


Figure 36. Proposed Roller-pavement Interaction model.

The asphalt mixture is regarded as a viscoelastic material effect (Xu and Solaimanian 2009), while the soil and base/subbase materials are regarded elastic for numerical simplicity. Some critical steps are summarized as follows:

1. The IC mapping would be performed on the soil and subbase/base before paving the fresh asphalt layer in order to capture the stiffness of each layer of the pavement from a "ground up" method;
2. With the measured displacements of the top HMA layer, the roller-pavement interaction force can be derived from the stress/force equilibrium of the roller-soil interaction system;
3. With the determined roller-pavement interaction force, the material property like the stiffness (k) value can be determined from the stress/force equilibrium of pavement structure;
4. With the k-E relationship, the E value can be determined from the computed k value; or
5. If a 2-Dimensional (2-D) analytical or numerical model such as a FE model is used for the pavement structure, the back-calculation can be performed to directly determine the moduli of pavement layer.

For the step 5 of 2-D model, a multi-layered pavement analysis program (e.g. ELSYM5) can be used, or a finite element (FE) model can be developed, to back-calculate pavement moduli. In addition, for step 1 if the IC mapping is not performed on the soil foundation and unbound layers underneath HMA, the back-calculation technique (e.g. optimization method) would be needed to determine the multi of the multi layers.

Chapter 3 Field Spot Tests for IC Implementation

Field spot tests are essential to IC Implementation to provide correlation to IC measurements. Various IC specifications have mandated specific field spot tests for verification tests, obtaining IC target values, and etc. The in-situ tests for soil/subbase and HMA recommended to be used in conjunction with ICMVs are described in the following sections. Note that the only "lab tests" that we'll include are Proctor (for soils) and bulk density tests of cores (for HMA).

In-Situ Spot Tests for Soils and Subbase

Several different in-situ testing methods were employed in this study to evaluate the in-situ soil physical and mechanical properties (see Figure 37):

- Zorn Light Weight Deflectometer (LWD) with a 200-mm diameter plate using 50 mm drop height to determine elastic modulus (E_{LWD-Z2}),
- DCP to determine California bearing Ratio (CBR),
- Calibrated nuclear gauge (NG) to determine moisture-density,
- Falling Weight Deflectometer (FWD) with a 300-mm diameter plate to determine elastic modulus (E_{FWD}),
- Static Plate Loading Test (PLT) with a 300-mm diameter plate to determine initial (E_{V1}) and re-load modulus (E_{V2}), and,
- D-SPA to determine low-strain elastic modulus (E_{D-SPA}).

Figure 37. Soil and Subbase in-situ test devices subgrade and flex base material.

Lightweight Deflectomer (LWD)

LWD tests were performed following manufacturer recommendations and the $E_{LWD\text{-}Z2}$ value was determined using Equation 4 (Zorn 2003). When padfoot roller was used for compaction, the material was carefully excavated down to the bottom of the pad to create a level surface for LWD testing.

$$E = \frac{(1-\upsilon^2)\sigma_0\gamma}{d_0} \times f_s \qquad (10)$$

Where E = elastic modulus (MPa), d0 = measured deflection (mm), v = Poisson's ratio, □0 = applied stress (MPa), r = radius of the plate (mm), fs = shape factor depending on stress distribution (assumed as 8/3 for flex base and □/2 for subgrade and lime stabilized subgrade materials).

Dynamic Cone Penetrometer (DCP)

DCP test was performed in accordance with ASTM D6951-03 to determine dynamic cone penetration index (DPI) and calculate CBR using Equation 5 (Webster et al., 1992, 1994). The DCP test results are presented in this report as CBR point values or CBR profiles. When the data is presented as point values, the data represents an average CBR of the compaction layer or the depth specified (e.g., $CBR_{0\text{-}250}$ represents 0-250 mm depth and $CBR_{250\text{-}500}$ represents 250-500 mm depth).

$$CBR = \frac{292}{DPI^{1.12}} \tag{11}$$

Falling Weight Deflectometer (FWD)

The FWD data were collected using a Dynatest. The test settings were as follows:

- Platen Size: 5.9" in radius (rigid plate)
- Geophone positions: 0, 12, 24, 36, 48, 60, 72 inches (7 sensors)
- Drops/Loads: 2 drops at targeting 6000 and 9000 lbs
- Field program: Dynatest R80
- File format: Dynatest F20.

$E_{FWD\text{-}D3}$ values were determined from the stiffness values using Equation 4 (f values were assumed as stated above).

Plate Loading Test (PLT)

Static PLT's were conducted by applying a static load on 300 mm diameter plate against a 6.2kN capacity reaction force. The applied load was measured using a 90-kN load cell and deformations were measured using three 50-mm linear voltage displacement transducers (LVDTs). The load and deformation readings were continuously recorded during the test using a data logger. The E_{V1} and E_{V2} values were determined from Equation 4, using appropriate stress and deflection values as illustrated in Figure 38 depending on the material/layer type. The D-SPA test developed by Nazarian et al. (1993) was used on the project. The resulting modulus values were determined by D-SPA field program.

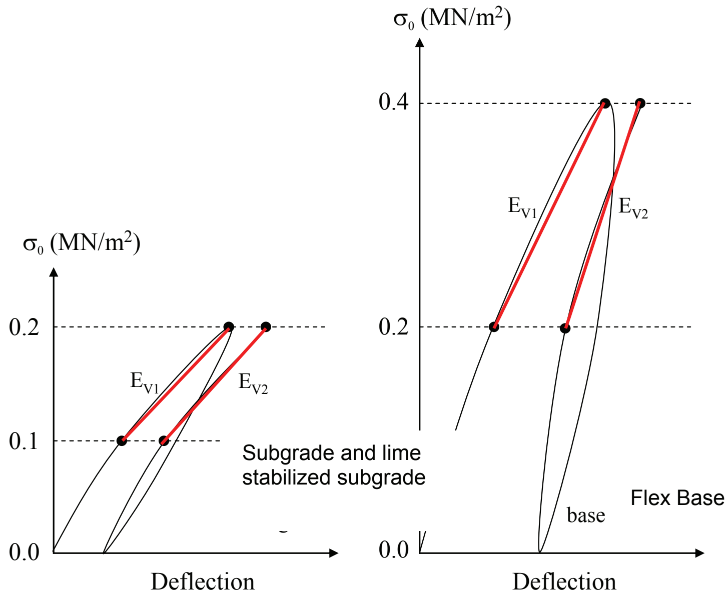


Figure 38. E_{V1} and E_{V2} determination procedure from static PLT for subgrade and flex base material.

In-Situ Spot Tests for HMA

Several different in-situ testing methods were employed in this study to evaluate the in-situ HMA physical and mechanical properties (see FIGURE 39):

Zorn and Dynatest Light Weight Deflectometers (LWD) to determine deflection, CBR, and elastic modulus, etc.,

Calibrated nuclear gauge (NG) to determine HMA NG density,

Non nuclear gauge (NNG) to determine HMA NNG density,

Falling Weight Deflectometer (FWD) with a 300-mm diameter plate to determine the deflection and back-calculate elastic modulus of pavement layers,

Portable Seismic Pavement Analyzer (PSPA) to determine low-strain elastic modulus;

Cores to determine the bulk density of HMA at laboratory.

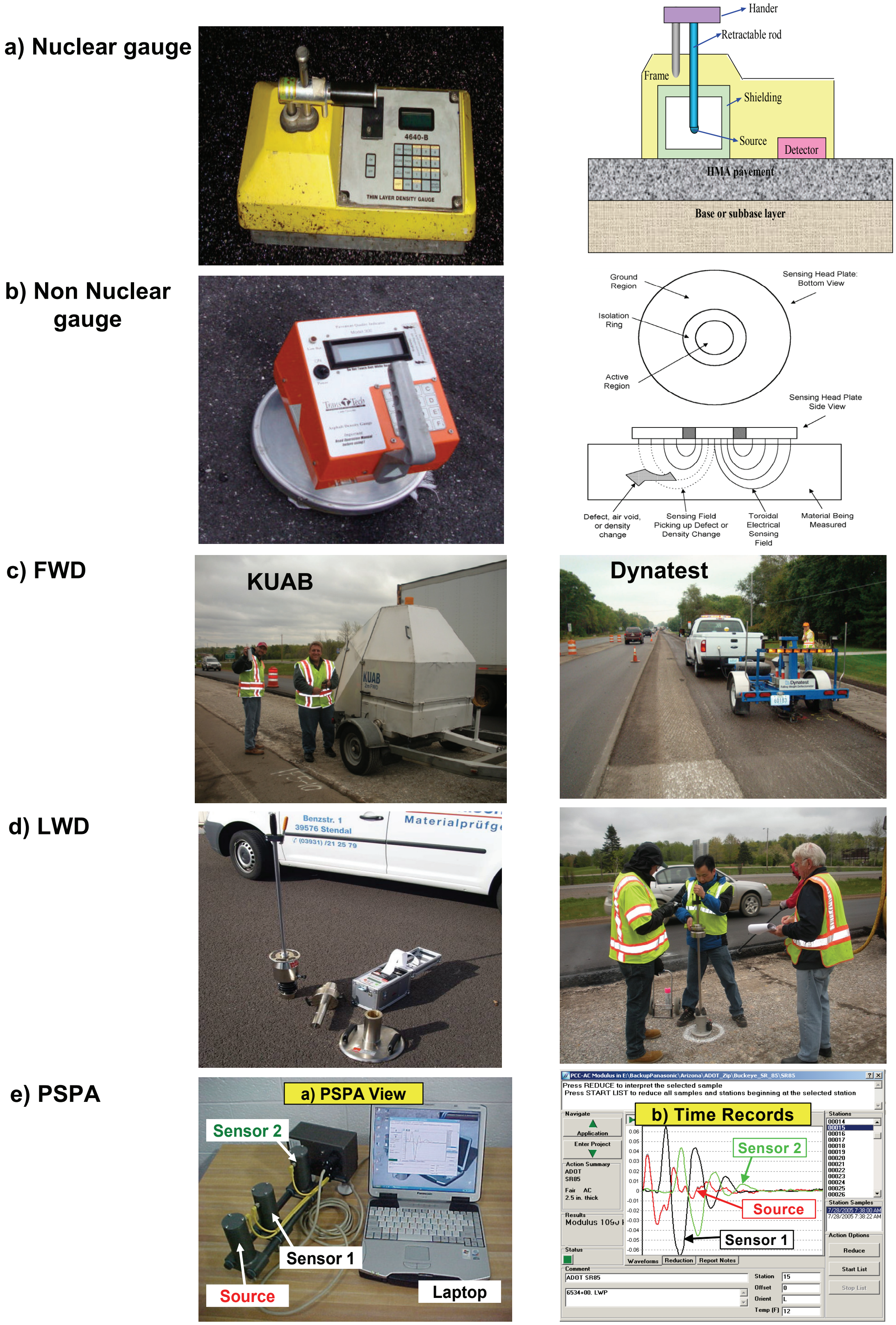


FIGURE 39. HMA in-situ test devices and mechanisms.

Falling Weight Deflectometer (FWD)

Primarily two machines are used in this project: the Dynatest FWD and the KUAB FWD. The Dynatest FWD test settings were as follows:

- Platen Size: 5.9” radius (rigid plate)
- Geophone positions: 0, 8, 12, 18, 24, 36, 48, 60, 72 inches (7 sensors)
- Drops/Loads: 4 drops each targeting 9,000 and 12,000 lbs
- Field program: Dynatest
- File format: F25, DDX, and MDB.

The KUAB 2m-FWD test settings were as follows:

- Platen Size: 5.9” radius (rigid plate)
- Geophone positions: -12, 0, 12, 18, 24, 36, 48 inches (7 sensors)
- Drops/Loads: 2 drops targeting 9,000 and 13,000 lbs
- Field program: KUAB 2m-FWD
- File format: FWD.

Deflections were measured at these sensors to achieve a deflection basin, and the moduli of pavement layers could be back-calculated from measurements using the FWD back-calculation programs.

Lightweight Deflectometer (LWD)

Primarily two LWD devices are used in these demonstration projects: Zorn 2000A and Dynatest LWD. ZFG 2000A was originally designed for testing existing HMA layers at ambient condition, but the most recent version is used for the testing on the hot HMA material. Further development is underway for testing on freshly paved HMA layers. The test settings were as follows:

- Drop weight: 10 kg or 15 kg;
- Drop height: 70 cm;
- Force: 10.6 kN;
- Pulse time: 17 ms.

The collected data for each drop includes the deflections with time series, the drop speed, etc. By using the deflection data collected from these sensors, the CBR of pavement layers were back-calculated by its own program.

For the Dynatest LWD, the electronics are interfaced to a handheld PDA via a wireless Bluetooth connection to record and store data. The test settings were as follows:

- Drop weight: 10 kg;
- Drop height: adjustble;
- Plate diameter: 300 mm.

The collected data for each drop includes the centre forces and deflections with time series, the centre peaking loading, etc. By using the deflection data collected from the geophone, the moduli of pavement layer were back-calculated by its own program.

Nuclear Density Gauge (NG)

The nuclear density gauge (NG) was used to measure the densities of HMA materials. The nuclear density gauge measures the in-place material density based on the gamma radiation. NG usually contain a small gamma source (about 10 mCi) such as Cesium-137 on the end of a retractable rod (University of Washington website, see reference).

The device consists of a hander, a retractable rod, the frame, a shielding, a source, and a Geiger-Mueller detector. The source emits gamma rays that interact with electrons in the HMA pavement through absorption, Compton scattering, and the photoelectric effect. The detector (situated in the gauge opposite from the handle) counts gamma rays that reach it from the source. Then, the received number of gamma rays by the detector is correlated to the density of HMA materials.

Non-Nuclear Density Gauge (NNG)

The Pavement Quality Indicator (PQI) developed by Transtech was used to measure in-situ HMA density. This technology is based on sensing field to changes in electrical impedance of the material matrix. The changes in electrical impedance are a function of the composite dielectric constant of the paving material and the air trapped in the voids of the material. Since the dielectric constant of air is much lower than that of the paving material, the combined dielectric constant increases because the percentage of air in the mix decreases as compaction increases. (Transtech, 2003) The PQI has been independently evaluated to correlate its readings to other devices.

Portable Seismic Property Analyzer (PSPA)

The seismic methods are based on generating and detecting stress waves in the pavement. A Portable Seismic Property Analyzer (PSPA) was used in this study for that purpose. The PSPA measures the average modulus of the exposed surface layers within a few seconds in the field (Nazarian et al., 2004).

The PSPA (see FIGURE 39) consists of two transducers (accelerometers in this case) and a source packaged into a hand-portable system, which can perform high-frequency (1 kHz to 50 kHz) seismic tests. The source package is also equipped with a transducer for consistency in triggering. The device is operable from a computer tethered to the hand-carried transducer unit through a cable that carries operational commands to the PSPA and returns the measured signals to the computer.

To collect data with the PSPA, the testing sequence is initiated and all the data acquisition tasks are handled automatically by the computer. The source, which is a computer-controlled solenoid, is activated several times to adjust the amplifiers and the dynamic range of the electronics. The voltage outputs (time records) of the three transducers from the final three impacts are saved and averaged for more reliability. These time records are used to determine the surface or Rayleigh wave velocity of propagation (VR) within the HMA layer. The Ultrasonic Surface Wave (USW) interpretation method is used to determine the Young's modulus, E, of the material through (Nazarian and Desai, 1993):

$$E = 2(1+\nu)\ \rho[V_R(1.13 - 0.16\nu)]^2 \qquad (12)$$

where ν is Poisson's ratio, and ρ is the density of the material.

In the absence of mix-specific dynamic modulus test results, empirical relationships can be used to adjust the E with temperature effect. This ratio at a temperature of 77°F is assumed to be equal to 3.2 (Aouad et al., 1993). The temperature varies from location to location during testing. The relationship suggested by Li and Nazarian (1994) can be used for adjusting the modulus of AC to a reference temperature of 77 °F in the absence of mix-specific master curve. That relationship is in the form of

$$E_{77^\circ} = E_t / (1.60 - 0.0078\, t) \qquad (13)$$

where E_{77} and E_t are the moduli at 77 °F and measured temperature (in Fahrenheit).

Chapter 4 IC Analysis and Report

IC Data

IC data are often massive and new to DOTs and industries. Thus, it requires practical guidelines and protocol to assist DOTs and industries to properly manage the IC data in order to provide support for decision-making and quality control/acceptance (QC/QA). Therefore, there is an immediate need to develop IC data management protocol to fulfill the needs. The following sections describe the recommended IC data elements in vendors' exported data and methods for viewing, analyses, and report of IC data.

Required IC Data Elements

IC data are often stored in proprietary formats. Therefore, it is very important to understand each vendor's IC software program to export IC data in ASCII or text format for post processing. The export would need to include "essential data information" (or meta-data) as described in Table 6 and "essential data elements" (for each measurement location) as described in Table 7.

Table 6: Essential IC Data Information

Items No.	Description
1	Section Title
2	Machine trade name
3	Machine type
4	Machine model
5	Drum width (m)
6	Drum diameter (m)
7	Machine weight (metric ton)
8	Name index of intelligent compaction measurement values (ICMV)
9	Unit index for ICMV
10	Reporting resolution for independent ICMVs – 90 degrees to the roller moving direction (mm)
11	Reporting resolution for independent ICMVs – in the roller moving direction (mm)
12	UTM Zone
13	Offset to UTC (hrs)
14	Number of IC data points

Coordinated Universal Time (UTC) is based on a twenty four hour clock. UTC is also known as GMT, or Greenwich Mean Time.

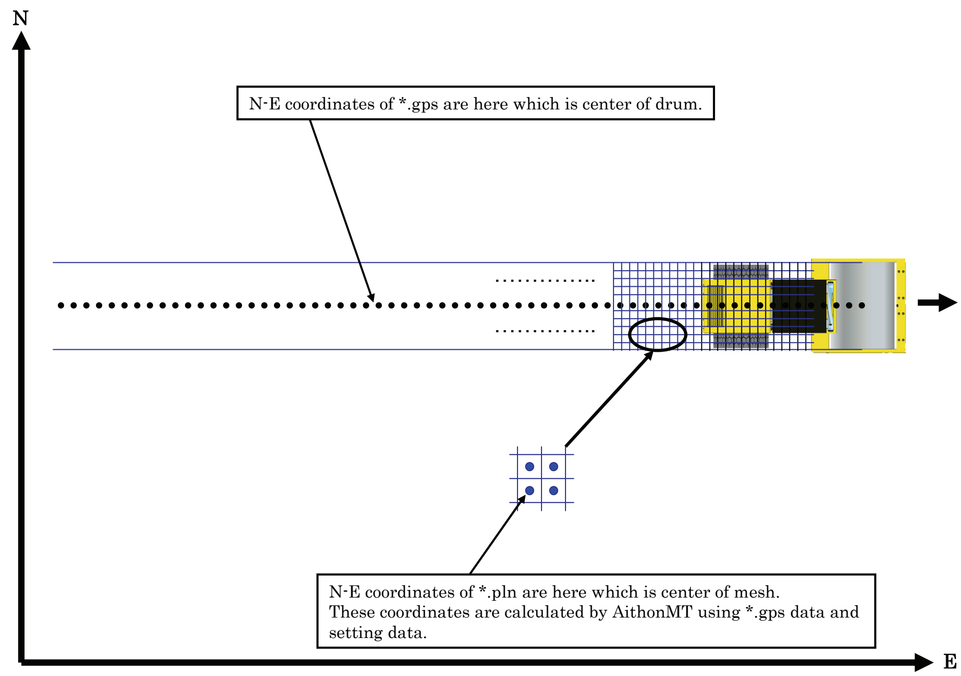
Table 7: Essential IC Data Elements.

Items No.	Data Field Name	Examples / Notes
1	Date Stamp (YYYYMMDD)	e.g. 20080701
2	Time Stamp (HHMMSS.S - military format)	e.g. 090504.0 (9 hr 5 min. 4.0 s.)
3	Longitude (decimal degrees)	e.g. 94.85920403
4	Latitude (decimal degrees)	e.g. 45.22777335
5	Easting (m)	e.g. 354048.3
6	Northing (m)	e.g. 5009934.9
7	Height (m)	e.g. 339.9450
8	Roller pass number	e.g. 2
9	Direction index	e.g., 1 forward, 2 reverse
10	Roller speed (kph)	e.g. 4.0
11	Vibration on	e.g., 1 for yes, 2 for no
12	Frequency (vpm)	e.g. 3500.0
13	Amplitude (mm)	e.g. 0.6
14	Surface temperature (^{o}C)	e.g. 120
15	Intelligent compaction measurement values	e.g. 20.0

IC Data Storage Types

IC vendors often store IC data in two different forms: *Time History Data* and *Post-Processed Data*.

- Time History Data: Time history data record the raw IC data during compaction operations. They normally include one data point at the bottom center of the drum at a point in time, usually at 10 Hz or approximately 1 ft/sec.
- Post-Processed Data: The Time History Data can be post-processed (sometimes in real-time for some vendors' solution) to produce data in finer meshes, often by duplicating data points over the drum width at a 1 ft. interval. Some vendors also provide users options to store the post-processed data in all-passes or proofing form.

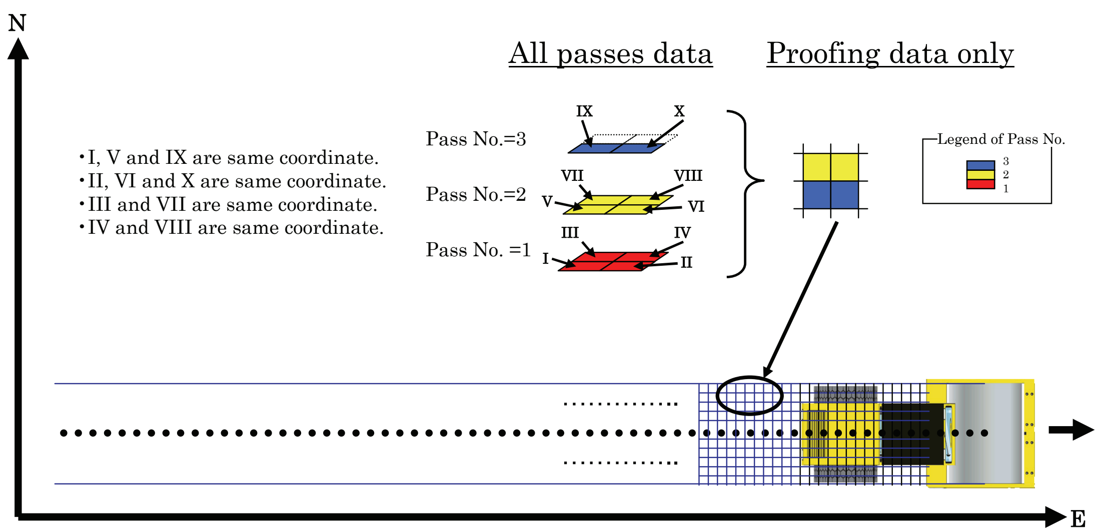


(Courtesy of Sakai)

Figure 40. Time history data vs. post-processed data (Sakai America).

The post-processed data can be in two sub-forms: *All-Passes Data* and *Proofing Data*. These two forms can be imported to Veda.

- All-Passes Data: As this term indicates, All-Passes Data include all passes within a given mesh (e.g., passes I through X in Figure 41).
- Proofing Data: The Proofing Data contain only the last passes with a given mesh (e.g., passes VIII and IX in Figure 41).



(Courtesy of Sakai)

Figure 41. All passes data and proofing data (Sakai America).

IC Data Comparisons

As of the time of writing, the following is a summary of the features for exported IC data from various vendors:

Table 8. Comparison of Exported IC Data.

Features	Ammann	Bomag	Caterpillar	Trimble	Sakai
Do not require export procedures	✓				
Filename extension(s) of exported data	log and xml	csv	csv (dBase option)	csv (dBase option)	*.pln and *.plns
Contains Geographic GPS (Long./Lat./Elev.)	✓				
Contains UTM or state plane grid data (Northing/Easting/Height)		✓	✓	✓	✓
Contains UTM zone or state plane references	✓ (in .xml)				
Contains all-passes data	✓	✓	✓	✓	✓
Contains proof data	?	?	?	?	✓
Contains pass count information					✓
Default data mesh size (h x v)	1.25m X 0.5m	0.3m X 0.3m	1.0m X 0.15m	1.0m X 0.15m	0.3m X 0.3m

Notes:

- Whether the exported data from various vendors contains "proofing data" is not yet confirmed by the above vendors except Sakai.
- The data mesh size is the horizontal and vertical scale of a data point (assuming a square area) that is represented on IC maps. The default data meshes were determined by comparing the IC maps by vendors' implementation with those from Veda. Confirmation of the actual data mesh sizes is still needed from the vendors.

Due to evolving nature of IC vendors' IC systems and software, this document will be updated as needed. The goal is to provide exact procedures for users to follow in order to produce compatible formats of Veda. Therefore, the subsequent viewing, analysis, and reporting can be standardized in national standards (e.g., AASHTO) and state specifications.

Viewing of IC Data

The Sakai AithonMT®, Bomag BCM Office®, Case/Ammann ACEplus®, Dynapac Dynamic Compaction Analyzer (DCA) ® software were used to extract the raw IC data. The Veda tool, developed by the Transtec Group, was also used to view, analyze, and report the IC geospatial data. Figure 42. shows a screen shot of the Veda results of the demonstration site and color–coded ICMV map for the Georgia HMA demonstration project. The Veda can also be used to perform data analysis and produce reports, including basic statistics and geostatistics, correlation of in-situ tests, and compaction curves, etc.

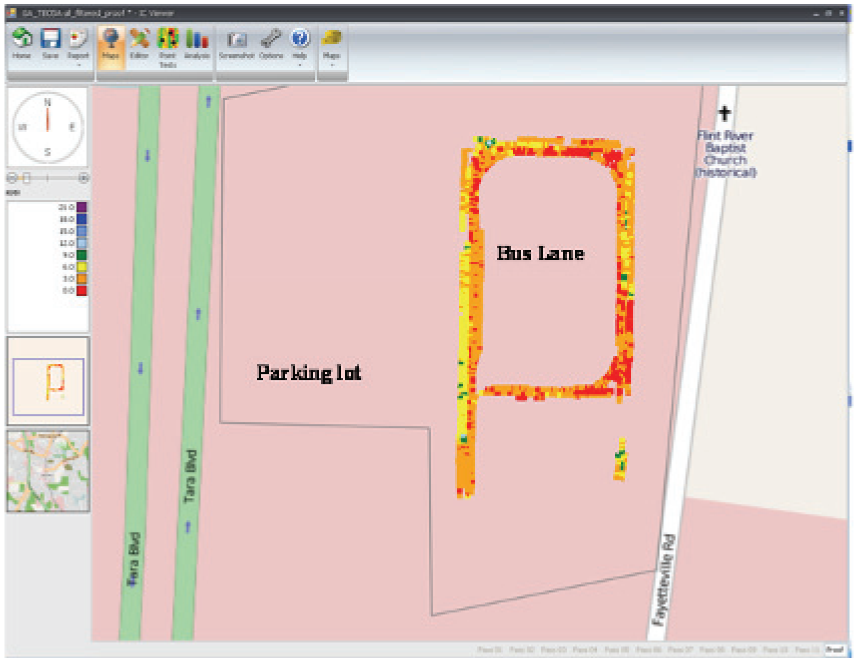


Figure 42. A Screen Shot of the Veda tool (GDOT IC demonstration).

Basic Statistics and Geostatistics

Basic Statistics

The conventional statistics, including the mean, standard deviation, and coefficient of variance (COV) are used to evaluate the roller measurements like ICMV, temperature, frequency, etc.

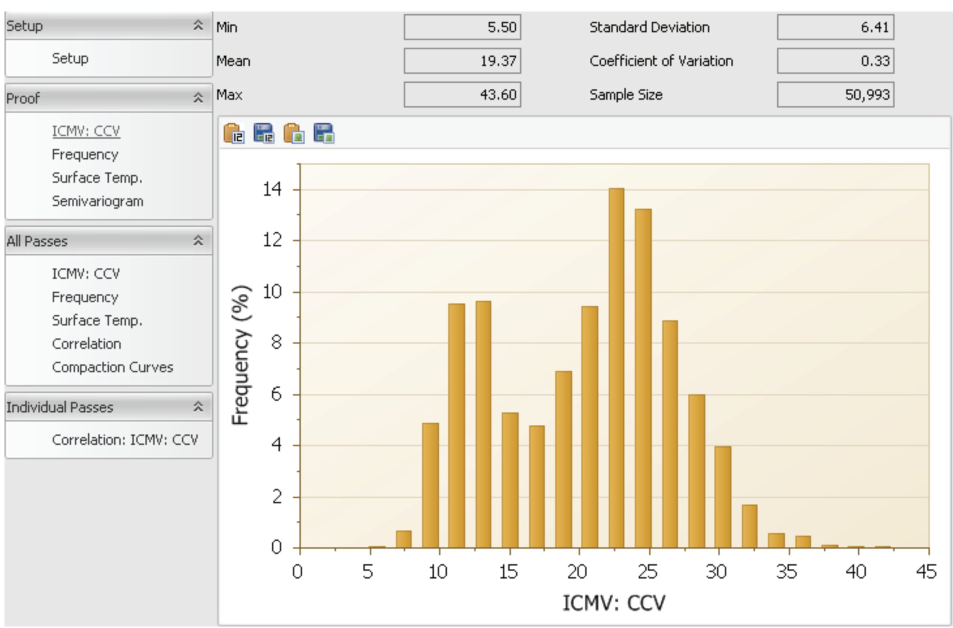


Figure 43. Basic univariate statistics and histogram report in Veda.

Geostatistics - Semi-variogram

Spatially referenced ICMVs can be used to quantify "uniformity" of compacted materials. Vennapusa and White (2010) demonstrated the use of semivariogram analysis in combination with conventional statistical analysis to effectively evaluate uniformity during earthwork construction. Figure 44. describes a typical semivariogram, as a plot of the average squared differences between data values as a function of separation distance (Isaaks and Srivastava 1989). The exponential model is used in this research for fitting the semivariogram results. Three important semivariogram parameters are: sill ($C+C_0$), range (R), and nugget (C_0) (Figure 44.). A low "sill" and longer "range of influence" represent best conditions for uniformity, while the opposite represents an increasingly non-uniform condition (Isaaks and Srivastava 1989, Clark and Harper 2002).

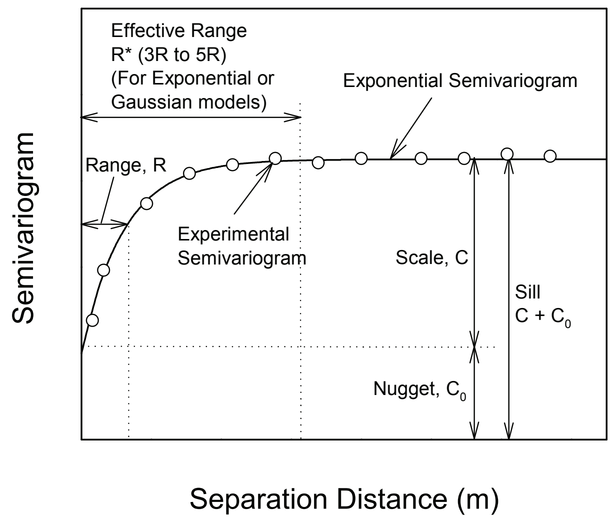


Figure 44. Semivariogram and the Fitted Parameters.

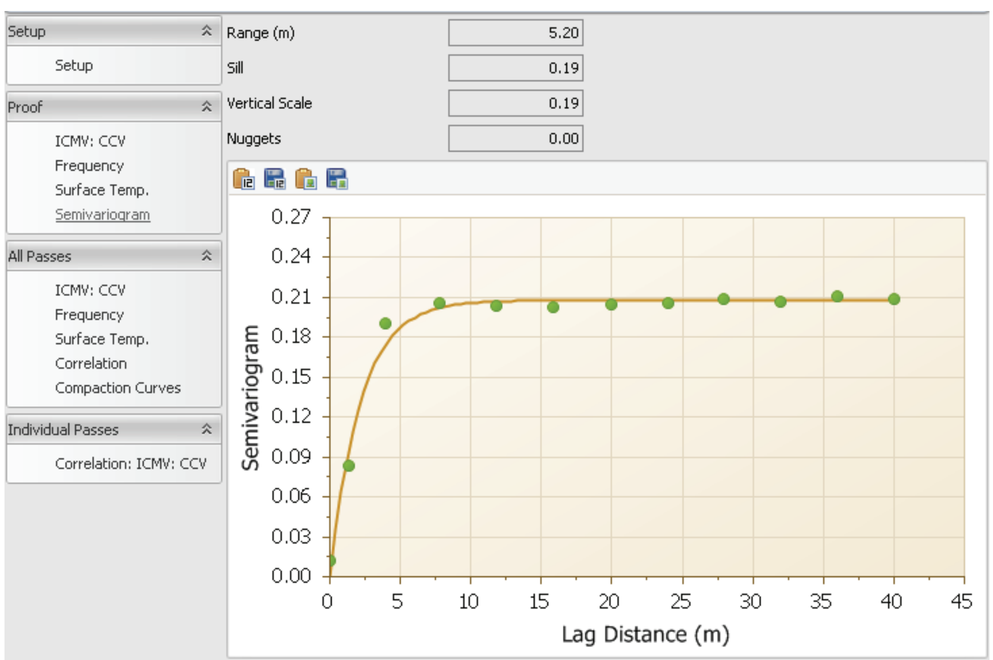


Figure 45. Semi-variogram report in Veda.

Compaction Curves

Generally, roller operators perform a certain number of roller pass based on experiences and measured NG densities at discrete locations. In this way, over or under compaction may occur without knowing the material property during compaction. With the IC technology, the compaction pattern can be easily reviewed and evaluated. The mean ICMV of a compacted area can be computed for each roller pass with the Veda. Then, the optimum roller pass number based on the target ICMV can be readily identified.

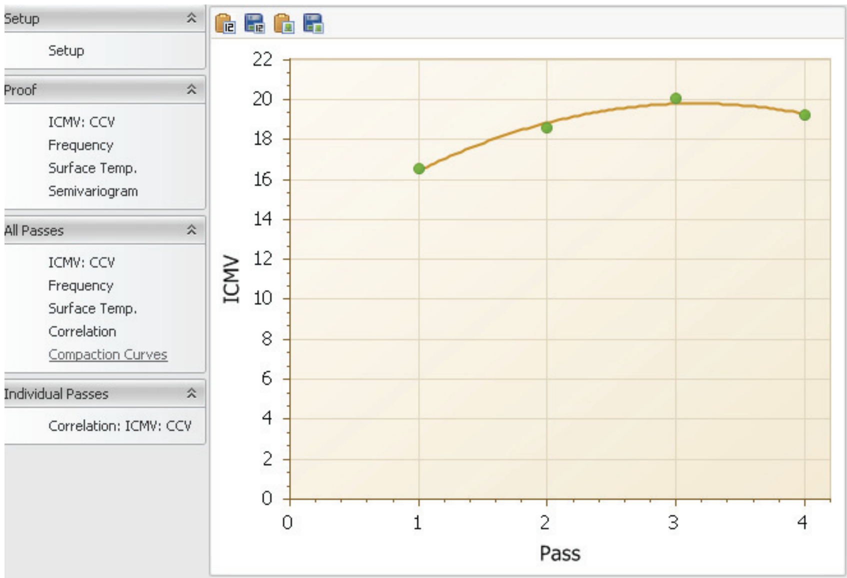


Figure 46. Compaction Curve Report in Veda.

Correlation Analysis

Univariate linear regression

ICMVs are correlated with in-situ measurements using the univariate linear regression method. To correlate with the in-situ test spot measurements, ICMV at any specific spot is a mean value of those data points fallen within a circled area with a diameter of roller width and the center at the spot, rather than a single point value at that test spot. Using a mean value will reduce the influence of variability.

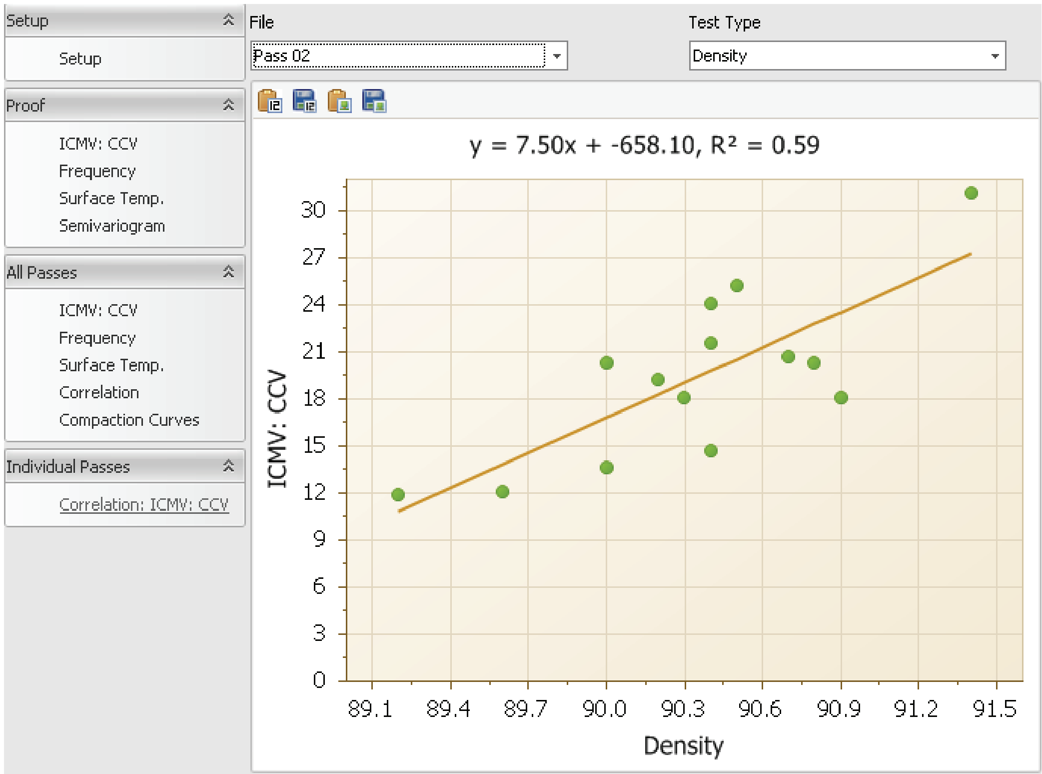


Figure 47. Correlation Report in Veda

Multivariate linear regression

The multivariate linear regression is also performed on a few demo samples for both soil/subbase and HMA demonstration projects, to evaluate the influence of multiple factors on ICMVs. In this analysis, for the soil/subbase compaction the influences of soil moisture content and vibration amplitude are evaluated, while for HMA compaction the influences of HMA temperature, frequency, underlying layer ICMV and frequency are evaluated. E.g. for the soil/subbase and HMA compaction the multi lineal models are presented as follows:

Soil/subbase: $RMV = b_0 + b_1 \cdot MV + b_2 \cdot a + b_3 \cdot w$ (14)

HMA: $RMV = b_0 + b_1 \cdot MV + b_2 \cdot T + b_4 \cdot F + b_3 \cdot RMV_{sub} + b_4 \cdot F_{sub}$ (15)

Where,

ICMV = roller measurement value,

b0 = intercept,

b1, b2, b3, and b4= regression coefficients,

a = amplitude (mm),

w = moisture content (%),

T = HMA temperature (^{o}F),

F = vibration frequency on HMA (vpm),

Fsub = vibration frequency on subbase (vpm).

Further information on the IC data analysis and reporting can be found from the MnDOT/FHWA IC Data Analysis Tool project.

Chapter 5 Demonstration Projects Overview

Field demonstration projects are the major work under the FHWA/TPF IC study. Key elements of the field demonstration include on-site training of TPF DOT and contractor personnel, comparison of IC roller technologies to traditional compaction equipment and practices, correlating IC roller measurements to in-situ spot test measurements, mapping the existing support to understand the influence of underlying layer support, selecting the appropriate machine operation parameters (e.g., speed, amplitude, frequency, etc.), and managing and analyzing the IC and in-situ test data.

The goals of the field demonstration project are to:

- Demonstration of soils/subbase and HMA IC technologies to TPF DOT personnel, contractors, etc.;
- Develop an experienced and knowledgeable IC expertise base within TPF DOTs;
- Assisting TPF DOT in the development of IC quality control (QC) specifications for the soils/subbase and HMA pavement materials, and
- Identification and prioritization of needed improvements and further research for IC equipment and data analysis.

The objectives of the field demonstration project are short-term goals for introducing soils and HMA IC technology to TPF DOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control. There are thirteen full scale field demonstrations and five smaller scale ("mini") demonstration conducted under this study in 13 states (see Figure 48).

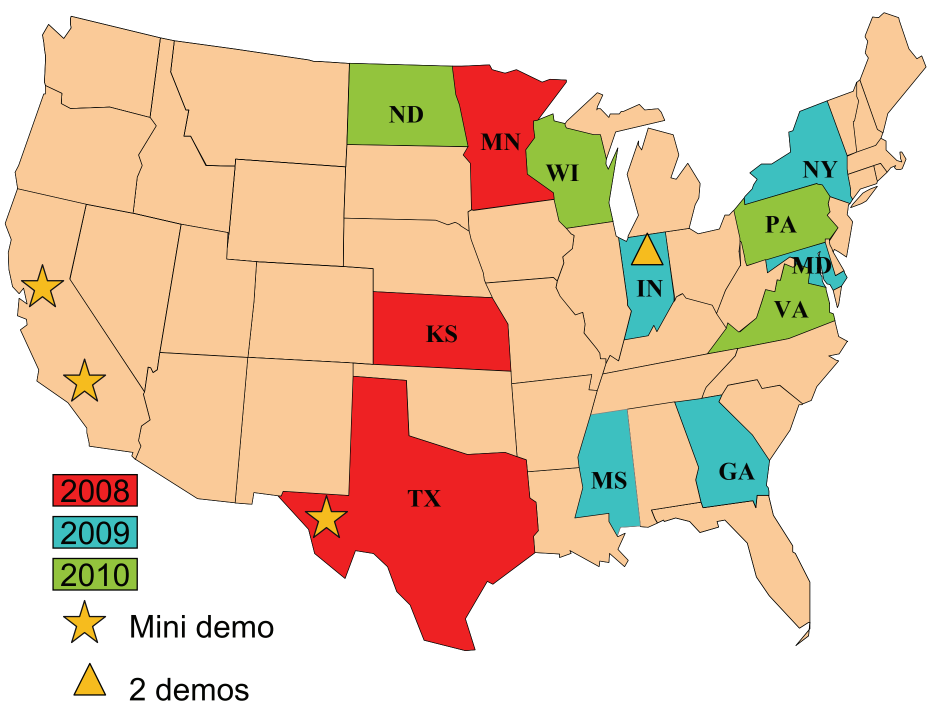


Figure 48. Distribution and Schedule of IC Field Demonstrations.

Soils and Subbase IC Demonstrations

Demonstration Activities

Table 9 summarizes the FHWA/TPF Soil/Subbase IC demonstration activities, including the project locations, IC demonstration elements, machines, and in-situ tests. Detailed information is presented in the respective reports (http://www.intelligentcompation.com). For some demonstration sites, the in-situ tests were measured following each breakdown roller pass.

Table 9. FHWA/TPF Soil/Subbase IC Demonstration Activities.

Location	Highway	IC Demonstration	Test beds	Machine	In-situ Tests
Fort Worth, TX	FM 156	Compaction on embankment, then the treated subbase and flex base	TB1,3: subgrade;TB2: flex base and lime stabilized subgrade;TB4,TB6/7: flex base;TB5: lime stabilized subgrade.	Case/Ammann, Dynapac smooth and padfoot drums	LWD,CP,NG,FWD,PLT,D-SPA
Springville, NY	219	Compaction on embankment subgrade and subbase materials	TBs1-2: embankment with underling by tire fill;TB3,8: embankment;TBs4-7,9: gravel subbase for production;TB10:1 or 2m trenches.	Caterpillar;Bomag AFC and manual modes	LWD,DCP,NNG,FWD,PLT,BCD
Waynesboro, MS	US 84	Compaction on granular (sandy) and cement treated subbase and soil with AFC and manual model	TB1,3:granular base;TB2,8: cement treated granular base;TB4: granular subgrade;TBs5-7,9: cement-treated granular subgrade;	Caterpillar,Case/Ammann AFC and manual	LWD,DCP,NG,FWD, PLT
Pleasanton, KS	US 69	Compaction on the cohesive soil (weathered shale and lean clay)	TBs1-5:calibration test strips; TB3: production construction with 7 lifts of weathered shale and lean clay fills on sg; TBs6-7:production area with stiff weathered shale and clean clay sg	Caterpillar and Sakai single-drum padfoot rollers	LWD, DCP,NG, FWD,PLT
Marmarth, ND	US 12	Compaction on silty subgrade and salvage base	TBs1-4: silty subgrade: 5-7: salvage base	Caterpillar padfoot and smooth drums	LWD, DCP, CBR, NG, FWD, and BST.
West Lafayette, IN	SR 25	Compaction on cohesive soil and granular materials	TBs1-3,6: sandy embankment fill;TB4-5:silty clay	Caterpillar single drum	LWD, DCP, FWD

Hot Mix Asphalt (HMA) IC Demonstration

Demonstration activity

Table 10 summarizes the FHWA/TPF HMA IC demonstration activities, including the project locations, IC demonstration elements, and in-situ tests. Detailed information is presented in the respective reports (see http:www.intelligentcompaction.com). For the in-situ tests, the NG/NNG density may be measured following each breakdown roller pass or the finishing roller pass only. The ICMV and in-situ measurements following each breakdown roller pass is called data for "all passes", and that following the last breakdown roller or finishing roller only is called "proof data", this concept will be used in the following study.

Table 10. FHWA/TPF HMA IC Demonstration activities.

Location	Highway	IC Demonstration	IC Rollers	In-situ Tests
Kandiyohi, MN	Route 4	Mapping subbase, HMA base and wearing course paving	Sakai	LWD,NG,Core
Springville, NY	219	Mapping subbase, 1st and 2nd lift HMA base, and binder course paving	Sakai	NG
Waynesboro, MS	US 84,	Mapping the subbase, HMA base paving	Sakai	FWD, NG
Frederick, MD	US 340	Mapping the milled existing HMA layer, SMA[1] overlay paving	Sakai, Bomag	FWD,NG/NNG,Core
Clayton, GA	Park & side	Mapping the GAB base, HMA intermediate and surface layer paving	Sakai	FWD, LWD,Core
West Lafayette, IN	US 52	Mapping the milled HMA layer on PCC slab, HMA overlay paving	Sakai, Bomag	NG,NNG,Core
Mosinee, WI	IH 39	Mapping the rubblized PCC base, HMA base, 2nd lift, and surface layer paving	Sakai	FWD, LWD, NG
El Paso, TX	FM 1281	Mapping the milled HMA surface, HMA surface paving	Sakai	FWD, LWD,NNG
Summerhill, PA	SR 53@SR 219	Mapping the milled HMA surface, paving HMA binder and wearing courses	Sakai, Volvo	LWD, NG
Markham, VA	I-66	Mapping the milled HMA surface, paving HMA surface	Sakai, Volvo	LWD, NG
La Habra, CA	residential area	Compact HMA overlay	Sakai	NG

Note: 1. stone matrix asphalt; 2. gradated aggregate base.

Recommendations

- Validation of the IC GPS setup prior to the compaction operation using a survey grade GPS hand-held unit on the same position of the IC roller GPS receiver is crucial to provide precise and correct measurements.
- In order for in-situ test locations to be accurately located and compared to IC data at precise locations, in-situ test locations must be established using a hand-held GPS "rover" unit that is tied into the project base station and offers survey grade accuracy.
- Obtaining IC measurements (mapping) of the underlying layers prior to the paving of upper layers is highly recommended in order to better identify possible weak spots and facilitate the interpretation of the measurements on the asphalt surface layers.
- Long term pavement performance monitoring is recommended in order to identify performance trends that may relate to ICMV values.
- Some data post-process should be conducted to evaluate the effectiveness of the IC data. For example, due to the uncertainty and acceleration of IC rollers, some measurement values maybe outliers and would be filtered out for data analysis purpose.
- A standardized IC data storage format, an independent software tool, and detailed data requirements to facilitate the management (viewing and analysis) of IC data (from all vendors) and related in-situ/lab test results are strongly recommended to be developed. The research team is currently developing guidelines for IC data collection, storage requirements, and data processing, a prototype of an independent software tool. An update on this will be published as part of the 2009 annual report.
- Further investigation on a global scale (e.g., segment-by-segment analysis of entire paved sections) is recommended to provide guidance of usage of IC mapping data on existing subbase and base with subsequent IC measurements during HMA paving (such as setting a target ICMV value from test trip data based on the onsite support condition and asphalt job mix). Nonetheless, the IC demonstration on this project site provides evidence that roller passes, temperatures, and measurement values (ICMV) can be tracked.
- To overcome GPS signal shadows at hilly areas, there are three alternatives: (1) Select a proper location for the GPS base station, then use signal repeaters to fill in the GPS "shadow areas". (2) Use virtual reference station (VRS) as along as there are good cellular reception. (3) Use internet base station and make use of server/client systems to transmit the signals.

Chapter 6 Demonstration Projects for Soils IC

This chapter summarizes the results from all soils/subbase IC demonstrations under the FHWA/TPF IC project.

State Demonstration Results

Texas IC Demonstration

The field IC demonstration was performed in Fort Worth, Texas from July 20 to 25, 2008 and an open house was conducted on June 24, 2008. The project was to relocate the highway to accommodate Alliance Airport's runway extension on the north end. The Case/Ammann single-drum padfoot and smooth drum vibratory rollers and the Dynpac single-drum smooth drum vibratory roller are used for compaction. The demonstration site and material of interest (including Type II cohesive subgrade soil, Type III granular base – termed flex base at TxDOT, and Type V stabilized materials). Figure 49 displays the IC demonstration site and materials.

The objectives of this demonstration project are short-term goals for introducing the soil IC technology to the TxDOT and contractors who may not have prior experience with IC, in order to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the soil and stabilized base material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Clay subgrade

Flex base and lime stabilized subgrade

Ponding of lime slurry on the scarified subgrae

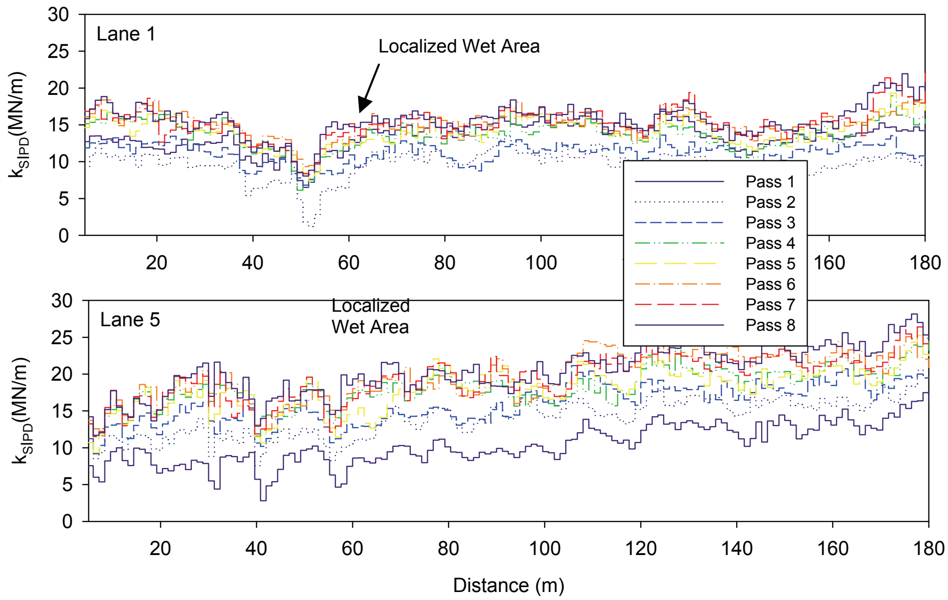
A day after compaction on flex base

Figure 49. Texas soil/subbase demonstration.

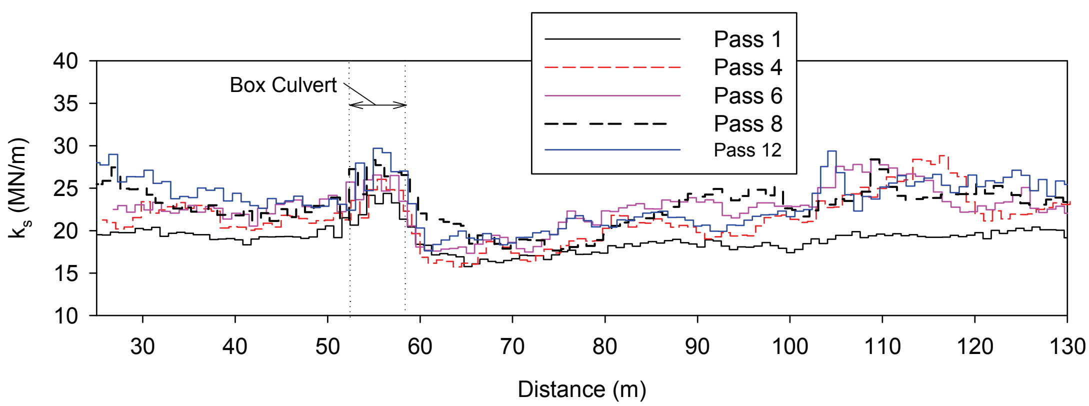
Major Findings

- It is the first time, based on published literature, that padfoot IC rollers were demonstrated to produce excellent compaction curves for clay materials, i.e. increasing compaction levels with increasing number of passes before leveling off. The compaction curves can be used to determine target stiffness values of compacted materials.
- IC rollers can effectively identified soft spots (e.g. wet zone that can not be compacted, see Figure 50a) and hard materials (e.g. box culvert, see Figure 50b) in underlying

pavement layers.



(a) Soft sports: kSIPD measurement from different passes on TB1 lanes 1 and 5 (nominal a = 0.8 mm, f = 35 Hz, and v = 3.5 km/h).



(b) Hard spots: kS$_I$PD measurements from different passes on TB 5 lane 3 calibration test strip (nominal a = 1.0 mm, f = 35 Hz, and v = 3.5 km/h).

Figure 50. Soft and hard spots identified by IC rollers.

- Both Case/Ammann and Dynapac roller measurement values (ICMVs) captured the wide variation in stiffness of the compacted lime stabilized subgrade and flex base materials (see Figure 51).

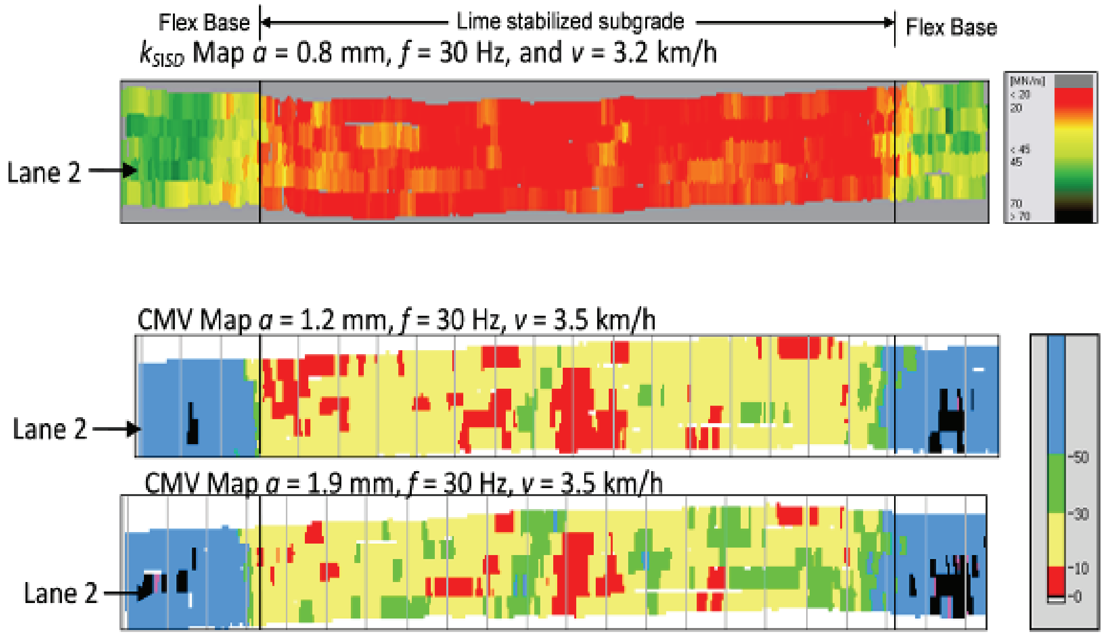


Figure 51. Comparison between Case/Ammann kSISD and DynapacCMV maps–Test Bed 2 flex base and lime-stabilized subgrade.

- Roller measurement values by the Case/Ammann rollers are influenced by soft zones in the compaction layer as well as that below the compaction layer.
- In-situ measurements using the calibrated moisture-density nuclear gauge, dynamic cone penetrometer (DCP), and light-weight deflectometer (LWD) do not match well with ICMVs which were influenced by the underlying soft layers.
- Plate bearing test (PLT) and falling weight deflectometer (FWD) produce better correlation with the ICMVs.
- As a result of increasing flocculation and agglomeration in flex base, the laboratory moisture-density relationships indicate that the optimum moisture content increases and the maximum dry unit weight decreases with time (Figure 52). This would provide strong evidence by setting proper target compaction values based on the state of the material.

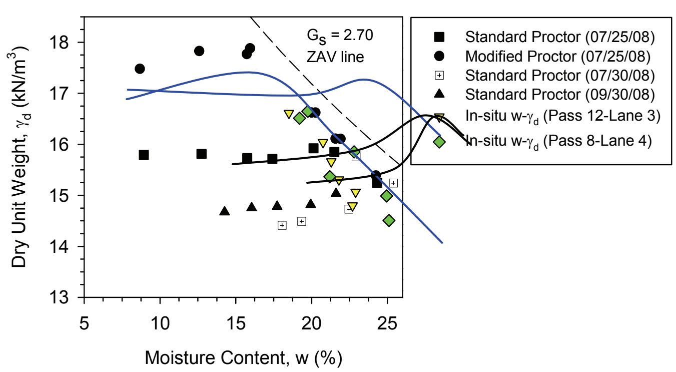


Figure 52. Comparison of laboratory Proctor curves and in-situ w-γ_d measurements – TB 5 lime-stabilized subgrade material.

- Test areas that indicate similar univariate statistics (e.g. coefficient of variation,COV) exhibit significantly different geostatistical semi-variograms. It demonstrates the advantage of using spatial statistics for a better characterization of non-uniform conditions than using univariate statistics.
- Lane 4 which was compacted in AFC mode with amax = 2.4 mm showed roller jumping within a 10 m zone as indicated on Figure 53. For this case the AFC mode did not necessarily prevent roller jumping or reduce the vibration amplitude. The CMV and BV measurement values on all lanes were repeatable (see Figure 53).

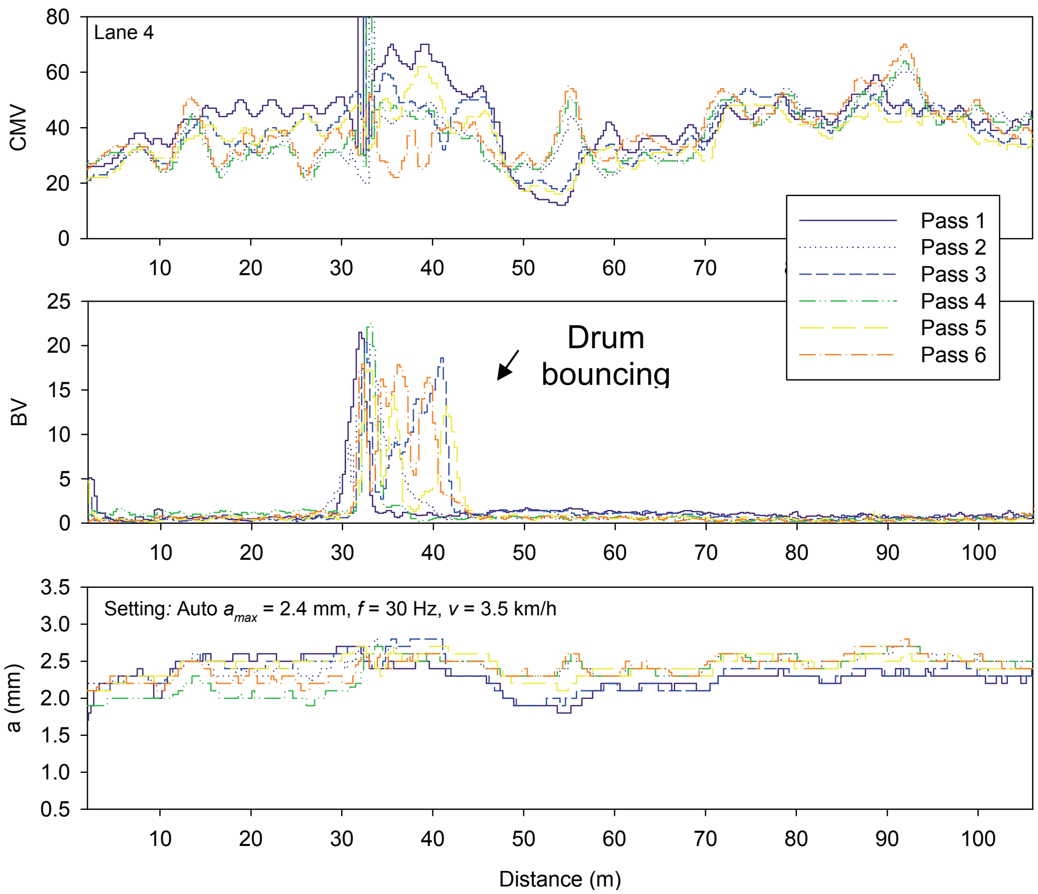


Figure 53. CMV, BV, and a values for compaction passes on lane 4 of TB6 flex base material.

- Smooth drum and pad drum achieves similar compaction effect as shown in Figure 54.

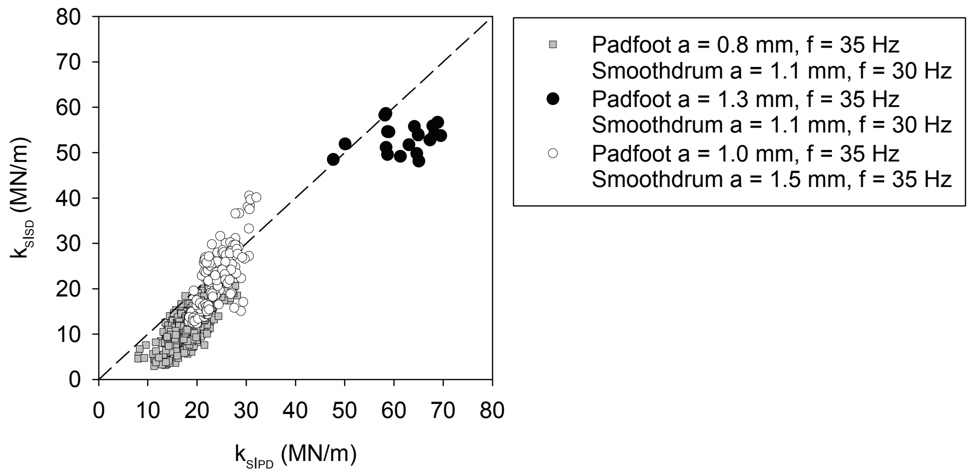


Figure 54. Relationship between kSIPD and kSISD measurements.

- The ICMV resulting from auto control and manual control has similar trend, but the auto control results in higher CMV values as illustrated in Figure 55.

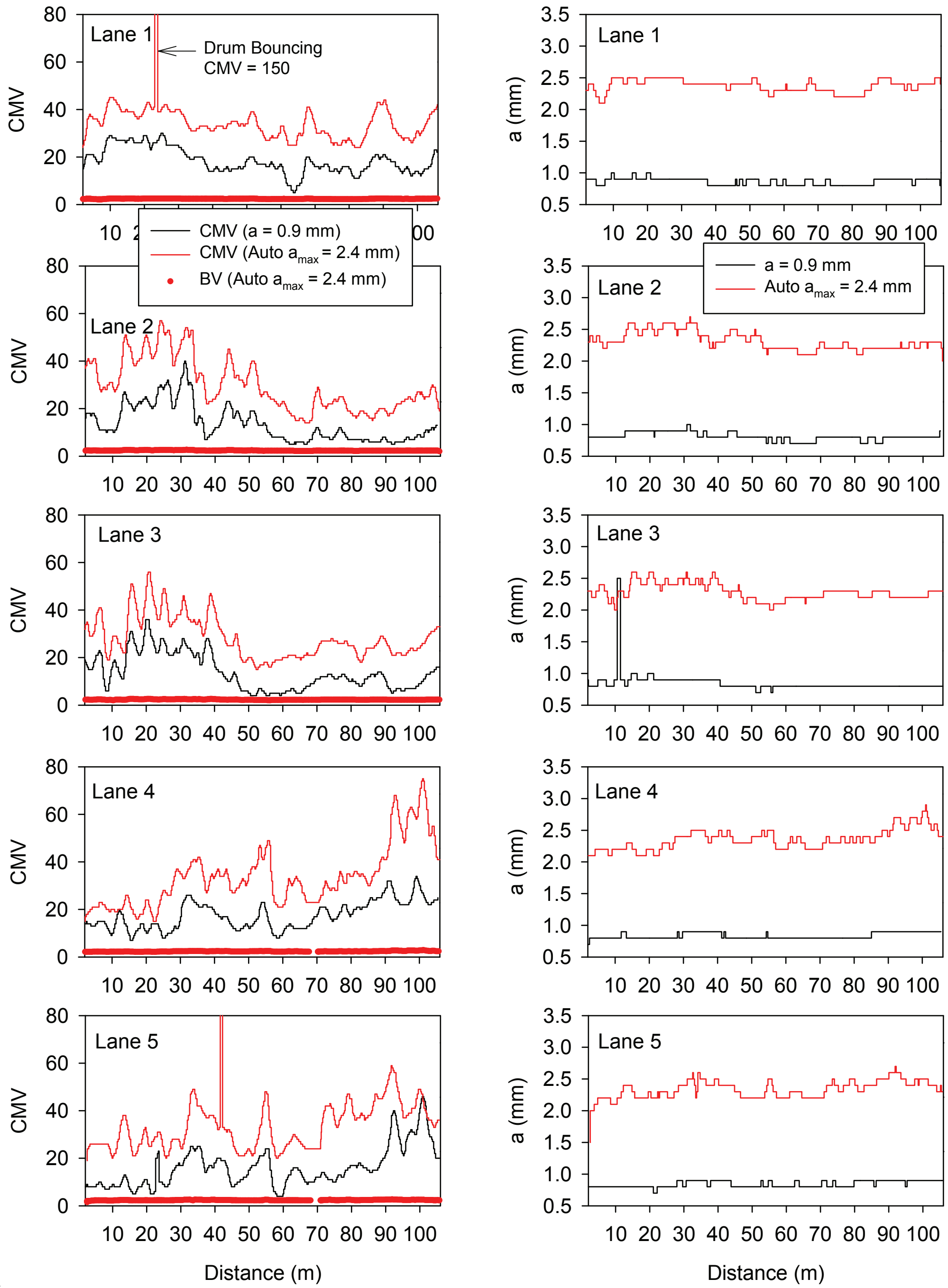


Figure 55. Comparison between CMV measurements in manual and automatic settings (nominal f = 30 Hz, v = 3.5 km/h).

Future research

- Relating full depth (up to 1 m) DCP-CPR profile with ICMVs should be further investigated.
- Based on the measurements from this demon, future in-situ testing should consider multiple measurements over the drum width for conditions where this type of

heterogeneity exists. Further study on the averaging scheme in correlation and calibration process using geostatistical approach is recommended.

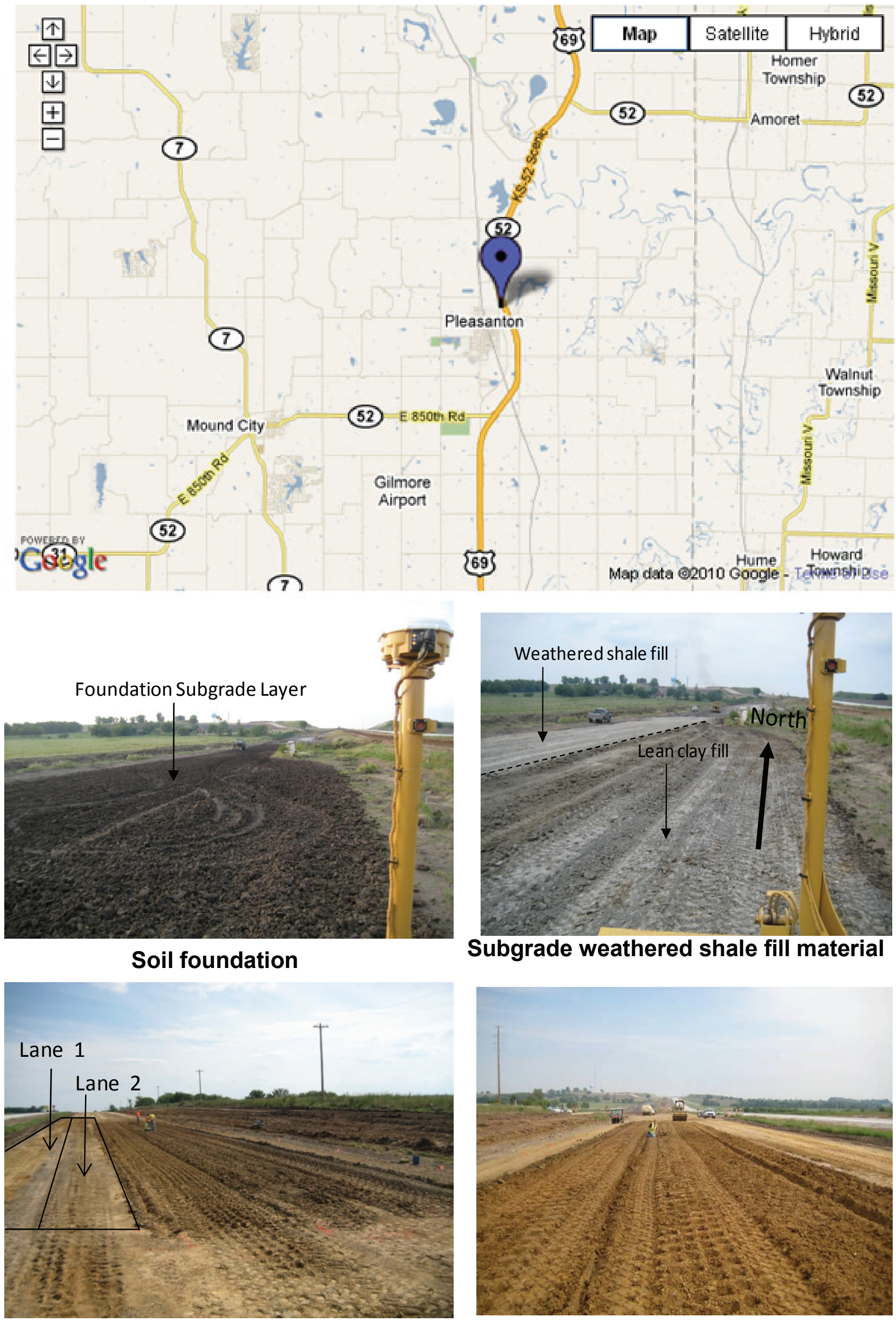
- Better correlations were observed with EFWD, EV1, EV2, and ELWD values (with R2 > 0.5) compared to ED-SPA and γd. Relationships with ED-SPA show encouraging trends in the data, however. The Case/Ammann roller integrated stiffness (kb) values were sensitive to moisture content of the compaction layer material. Further investigation on using D-SPA to correlate ICMVs is recommended.
- The Dynapac CMV measurements are influenced by the vibration amplitude and show that increasing amplitude generally causes an increase in CMV on the material studied in this report. But further investigation is warranted.
- Comparison between Case/Ammann padfoot roller measurements (k_{SISD}) and padfoot roller measurements (k_{SIPD}) show that kSIPD values are generally greater than k_{SISD}. Note that the values were obtained at different amplitude settings. Future studies may focus on obtaining correlations from the two measurements at similar amplitude settings. Comparison padfoot penetration depth measurements in conjunction with k_{SISD} and k_{SIPD} measurements in future studies may help provide additional insights into the correlations between k_{SIPD} and k_{SISD} values. Nevertheless, the trends observed between k_{SIPD} and k_{SISD} are encouraging and the padfoot roller measurements demonstrate similar advantages as the smooth drum roller measurements.

Kansas IC Demonstration

The IC demonstration site is a part of the US 69 expansion project in Pleasanton, north of Fort Scott, KS. The field IC demonstration was performed from August 16 to 22, 2008 and an open house was conducted on August 21, 2008. The materials include the Type II cohesive subgrade soils. Figure 56 summarizes the IC demonstration site and materials.

This is an IC field demonstration conducted on US 69 which is located near Pleasanton, Kansas from August 17 to 25, 2008 using Caterpillar and Sakai single drum IC rollers. Key attributes for this field demonstration included on-site training of DOT and contractor personnel, comparison of IC roller technologies to traditional compaction equipment and practices, correlating IC roller measurements to in-situ spot test measurements, evaluating machine operation parameters (e.g., speed, amplitude, frequency, etc.), and managing and analyzing the IC and in-situ test data.

The objectives of this demonstration project are short-term goals for introducing the soil IC technology to the KSDOT and contractors who may not have prior experience with IC, in order to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the soil and stabilized base material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.



Soil foundation

Subgrade weathered shale fill material

Stiff lean clay subgrade

Stiff lean clay subgrade

Figure 56. Kansas soil IC demonstration.

Major Findings

- Results indicate that the Sakai CCV and Caterpillar MDP measurement values are repeatable (see Figure 57).

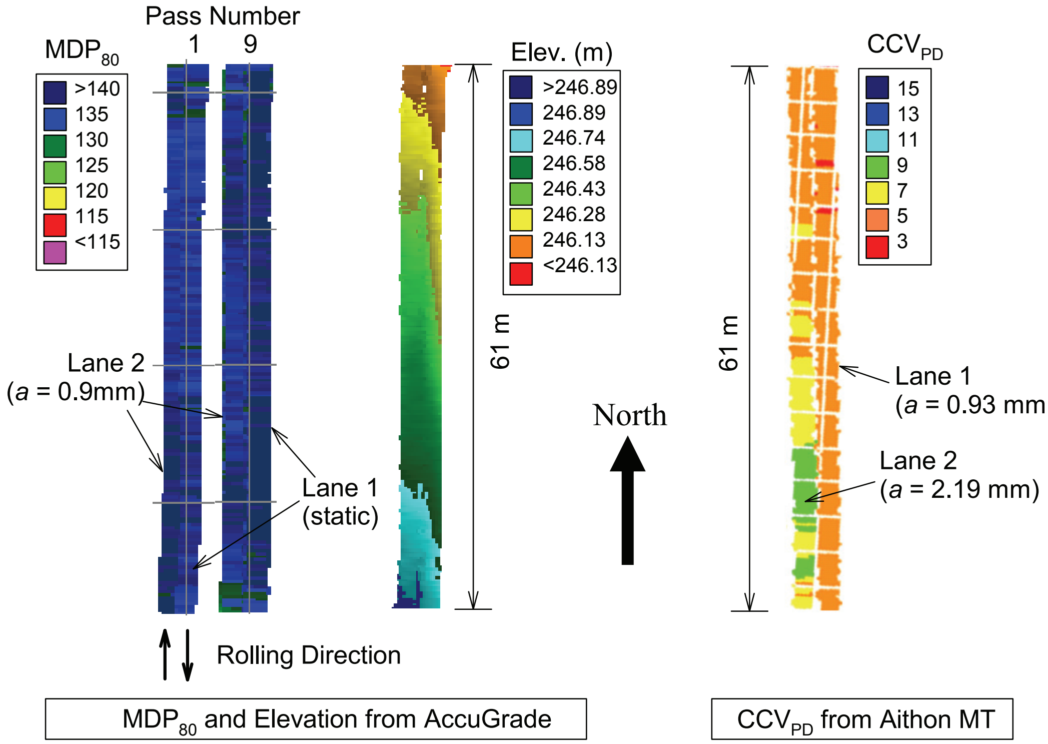


Figure 57. Caterpillar MDP_{80} and elevation maps and Sakai CCV_{PD} (TB1 subgrade clay material lanes 1 and 2)

- Linear regression analysis produced poor to good correlations between IC and point measurement values. Reasons for cases with poor correlations are attributed to influence of underlying support conditions, variations in moisture content, and narrow range of IC and point measurement values at the test locations. Multiple regression analysis indicated that IC measurements are influenced by amplitude and in some cases by moisture content and grade slope, in correlations with in-situ point measurements. For two cases in this project, compaction using high amplitude setting resulted in comparatively similar or higher relative compaction than using low amplitude or static settings.

- Color-coded maps of IC data with 100% coverage information provided the opportunity to visualize compaction quality over a production area or at a given point location. This opportunity can be beneficial to make informed decisions on compaction process to promptly adjust process control measures.

- Geostatistical analysis methods (i.e., semi-variogram analysis) in combination with univariate statistics were applied to production area IC measurements to quantify spatial uniformity of the compacted materials. The results from these analysis methods showed interesting trends in change in compaction quality (in terms of spatial continuity and uniformity) with increasing roller passes (e.g. compaction uniformity may decrease with increasing roller pass). The use of such analysis methods in construction QC/QA procedures represent a paradigm shift in how compaction analysis and specifications could be implemented in the future.

- The Sakai CCV measurements obtained from the Sakai padfoot roller were well correlated with measurements obtained from the same roller with a smooth drum shell kit at this site. Although there was scatter in the relationships, the trends were quite encouraging. The CCV padfoot roller measurements demonstrate similar advantages as the smooth drum roller measurements (see Figure 58).

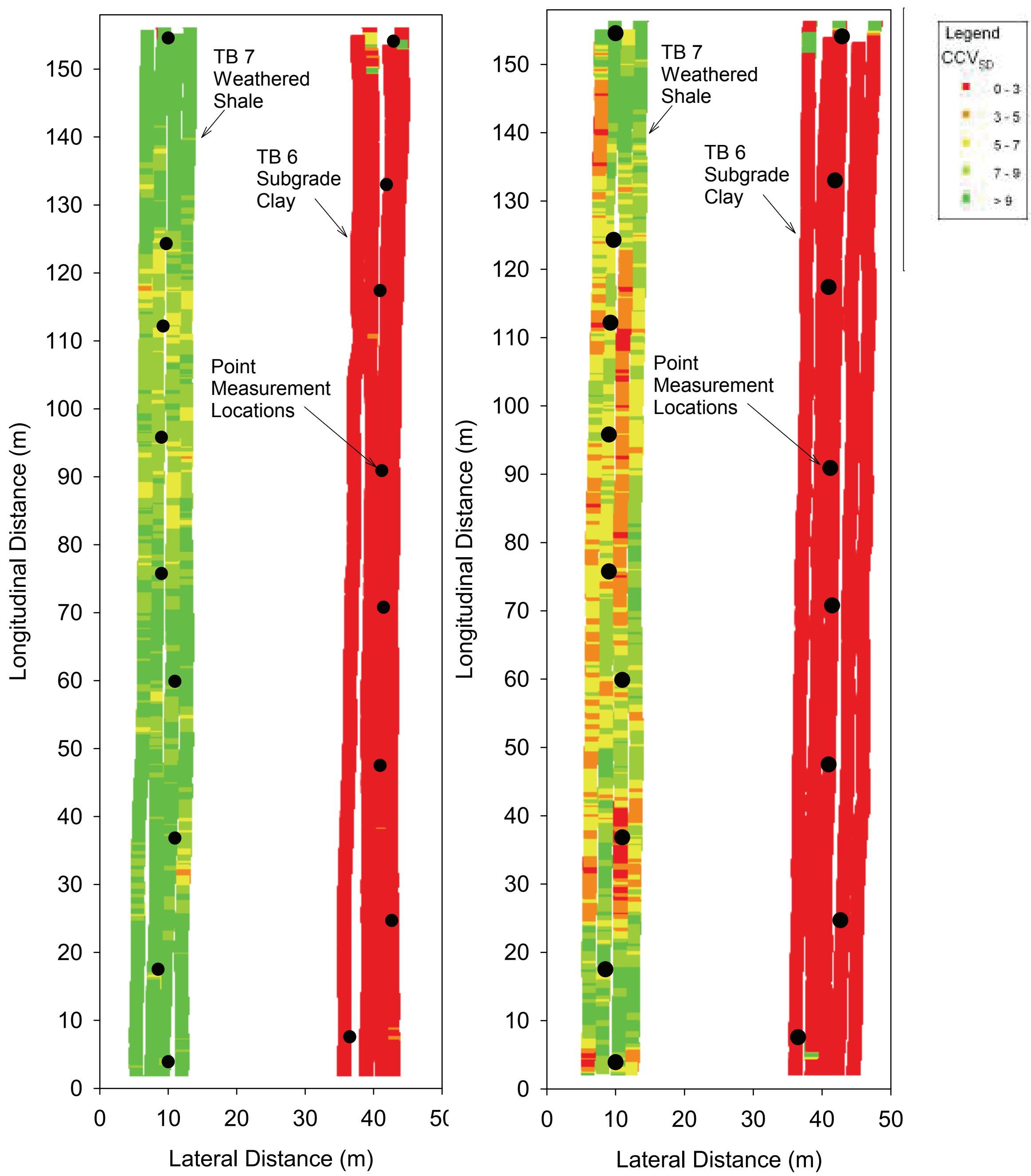


Figure 58. Sakai CCV_{PD} (pad-foot drum, left) vs. CCV_{SD} map (right, smooth drum, right)

- Production compaction using the Caterpillar padfoot IC roller successfully track compaction levels of various materials such as fat clay and lean clay subgrade. . The elevation data indicates that the area generally slopes down from north to south. The MDP80 data on the foundation layer appears sensitive to driving grade slope with relatively high MDP80 values driving downhill (north to south) and relatively low

MDP80 values driving uphill (south to north), as shown in Figure 59.

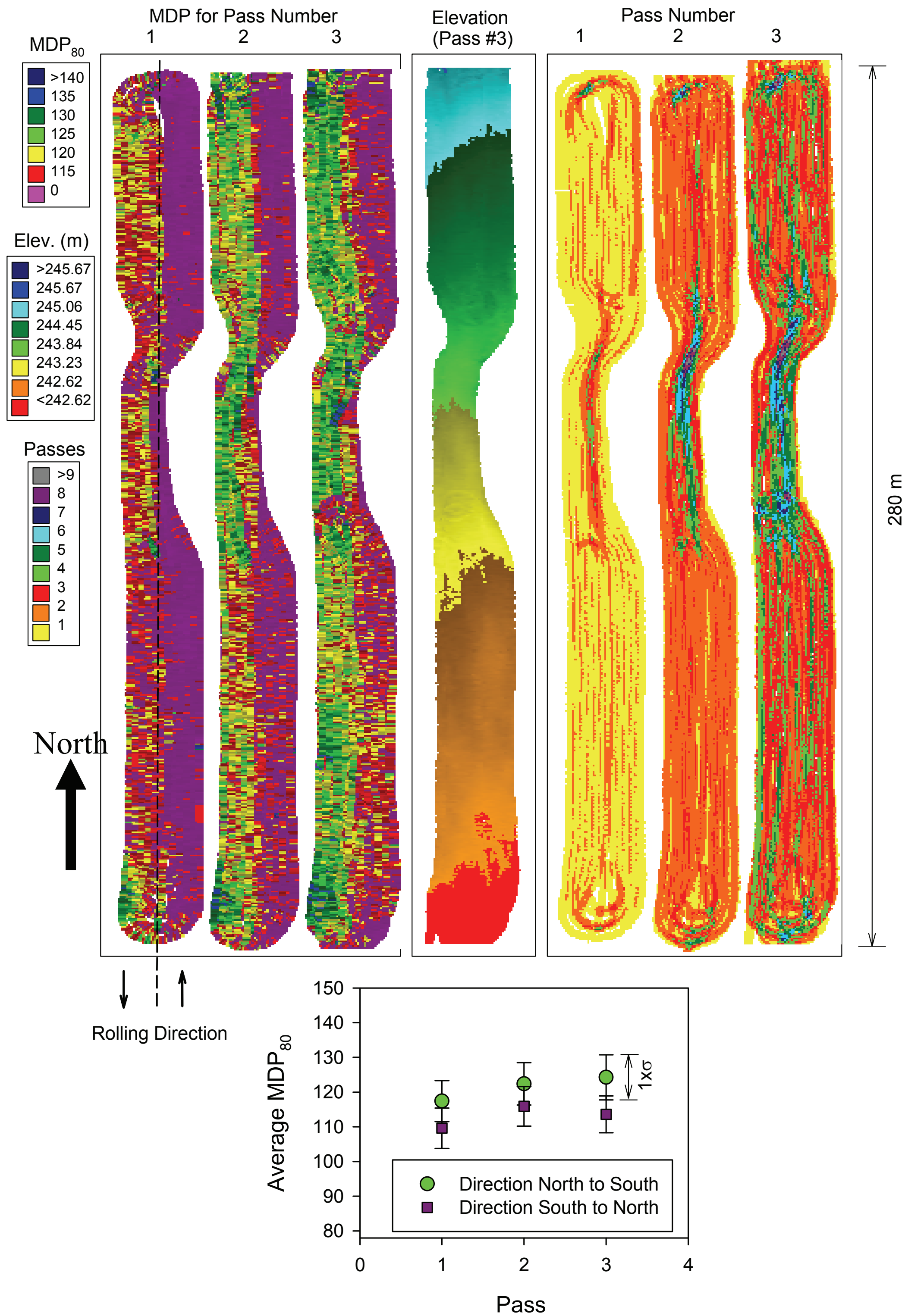


Figure 59. MDP_{80}, elevation, pass coverage, and average MDP_{80} (a = 0.90 mm, f = 33 Hz, v = 4 km/h) per pass on TB3 foundation subgrade layer

- An isolated soft/wet spot was identified with low MDP_{80} values on the map (Figure 60).

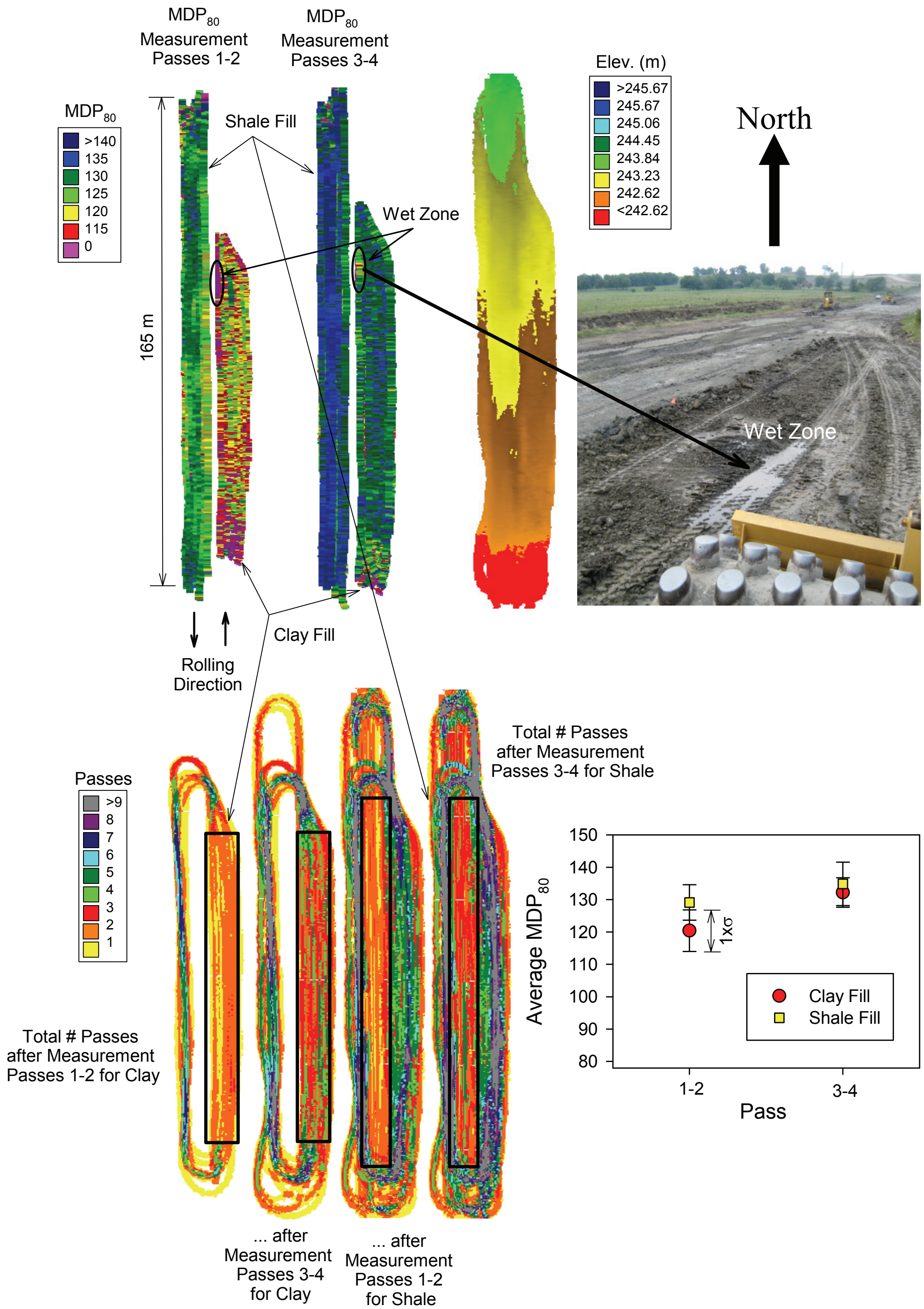


Figure 60. MDP_{80}, elevation, pass coverage, and average MDP_{80} (a = 0.90 mm, f = 33 Hz, v = 4 km/h) per pass on TB3 lift 1 clay fill and shale fill material

- On average the MDP_{80} values increased with roller passes, and the weathered shale fill material was relatively stiffer compared to the lean clay fill material (see the compaction curve presented in Figure 60).
- The MDP_{80} and CCV_{PD} values along the test bed generally track well with changes in in-situ point measurements including FWD and LWD measured moduli.

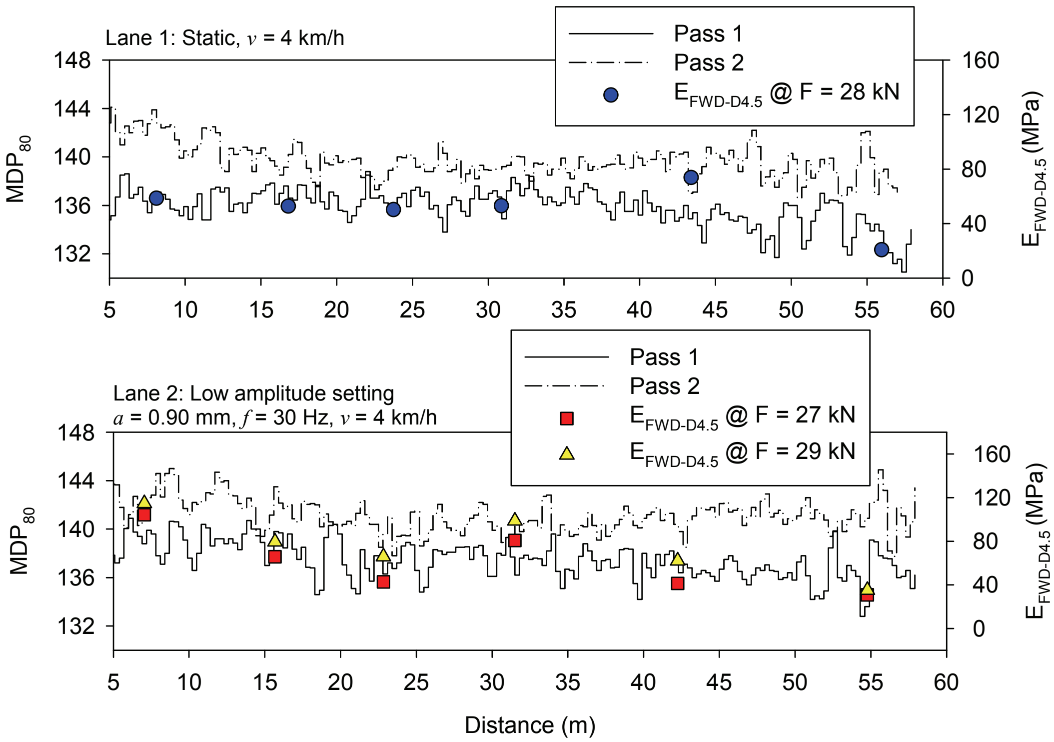


Figure 61. Comparison between MDP_{80} and $E_{FWD\text{-}D4.5}$ point measurements – TB1 subgrade clay material (note: passes 1 and 2 with opposite machine direction of travel)

Future research

Although influence of amplitude can be accounted for through multiple regression analysis, it is recommended that all measurements obtained from calibration areas and production areas during QA be obtained at a constant amplitude setting to avoid complication in data analysis and interpretation.

Mississippi IC Demonstration

The field IC demonstration was performed from July 13 to July 17, 2009 on US 84, Wayne county, MS. The materials include the subgrade embankment and untreated and treated granular (sandy) base (with 5% cement as the MSDOT 9C chemically treated granular material).

The objectives of this demonstration project were short-term goals for introducing soil/subbase and HMA IC technology to MSDOT and contractors who may not have prior experience with IC. The project was intended to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Figure 62. Mississippi Soil/subbase IC demonstration.

Major findings

- Empirical correlations between ICMVs and different in-situ measurements sometimes showed weak correlations when evaluated independently for each test bed, because of the narrow measurement range. The correlations improved when data are combined for site-wide correlations with a wide measurement range (see Figure 63).

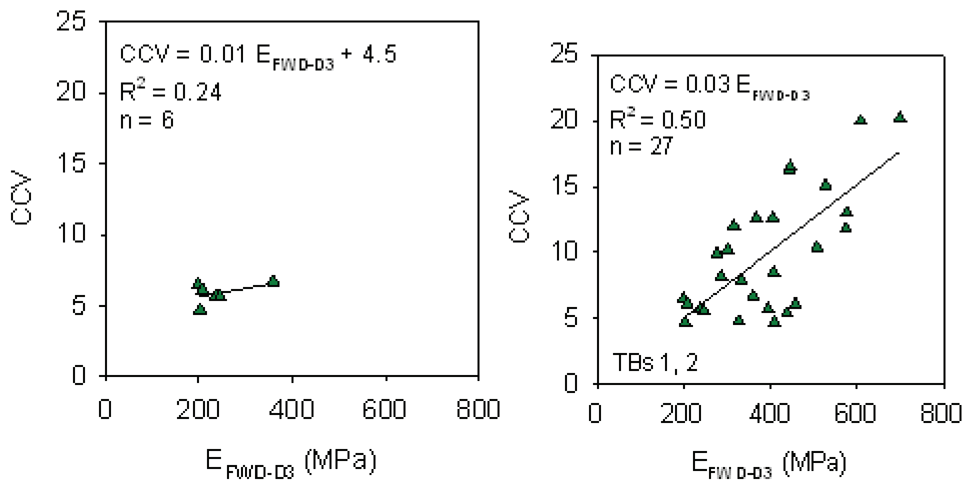


Figure 63. Regression analyses between CCV and FWD measurements – TB 1 (left), TBs 1 and 2 (right)

- ICMVs generally correlated better with modulus based in-situ in-situ measurements (i.e., ELWD-Z3, EFWD-K3, EV1, and EV2) and CBR point MVs than with dry density in-situ measurements. Correlations between ICMVs and EFWD-K3, and ICMVs and EV1 showed strongest correlation coefficients.

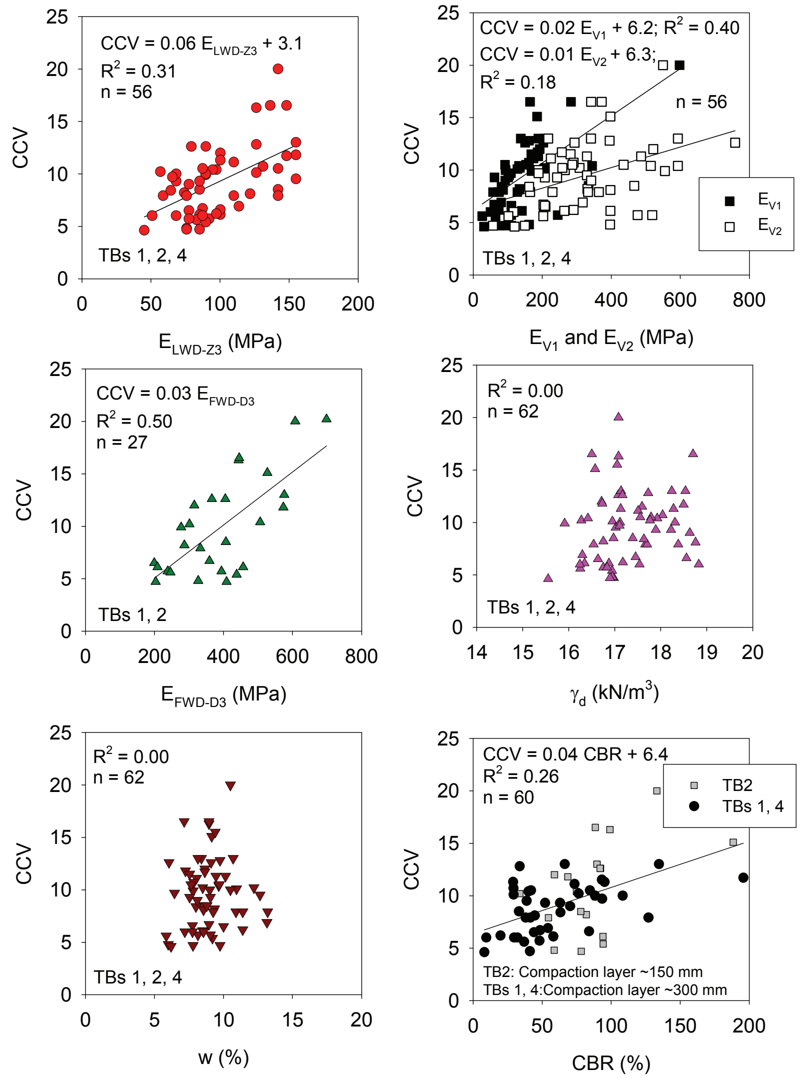
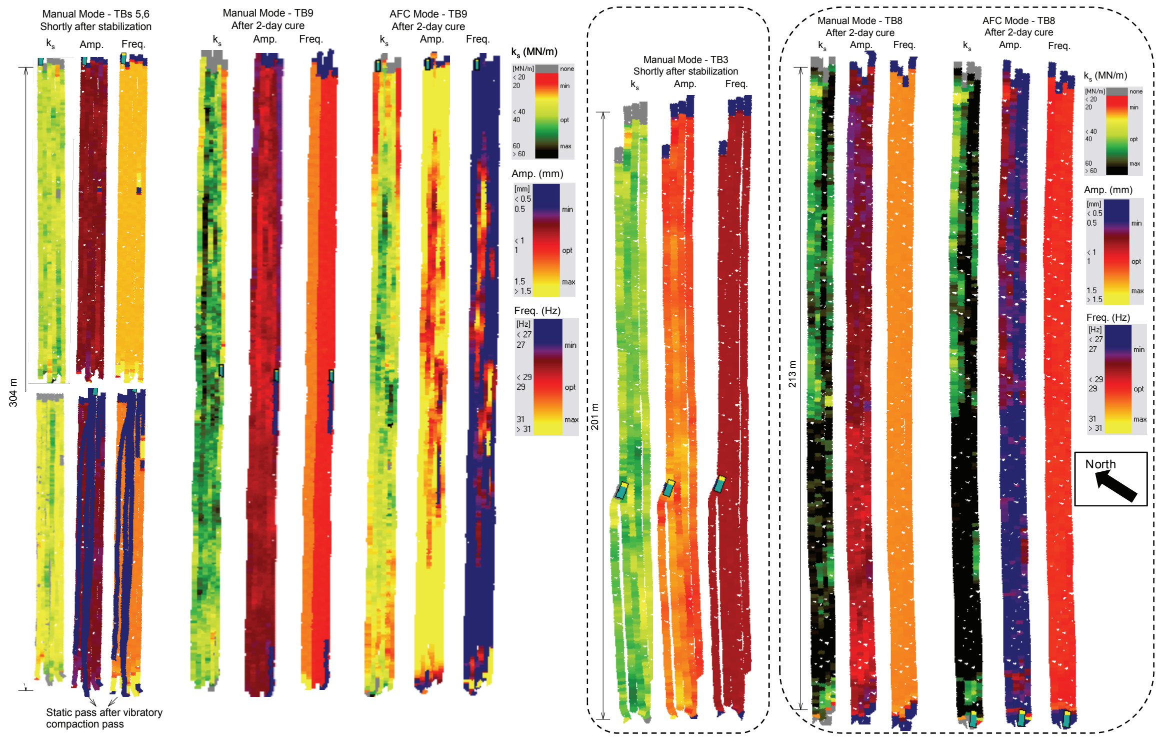


Figure 64. Regression analyses between CCV and LWD measurements.

- ICMV mapping operations were performed in AFC mode using low, medium, and high performance settings on TB8, TB7, and TB9, respectively. When operated in high performance setting, the vibration amplitude was decreased and the excitation frequency was increased with increase in ks (see Figure 65 a). When operated in low and medium performance settings, the vibration amplitude was decreased with increase in ks while the frequency remained relatively constant (see Figure 65 b).



a) TB5/6 (left) and TB9 (right, manual to AFC) b) TB3 (left) and TB8 (right, manual to AFC)

Figure 65. Comparison of k_s, a*, and f maps obtained shortly after compaction (TB3 and TB5/6) and after 2-day cure in manual and AFC modes (TB8 and TB9)

- IC data indicated that the response distance for altering the amplitude and/or frequency was about 1 to 2 m for a roller travel speed of about 4 km/h. Case/Ammann machine on this project reported ICMVs every 1 m. Denser sampling rate is required to accurately evaluate the response distance.
- CCV and modulus/CBR on the cement treated base layer (TB2) are greater than on the untreated base layer (TB1). The average CCV on TB2 is about 2.1 times greater than on TB1. The average $E_{LWD\text{-}Z3}$, E_{V1}, E_{V2}, $E_{FWD\text{-}D3}$, and CBR in-situ measurements are about 1.3, 2.6, 1.7, 1.8, and 1.8 times, respectively, greater on TB2 than on TB1.
- Curing has improved the ks value (e.g. 33% after two day curing) when moisture content decreases (e.g. from 10.5% to 7.1%) as shown in Figure 65.
- Geostatistical analysis results indicated that the spatial non-uniformity is higher on the treated subgrade and base layers after two days of curing compared to shortly after compaction and untreated layers in contrary to the common presumption that stabilization creates a more "uniform" working platform. A number of construction related factors likely contribute to this increased non-uniformity which includes non-uniform application of cement, water content, compaction delay time, and compaction energy across the test bed area.

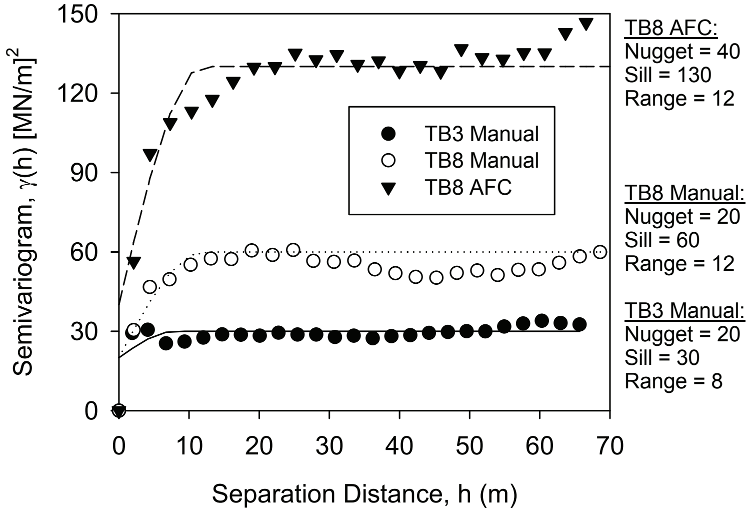


Figure 66. Semi-variograms of k_s measurements obtained on TB3 (shortly after mixing and compaction) in manual mode, TB8 (after two days of curing) in manual mode, and TB8 in AFC mode

- The CCV semi-variograms show that treatment base has lower uniformity compared to the untreated base (.e.g. with a sill of 28 on TB2 compared to sill value of 6 on TB1).
- Different measurements including CMV, MDP and Ks all identify the weaker or stiffer areas with similar zones, which tracks well with in-situ measurements such as CBR (see Figure 67).

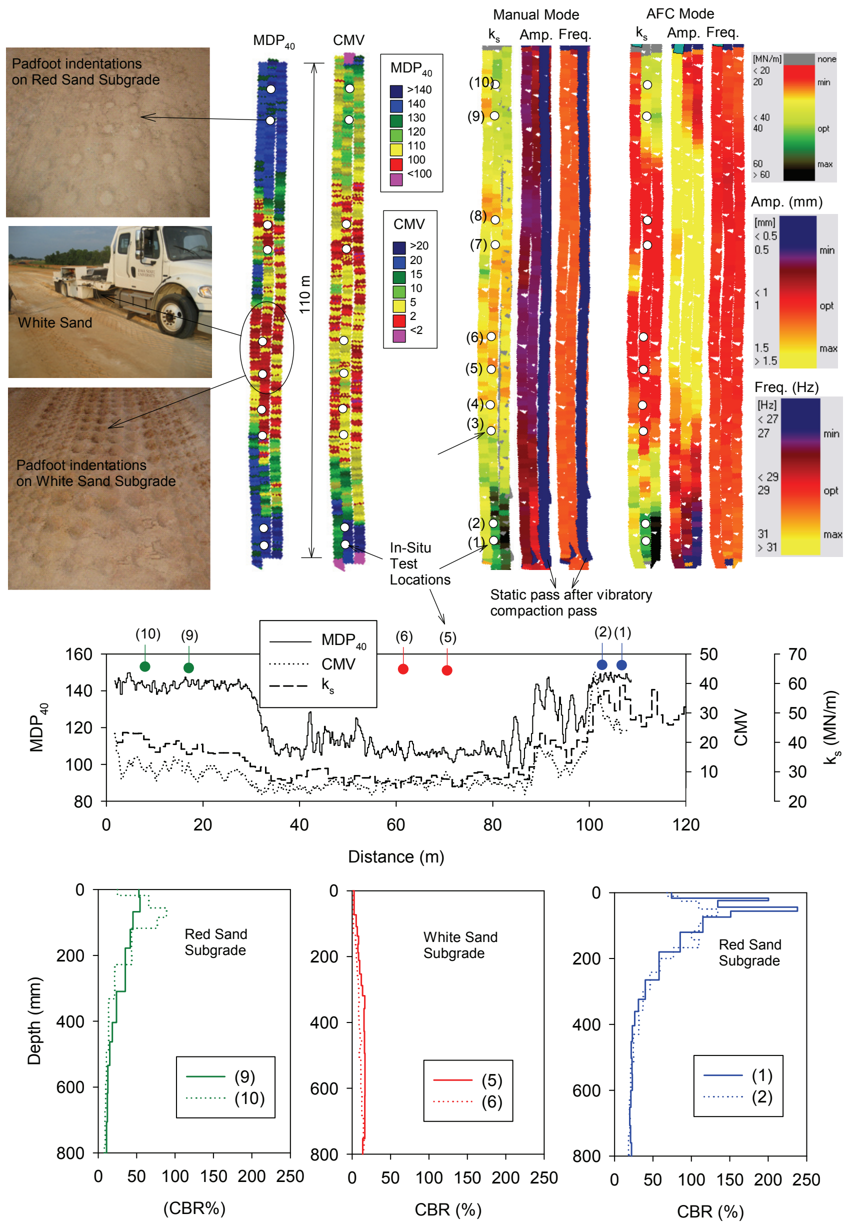
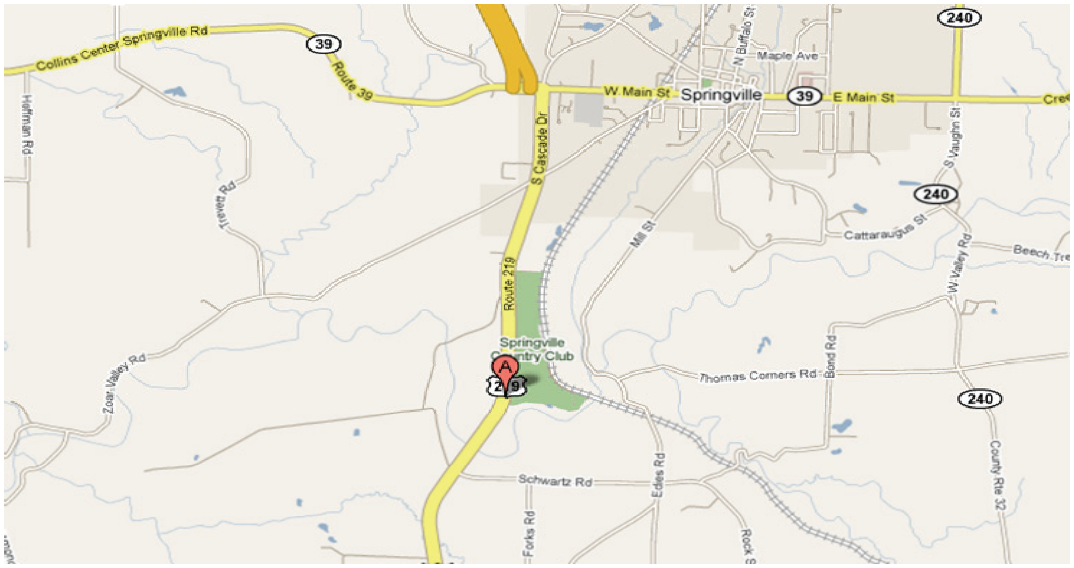


Figure 67. Roller spatial maps, MDP$_{40}$, CMV, and k$_s$ measurements along the middle lane, and DCP-CBR profiles at selected locations – TB7 granular subgrade material

New York IC Demonstration

The field IC demonstration was performed from May 17 to May 22, 2009 on US 219. A total of ten test beds including two different materials (i.e., embankment subgrade and subbase materials) were studied. The Caterpillar and Bomag IC machines are used in this demonstration project.

The objectives of this demonstration project were short-term goals for introducing soil/subbase and HMA IC technology to NYSDOT and contractors who may not have prior experience with IC. The project was intended to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.



Embankement material

Gravel subbase material

FIGURE 68 New York soil/subbase IC Demonstration.

Major Findings

- One of the major findings is that good correlation between IC roller measurement values and in-situ point tests can be obtained as long as both tests are conducted properly. See the following example for the Bomag and FWD tests on test bed 3 embankment materials.

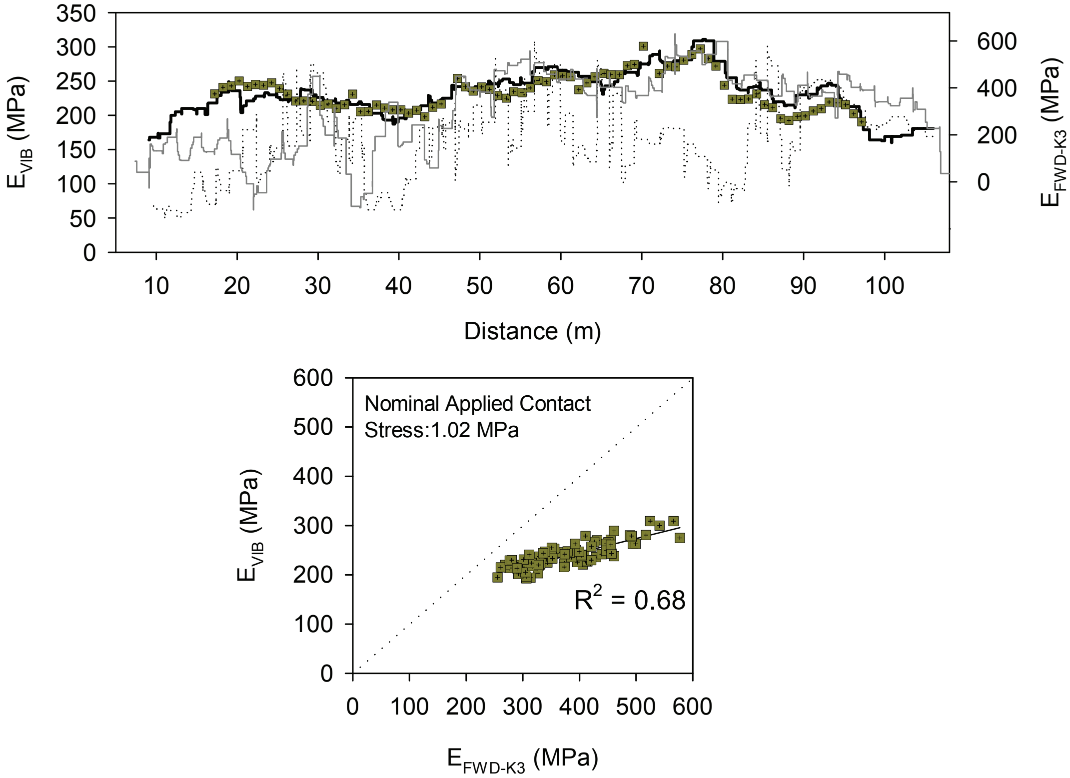


Figure 69. Good correlation between Bomag E_{VIB} (pass 3) and FWD tests on lane 3 (TB3 embankment material).

- Performance of the Bomag automatic feedback control (AFC) compaction operations in comparison with conventional operations using the Bomag IC roller were evaluated as part of this study. Following are some key observations:

- TB 3 (embankment): Amplitude measurements along the test strip indicated that when E_{VIB} < target E_{VIB}, the amplitude is at the a_{max}, and the amplitude is effectively reduced to 0.60 mm when E_{VIB} > target E_{VIB}. However, roller jumping was still observed at several short segmented sections along the test strip.

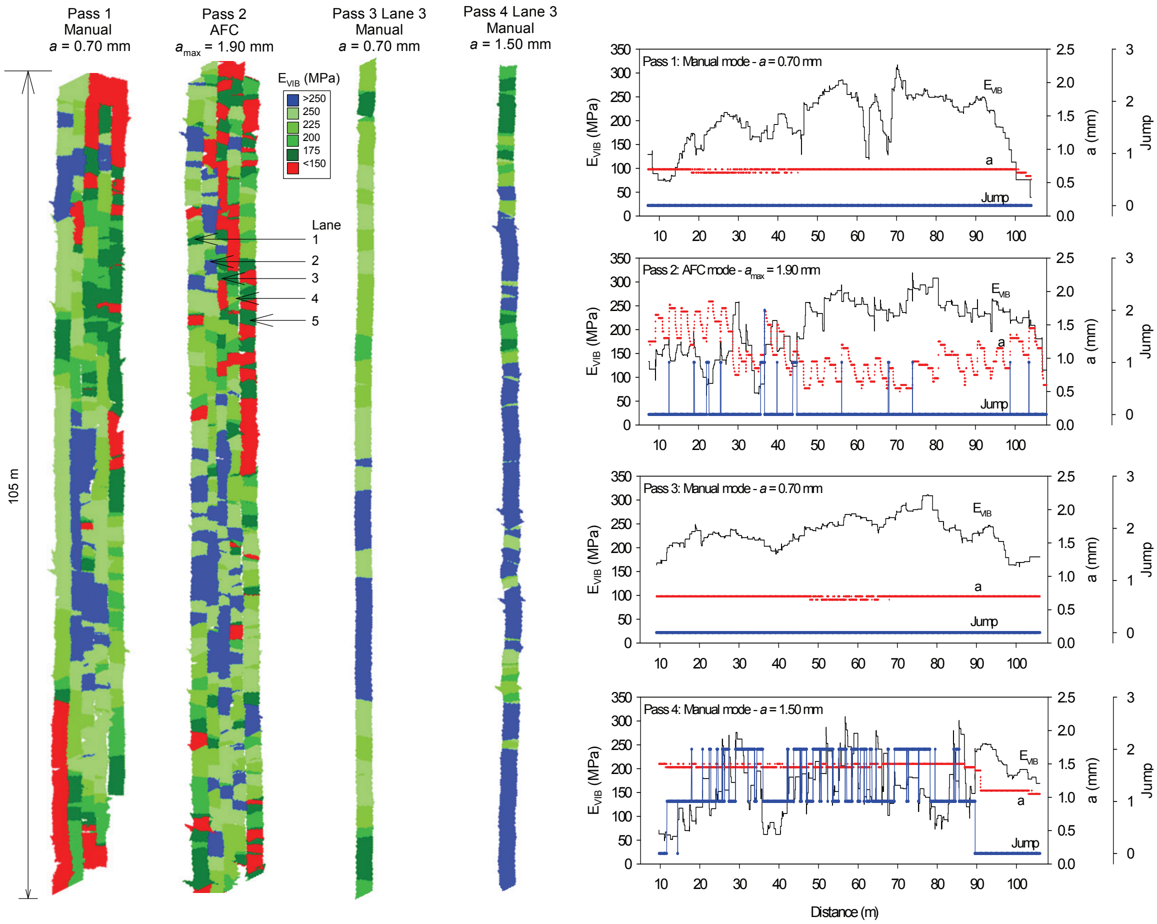


Figure 70. E_{VIB} spatial maps with different machine amplitude settings in manual and AFC mode – TB3 embankment material, and jumping

- TB 5 (gravel subbase): In this test bed two side-by-side lanes were compacted in manual a = 0.70 mm mode and AFC mode (a_{max} = 1.10 mm, target E_{VIB} = 150 MPa). The average E_{VIB} values obtained in AFC mode (a = 1.0 mm on average) are on-average about 1.3 times higher than the average E_{VIB} values obtained in manual mode operation. Average E_{LWD-Z3} values in the lane compacted in AFC mode were about 1.6 times higher than in the lane compacted in manual mode. However, the average relative compaction values, average E_{FWD-K3} values, and CBR values are similar for the two lanes after pass 8. Although the E_{VIB} values showed low COV with AFC operations compared to COV with manual mode operations, In-situ measurements did not show considerable difference in the COV values. More testing is recommended in future projects with different a_{max} and target E_{VIB} settings to further evaluate AFC mode compaction operations with variable subsurface conditions.

- TB 10 (trench): In this test bed, deep trenches were excavated and compacted in side-by-side lanes using manual and AFC settings. The compaction curves of average dry density, modulus, and CBR measurements generally increased with increasing passes up to pass 8 in the trench areas. However, no significant difference was measured in terms of density of the material at the surface in the trenches between lanes compacted using AFC mode and manual mode (91% relative compaction in the 1m trench and 88 to 89% relative compaction in the 2m trench). Similarly, E_{LWD-Z3} and CBR_{300} measurements did not demonstrate considerable differences between AFC mode and manual mode compacted lanes. Analysis of incremental increases in CBR with depth relative to pass 1 in the 2 m wide x 1 m deep trench did not present considerable differences between AFC mode and manual mode compaction.

- To study the influence of amplitude on Caterpillar MDP_{40} ICMVs, two side-by-side gravel subbase lanes were compacted in static and low amplitude modes. The average MDP_{40} values obtained in static mode are on average about 1.1 times higher than the MDP_{40} values obtained in low amplitude mode. The average $E_{LWD\text{-}Z3}$ values obtained after pass 8 in the lane compacted in static mode is about 1.6 times higher than in the lane compacted in low amplitude mode. However, the average relative compaction and CBR values are similar for the two lanes after pass 8.

- Geostatistical analysis methods were utilized to analyze spatially referenced ICMV data to assess spatial non-uniformity of compacted fill materials. Some ICMV data sets showed nested semi-variogram structures with short-range and long-range components. It is possible that the long-range components are because of differences in the underlying support conditions (i.e., shredded tire fill at depths < 1 m) while the short-range components are a result of spatial variations of soil properties close to surface. Additional studies are needed to better understand this finding.

- Five different test devices were used to determine elastic modulus: (a) 200 mm Zorn LWD; (b) 300 mm Zorn LWD; (c) BCD; (d) KUAB FWD; and (e) static PLT. Regression relationships between modulus measurements obtained from these five different devices are presented in this report. Some key findings from these relationships are as follows:

- Relationships between 200 mm and 300 mm LWD measurements indicated that $E_{LWD\text{-}Z2}$ measurements are on average 1.3 times greater than $E_{LWD\text{-}Z3}$ measurements. Differences in modulus between $E_{LWD\text{-}Z2}$ and $E_{LWD\text{-}Z3}$ measurements are attributed to: (a) different plate diameters; (b) differences in measurement influence depths; and (c) differences in applied contact stresses.

- Relationship between FWD and LWD indicated that $E_{FWD\text{-}K3}$ is on average about 3.4 times greater than $E_{LWD\text{-}Z3}$ measurements. Differences are attributed to: (a) type and location of deflection measurement sensors; and (b) applied contact stresses.

- Relationships between $E_{LWD\text{-}Z3}$ vs. E_{BCD}, and $E_{FWD\text{-}K3}$ vs. E_{V1} and E_{V2} produced weak correlations (R^2 = 0.10 to 0.13). Weak correlations between $E_{LWD\text{-}Z3}$ and E_{BCD} are attributed to the difference in the applied contact stresses. E_{LWD} is determined using contact stresses that are about10 times higher than contact stresses applied to determine E_{BCD}. Weak correlations between $E_{FWD\text{-}K3}$ and E_{V1} or E_{V2} are in part attributed to the limited number of measurements (n = 23) and the limited measurement range over which the tests were performed (all the tests were performed on very stiff material E_{V1} > 250 MPa).

- Three different test devices were used to determine dry unit weight and moisture content: (a) Troxler nuclear gauge; (b) Humboldt nuclear gauge; and (c) Transtech's soil density gauge. Regression relationships between dry unit weight and moisture measurements obtained from these three different devices are presented in this report. Some key findings are as follows:

- Relationship between $\gamma_{d(H)}$ and $\gamma_{d(T)}$ produced strong correlation with R^2 = 0.73. However, on average the $\gamma_{d(T)}$ measurements were about 1.04 times greater than $\gamma_{d(H)}$ measurements.

Relationship between $w_{(H)}$ and $w_{(T)}$ yielded weak correlation with $R^2 = 0.10$. On average the $w_{(H)}$ measurements were about 1.7 times greater than $w_{(T)}$ measurements.

- Relationship between $\gamma_{d(H)}$ and $\gamma_{d(SDG)}$ produced weak correlation with $R^2 = 0.41$. On average the $\gamma_{d(SDG)}$ measurements were about 1.02 times greater than $\gamma_{d(H)}$ measurements. No statistically significant relationship was identified between $w_{(H)}$ and $w_{(SDG)}$.
- Relationship between $\gamma_{d(SDG)}$ and $\gamma_{d(T)}$ also produced a weak correlation with $R^2 = 0.27$. However, the measurements were scattered around the line of equality. Relationship between $w_{(H)}$ and $w_{(T)}$ similarly produced weak correlation with $R^2 = 0.10$. On average the $w_{(SDG)}$ measurements were about 1.2 times greater than $w_{(T)}$ measurements.

North Dakota IC Demonstration

This report presents results from a field investigation conducted on US Highway 12 in Marmarth, North Dakota. The machine configurations and roller-integrated measurement systems used on this project included: a Caterpillar CP56 smooth drum roller with a padfoot shell kit (here after referred to as padfoot roller) equipped with machine drive power (MDP), and a Caterpillar CS563E vibratory smooth drum roller equipped with MDP and compaction meter value (CMV) intelligent compaction (IC) measurement technologies. The machines were equipped with real time kinematic (RTK) global positioning system (GPS) and on-board display and documentation systems.

The project involved construction and testing of seven test beds. Four of these test beds included silty subgrade materials and the remaining three included salvage base materials. The test beds with salvage base materials varied in terms of their underlying support conditions. One test bed was reinforced with two layers of geogrid in the base layers, one test bed was partially treated with over excavation and replacement due to soft subgrade conditions, and the other test bed served as a control section with no special treatments. Six different in-situ testing methods were used in this study to evaluate the in-situ soil engineering properties: (a) Zorn light weight deflectometer setup with 200 and 300 mm diameter plates to determine elastic modulus (E_{LWD-Z2} for 200 mm plate diameter and E_{LWD-Z3} for 300 mm plate diameter), (b) dynamic cone penetrometer (DCP) to determine California bearing ratio (CBR), (c) calibrated Humboldt nuclear gauge (NG) to measure moisture content (w) and dry unit weight (γ_d), (d) Dynatest falling weight deflectometer (FWD) setup with 300 mm diameter plate to determine elastic modulus (E_{FWD-D3}), (e) Kuab falling weight deflectometer (FWD) setup with 300 mm diameter plate to determine elastic modulus (E_{FWD-K3}), and (f) in-situ bore hole shear test (BST) to determine soil drained shear strength properties. Figure 71 presents the demonstration site, materials, machines, and in-situ tests.

Figure 71. North Dakota IC demonstration.

Major findings

- MDP increases with pass count, and high-amplitude setting results in lower MDP than low-amplitude setting (see Figure 72).

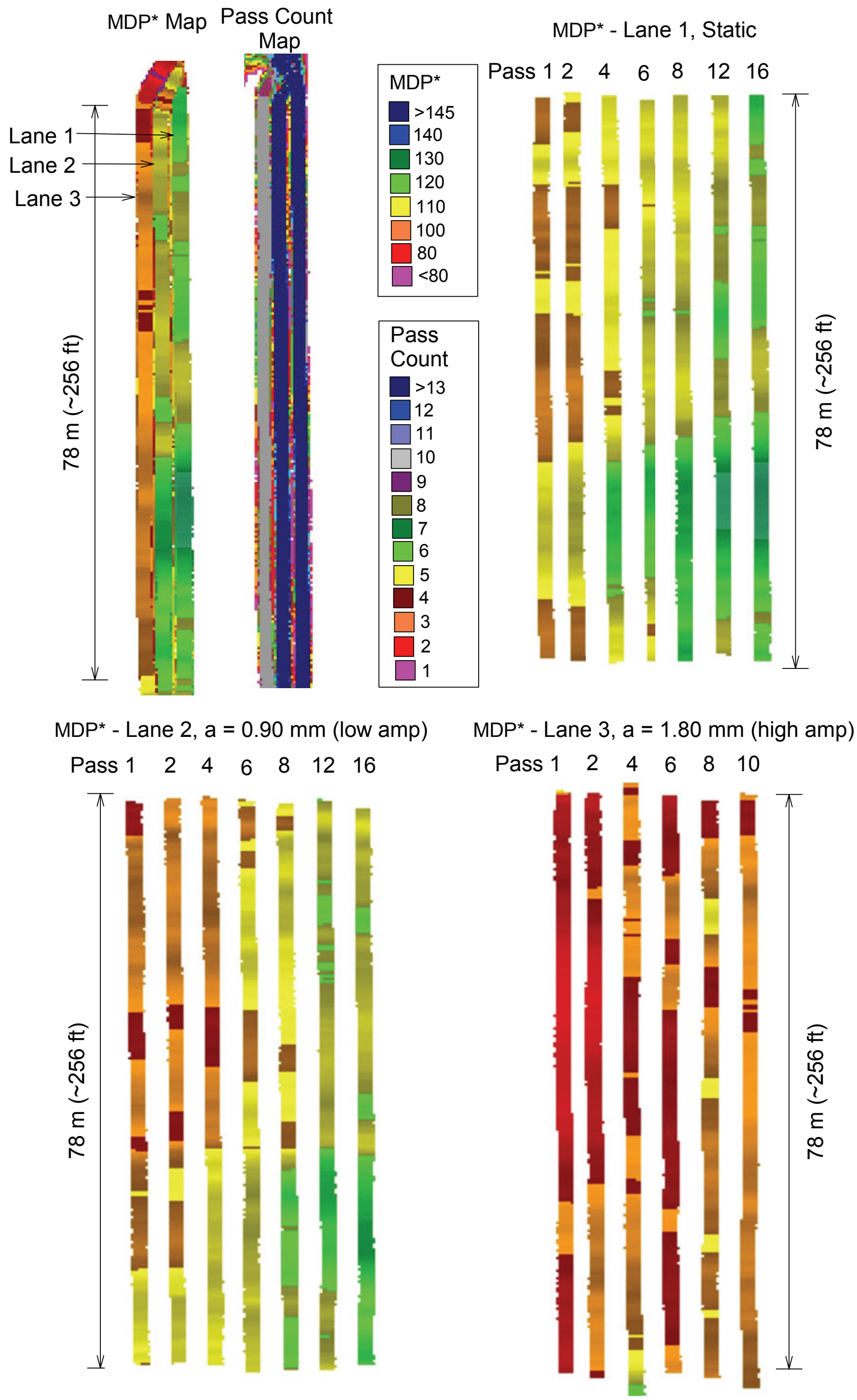


Figure 72. MDP* and elevation maps of lanes 1 to 3, and MDP* spatial maps for multiple padfoot roller passes on lanes 1 to 3 – TB1

- MDP* semi-variogram on the mixed subgrade layer showed a nested spatial structure with both short-range and long-range components, while the semi-variograms on the base layers 1 and 2 did not.

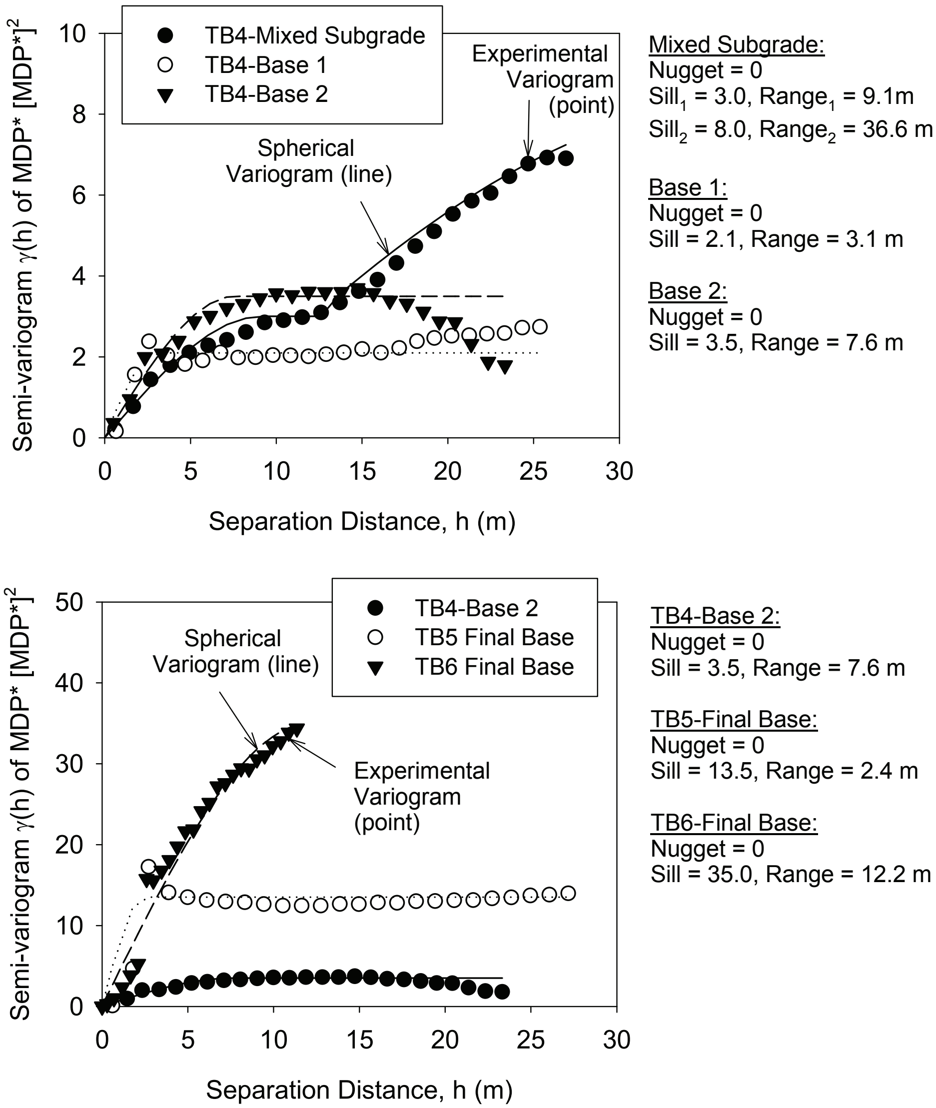


Figure 73. (a) Comparison of MDP semi-variograms on TB 4 mixed subgrade, base 1, and base 2 layers, (b) Comparison of MDP semi-variograms on TB4, 5, and 6 base layers

- The static MDP* ICMVs in TB3 production area showed more variability with high sill values compared to the vibratory MDP* ICMVs with low amplitude. This was also evident with a slightly higher standard deviation (σ) value for static MDP* over the vibratory low amplitude MDP*.
- The average ELWD-Z2 and CBR250 point-MVs were lower on low and high amplitude mode lanes, compared to the lanes compacted in static mode. In contrary, the average γd was greater on low and high amplitude mode lanes than on static mode lane.
- MDP* ICMVs obtained during compaction of salvage base layers indicated slightly

different trends in the average MDP* compaction growth for forward (in low amplitude mode) and reverse (in static mode) passes. MDP* ICMVs were repeatable for forward passes but were affected by variable machine speed for reverse passes, and therefore were not repeatable.

- MDP* ICMVs were slightly lower (by about 1.04 times) on TB5 control section than on the TB4 geogrid reinforced section. The EFWD-K3 point-MVs were also on average slightly lower (by about 1.1 times) on TB5 than on TB4, while the average ELWD-Z3 point-MVs were about the same. The COV of MDP* ICMVs and point-MVs on TBs 4 and 5 were quite similar.

Figure 74. Photographs of TB4 during placement of TX5 geogrid and salvage base layers

Indiana IC Demonstration

The field IC demonstration was performed on the State Route 25 (SR-25), which is a new highway alignment extending from I-65 to CR750E north of Buck Creek, West Lafayette, Indiana, from August 16 to 19, 2010 and an open house was conducted on August 19, 2010. The machine configurations and roller-integrated measurement systems used on this project included: a Caterpillar CS56 smooth drum with a padfoot shell kit for the cohesive soil and a Caterpillar CS563E smooth drum vibratory roller for the granular embankment, both equipped with machine drive power (MDP) IC measurement technology.

The project involved constructing and testing six test beds consisting of cohesive and granular embankment fill materials. The intelligent compaction (IC) measurement values (MVs) were evaluated by conducting field testing in conjunction with a variety of in-situ testing devices measuring density, moisture content, California bearing ratio (CBR), and elastic modulus. These field testing devices and measurements included:): (a) calibrated Humboldt nuclear gauge (NG) to measure moisture content (w) and dry unit weight (γ_d), (b) dynamic cone penetrometer (DCP) to determine California bearing Ratio (CBR), and (c) Zorn light weight deflectometer setup with 300 mm plate diameter to determine elastic modulus. Assistance with field testing was provided by several INDOT personnel.

The goals of this field investigation were similar to previous demonstration projects and included the following:

- document machine vibration amplitude influence on compaction efficiency,

- develop correlations between IC measurement values (ICMVs) to traditional in-situ point measurements (point-MVs),
- compare IC results to traditional compaction operations,
- study IC measurement values in production compaction operations, and
- evaluate IC measurement values in terms of alternative specification options.

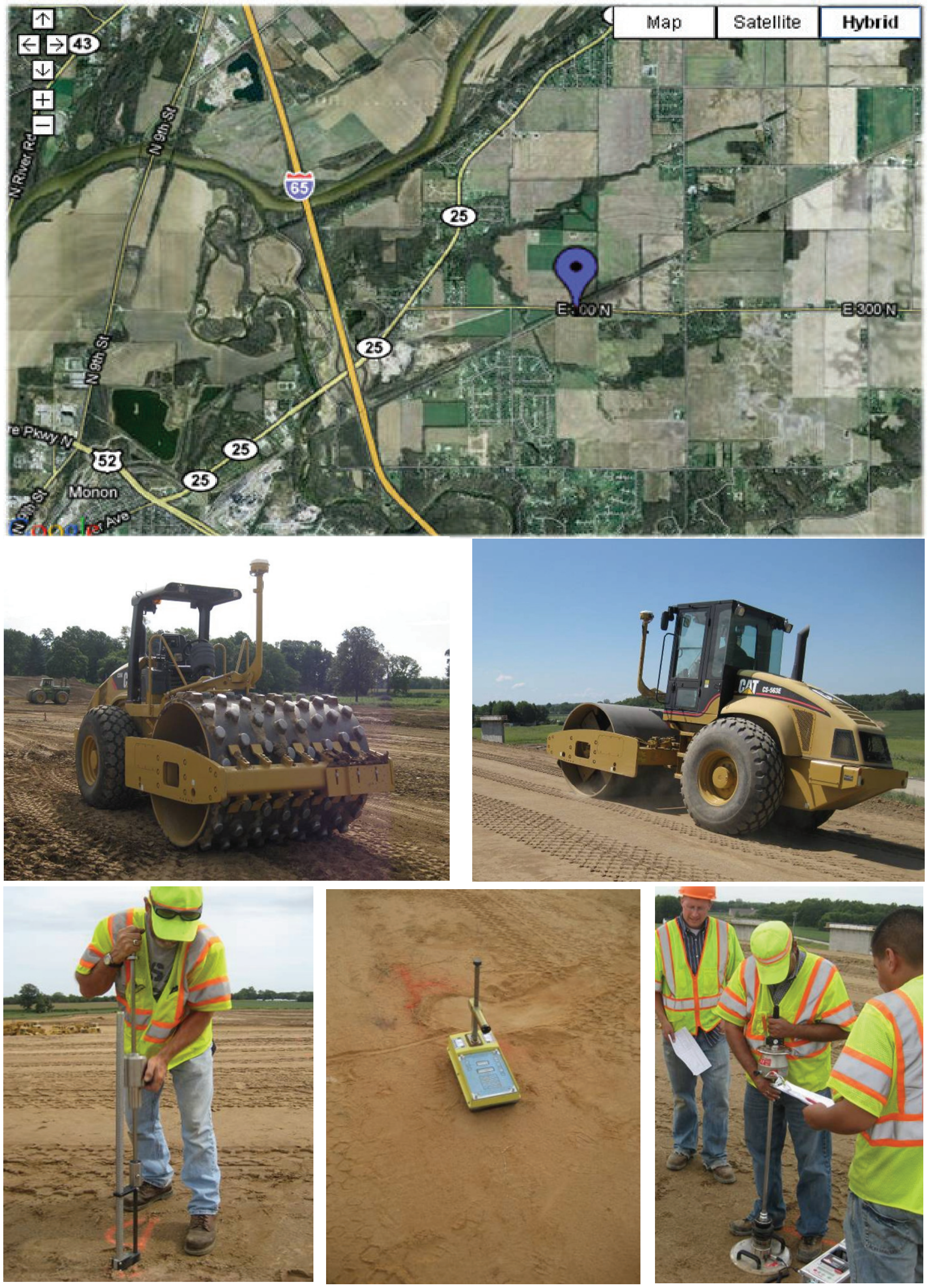


Figure 75. Construction site, materials and in-situ testing

Major findings

- Granular embankment fill MDP* generally increased with increasing number of passes, but no significant differences are noticeable using different amplitude settings (see Figure 76 on lanes 1 and 2).

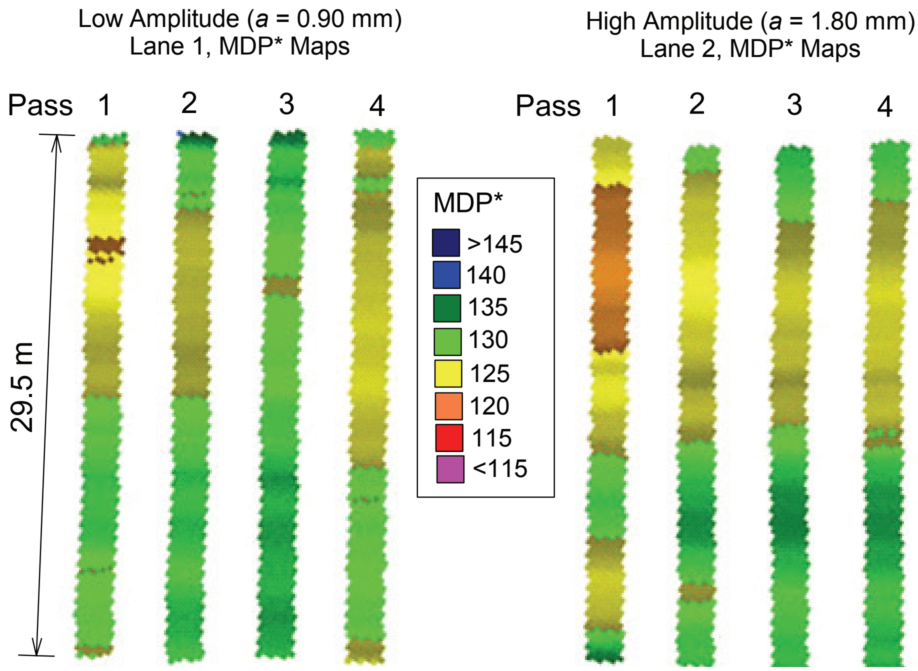


Figure 76. MDP* maps on lanes 1 and 2 – TB1 granular embankment fill

- MDP* values are repeatable in both forward and reverse passes though some differences are observed which are due to various operating conditions (see Figure 77).

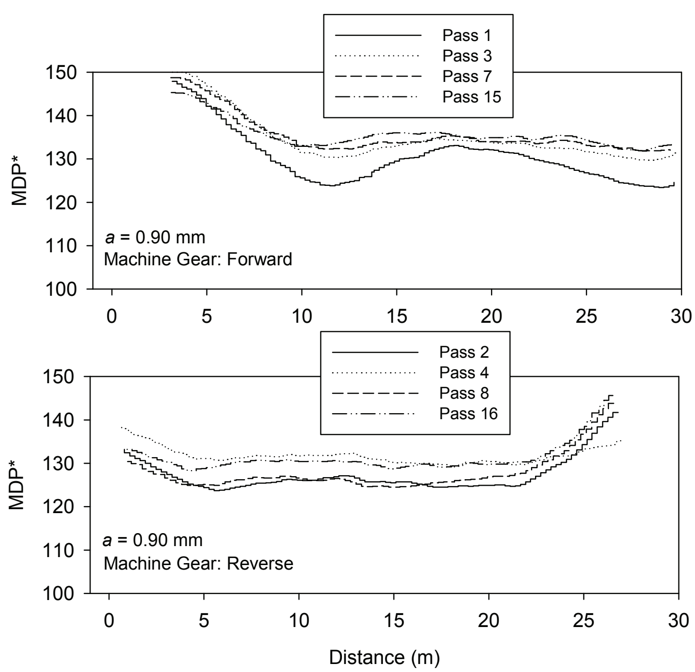


Figure 77. Average MDP* with increasing roller passes in forward and reverse gears – TB2 granular embankment fill

- Results indicate that for the silt clay subgrade on average, E_{LWD-Z3}, DCP-CBR, and γ_d values on lane 2 compacted in static mode were about 1.5, 1.03, and 1.3 times, respectively higher compared to the values on lane 1 compacted in low amplitude mode as shown in Figure 78. The reason for lower values on lane 1 is attributed to possible surface disturbance under vibration.

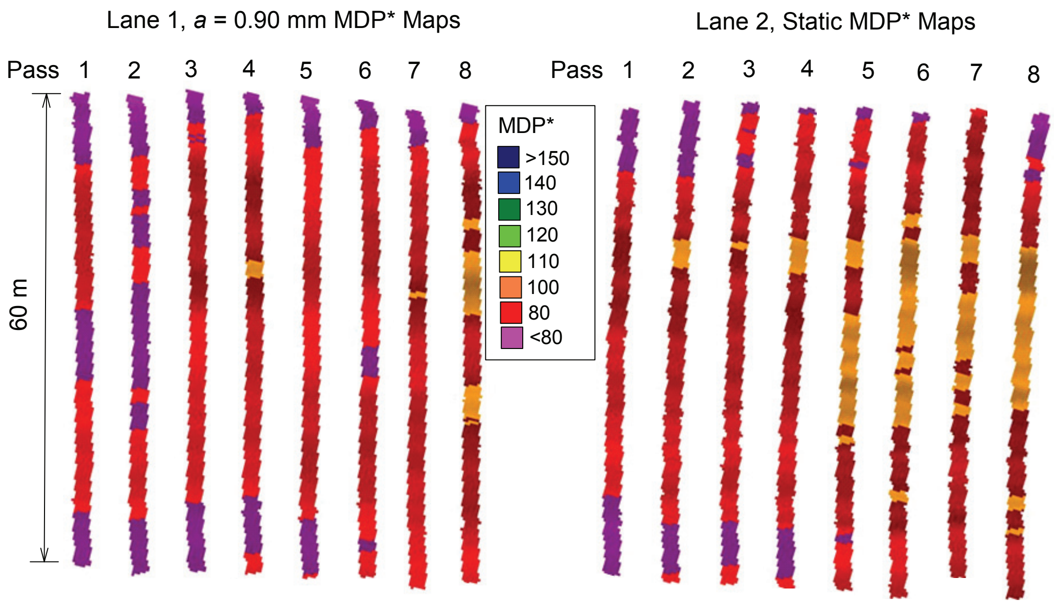


Figure 78. MDP* maps from passes 1 to 8 on lanes 1 and 2 – TB4 silty clay subgrade

- The experimental semivariograms values showed a nested spatial structure with short-range and long-range components, similar as observed before in the New York and North Dakota IPF projects. It is possible that the long-range spatial structure is linked to the spatial variation in underlying layer support conditions while the short-range spatial structure is a result of soil properties close to the surface.

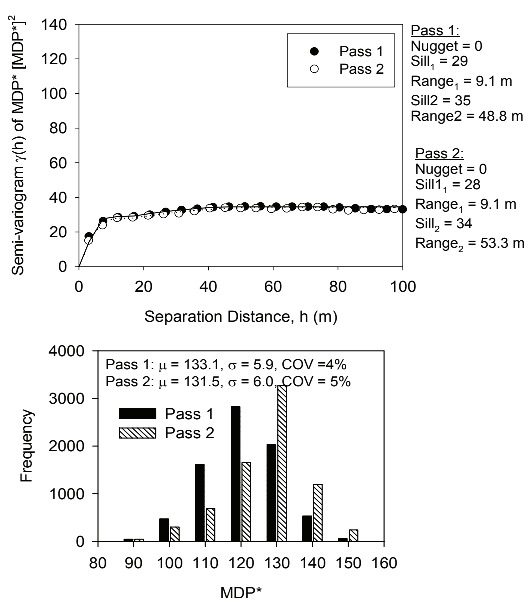


Figure 79. Geostatistical semi-variograms and histograms of passes 1 and 2 on lift # 1 – TB 3 granular embankment fill production area

- E_{LWD} values were correlated best to the MDP values. Spatial analysis showed changes in semi-variance as a function of roller pass coverage and demonstrates an approach for characterizing spatial non-uniformity.

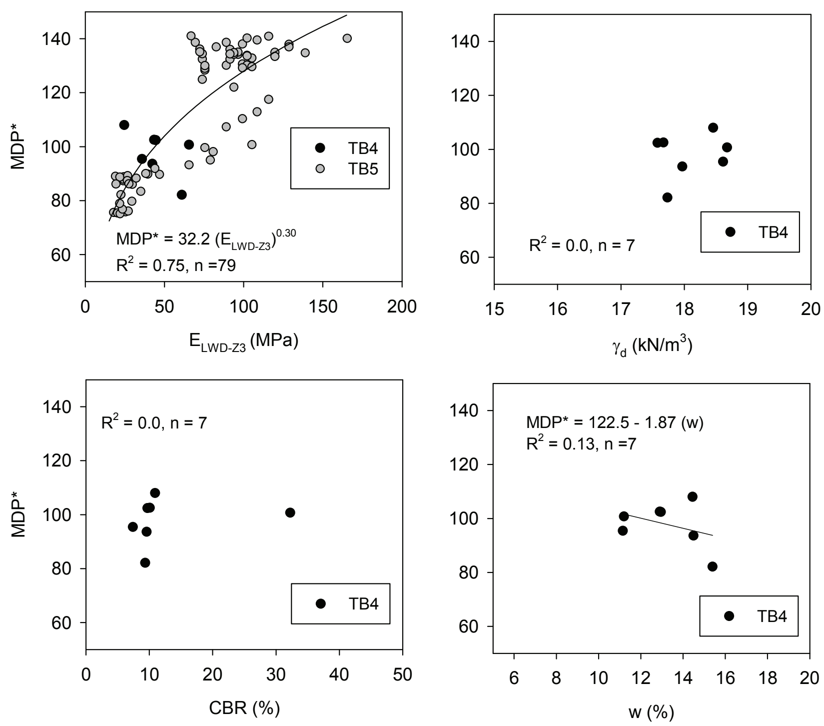


Figure 80. Correlations between MDP* and in-situ point-MVs – padfoot roller with static setting (TBs 4 and 5 cohesive embankment fill)

Compaction Curves

Figure 81 to Figure 85 show the compaction curves for the Network, Texas, Kansas, and North Dakota demonstration projects, respectively. The main findings are summarized as follows:

- Generally ICMV and in-situ measurements increase with increasing pass number and the increase rate gradually decreases until close to be a constant.
- At some cases, the ICMV drops from the 1st pass to the 2nd pass and then increases. The reduction of ICMV at the 2nd pass count is possibly due to knocking down the rough ground condition at the first pass.
- For some test strip and materials, ICMV may increase first and then decrease and the optimum pass number can be identified.
- The variation trends of ICMV and in-situ measurements are similar, but at some cases their trends may be inconsistent dependent on material type. E.g. for the Texas project, E_{LWD} showed a reduction in the average value after 12 passes, likely because of surface de-compaction. The average ksIPD value reached an asymptotic value by 8 passes and showed an increase from pass 11 to 12 while ICMV increases continuously.
- Compaction curve can show the development of material strength with time. E.g. for the TX TB2 flexible base material, strength gains significantly over time as the material dries

and is further compacted under construction traffic.

- Compaction curve results are very dependent on material type under construction. E.g. compaction curves show higher values (more stiffness) for the weathered shale fill material compared to that of the lean clay fill material (KS projects).
- Compaction curve is affected by material moisture condition, and the dry and optimum moist result in higher ICMV for each roller pass (e.g. TX project).
- The sloping grade of compaction area also affects the compaction curve. E.g., for the KS TB3 subgrade the MDP_{80} compaction curves of driving downhill (north to south) are higher than that of driving uphill (south to north).

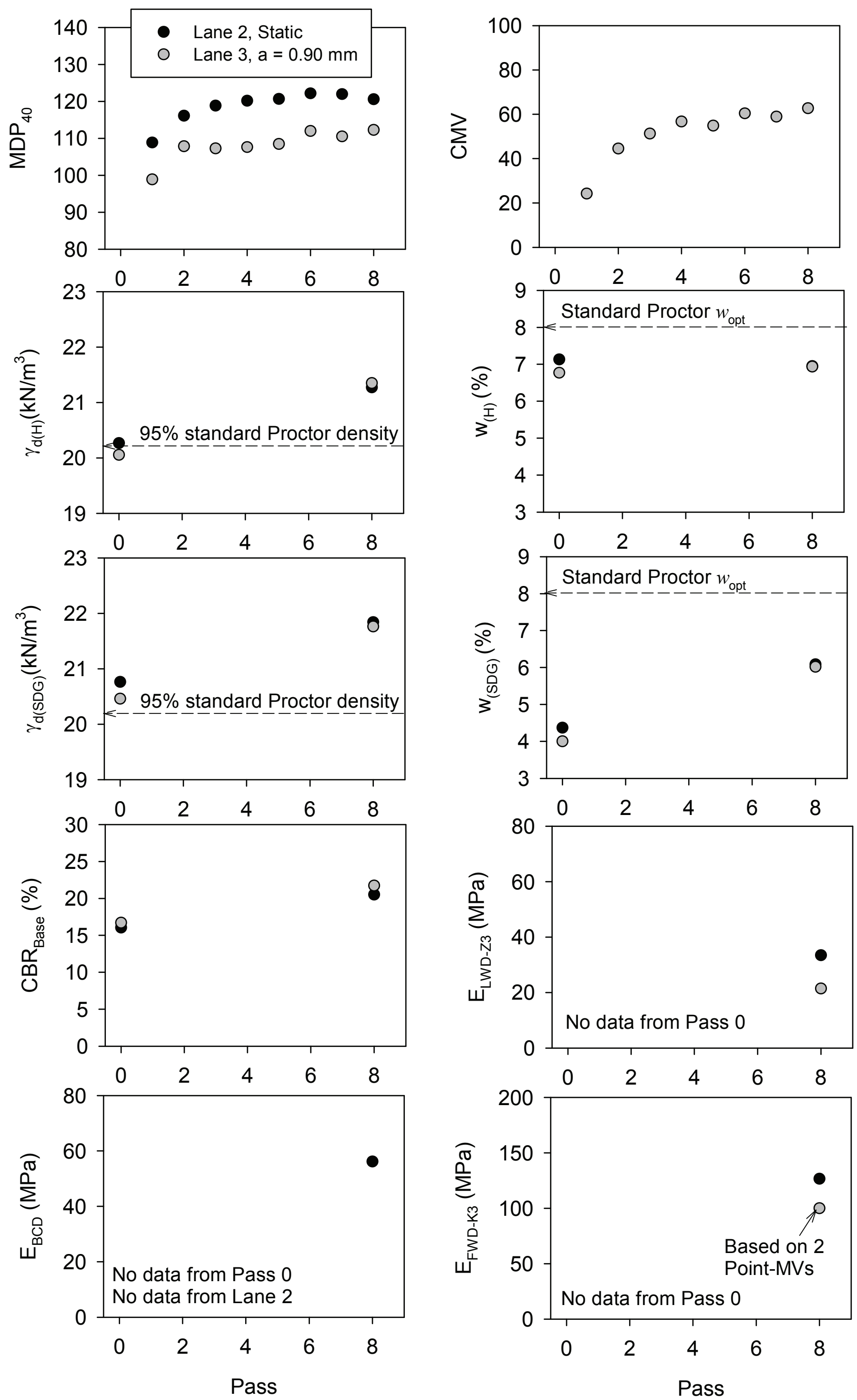


Figure 81. NY project: average ICMV and In-situ measurement compaction curves on lanes 2 and 3 – TB4 gravel subbase material

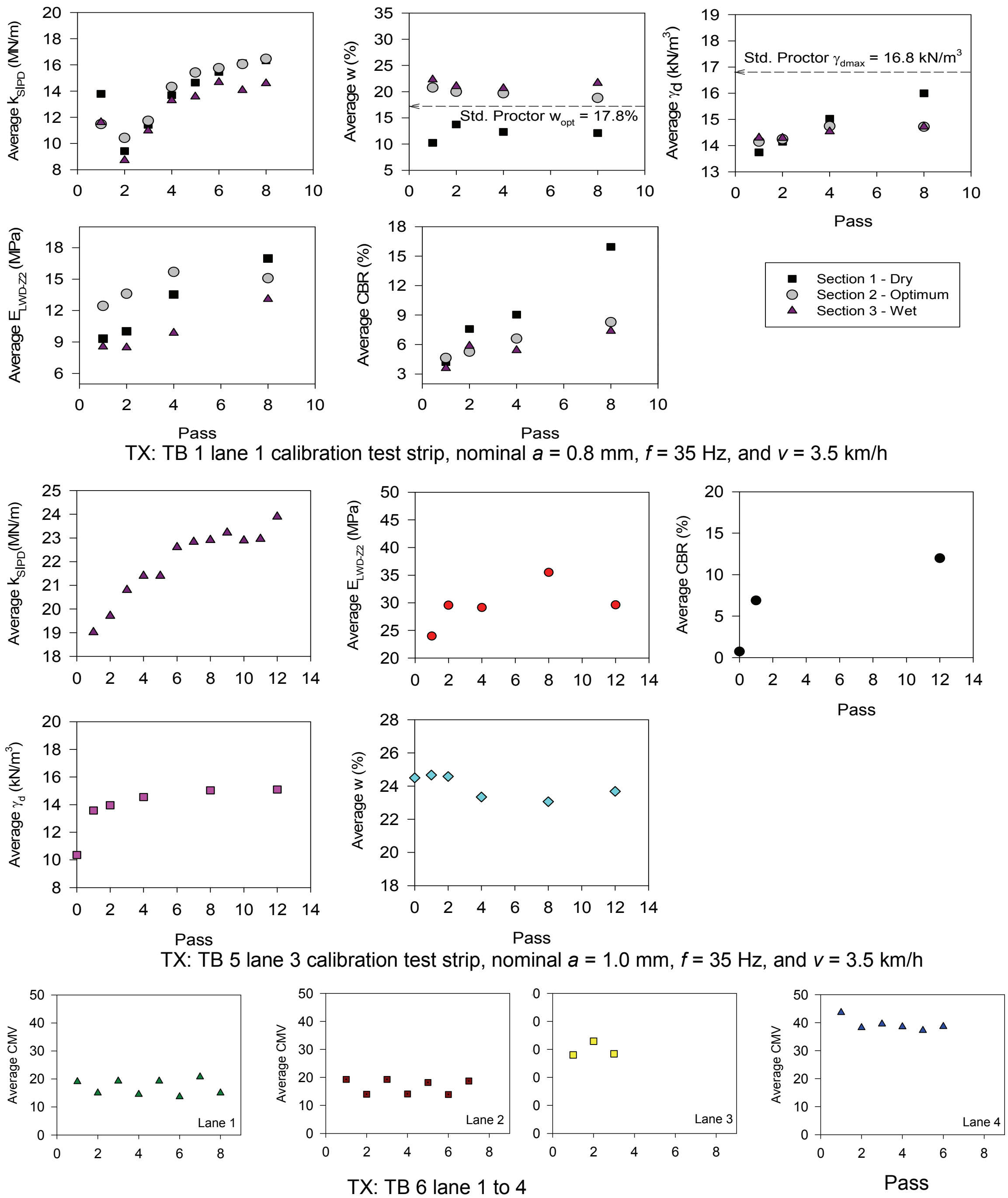
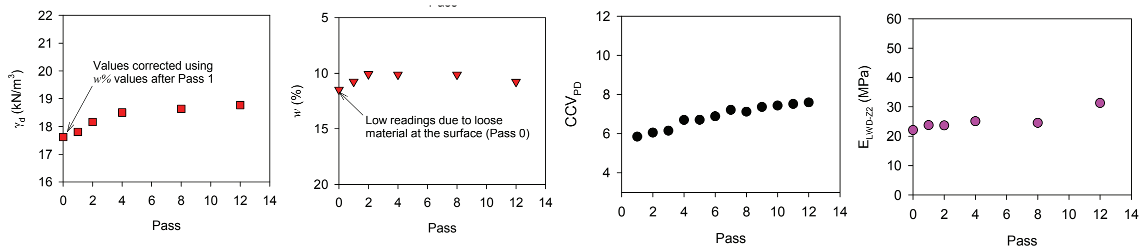
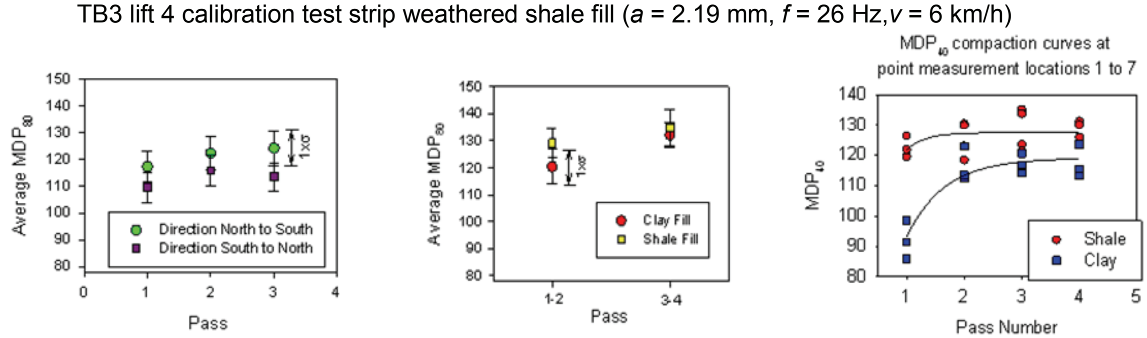


Figure 82. TX project: average ICMV and In-situ measurement compaction curves

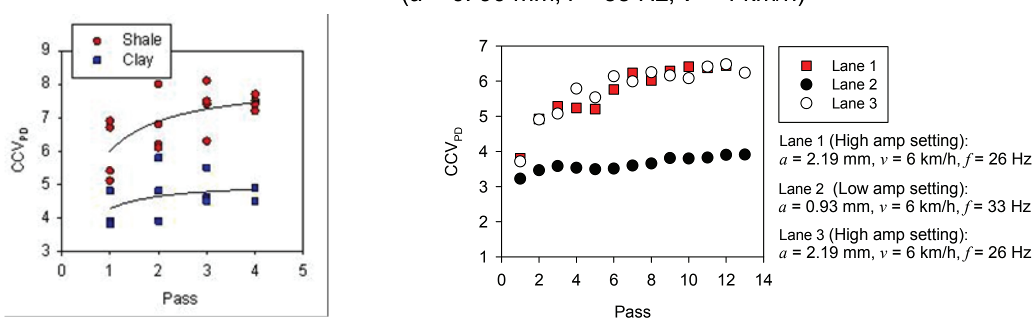


TB3 lift 4 calibration test strip weathered shale fill (*a* = 2.19 mm, *f* = 26 Hz,*v* = 6 km/h)



KS: TB3 foundation subgrade layer KS: TB3 lift 1 clay and shale fills KS: TB3 lift 3 clay and shale fills

(*a* = 0. 90 mm, *f* = 33 Hz, *v* = 4 km/h)



KS: TB3 lift 4 clay and shale fills KS: TB4 subgrade clay material lanes 1, 2, and 3

Figure 83. KS project: average ICMV and In-situ measurement compaction curves

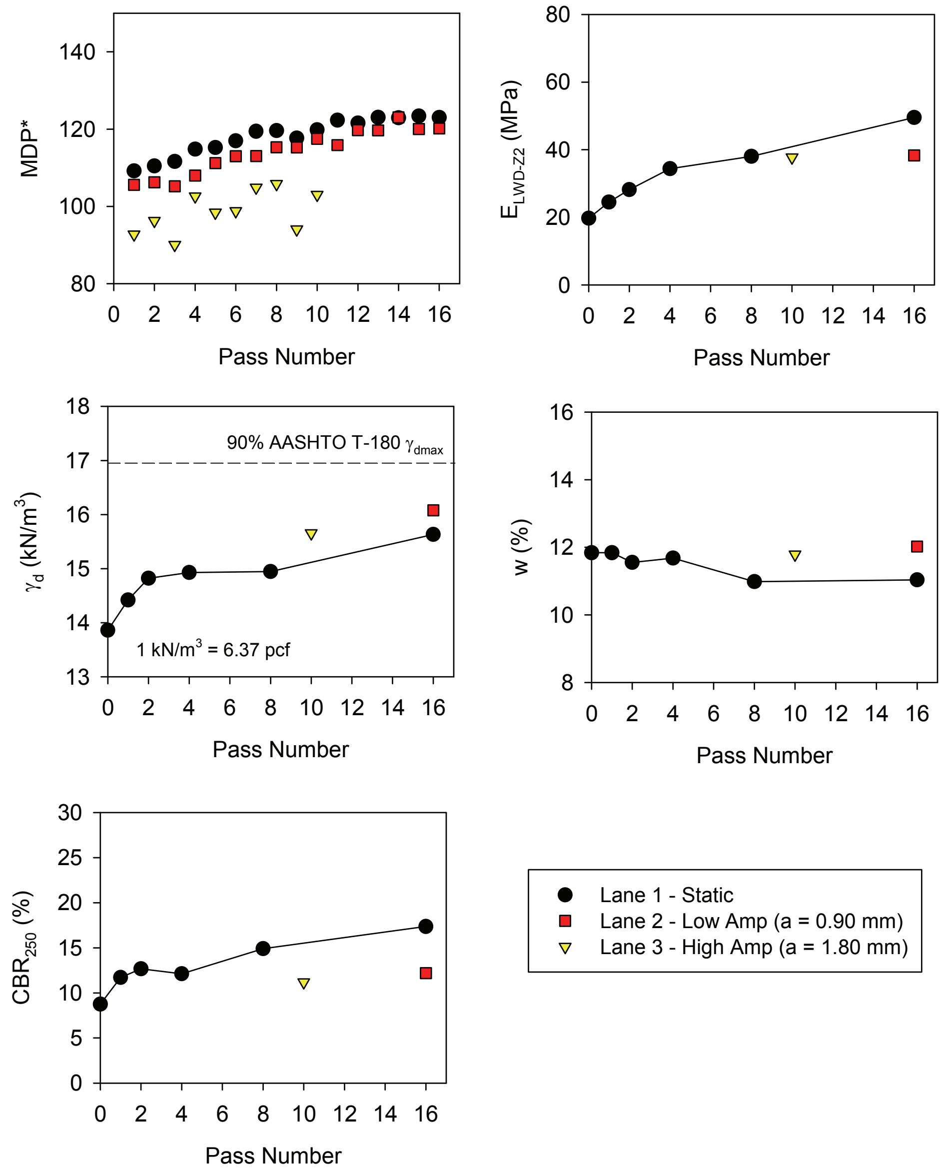


Figure 84. ND average MDP* and in-situ point measurement values with increasing roller passes on lanes 1 to 3 – TB1

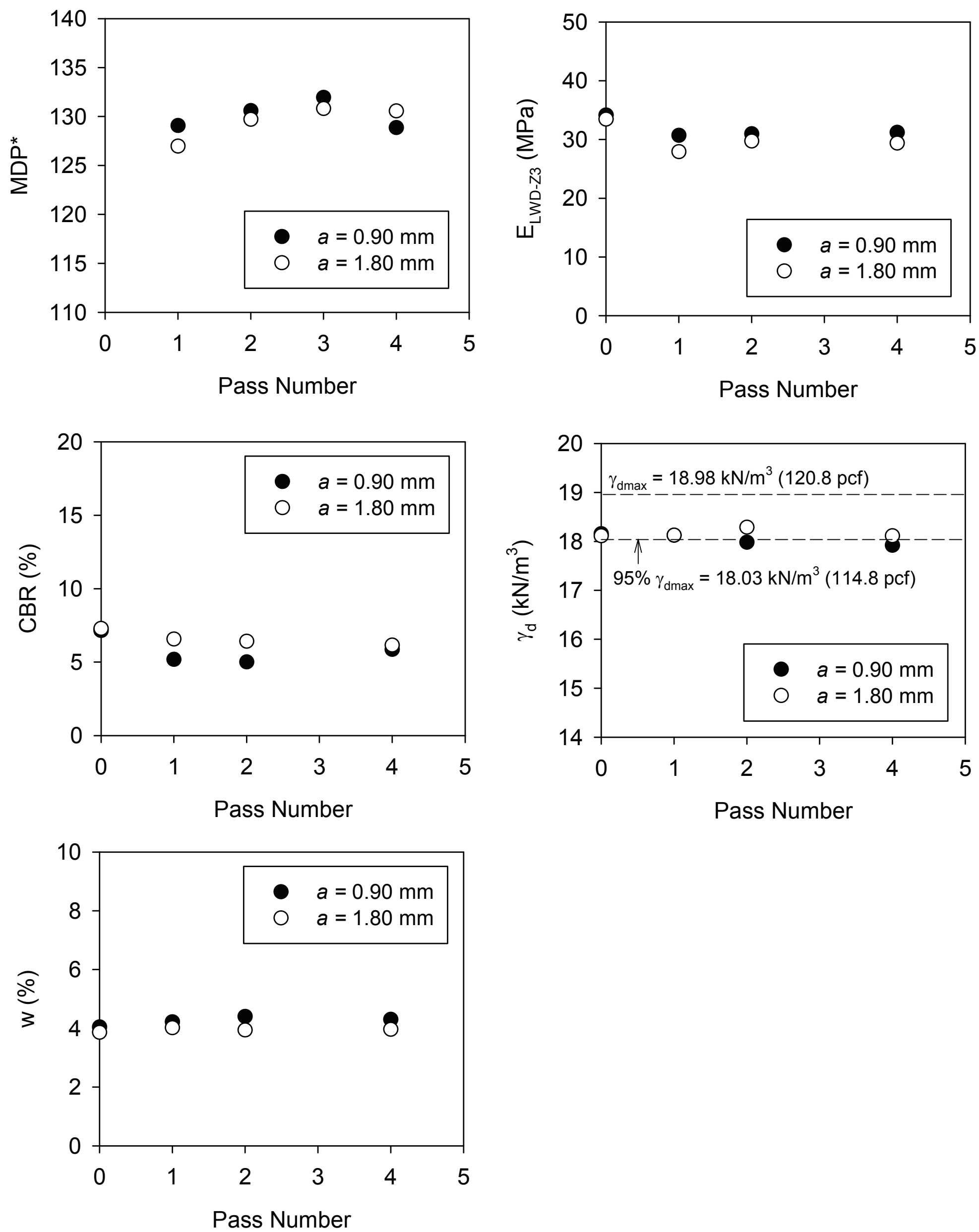


Figure 85. Indiana MDP* and in-situ point-MV compaction curves lane 1 (*a* = 0.90 mm) and lane 2 (*a* = 1.80 mm) – TB1 granular embankment fill

Compaction Uniformity

Compaction uniformity is evaluated using the Geostatistical semi-variogram knowledge. Kriging (e.g. ordinary Kriging) is used to pre-preprocess the geospatial data before doing the geostatistical analysis. Kriging is a method to estimate a value at a point of a region for which a variogram is known, using data in neighborhood of the estimation location (Wackernagel, 1998). Basically, Kriging normally provide better interpolation of a spatial data points. Consequently, semi-variograms are computed with the parameters presented. Figure 86 to Figure 90 show the semi-variograms of the Texas, Kansas, New York, Mississippi, and North Dakota, respectively. The main findings are summarized as follows:

- Results show that usually a higher vibration amplitude results in lower compaction uniformity (e.g. for the TX demonstration, a higher sill is achieved when using an amplitude a = 1.1 mm than using a = 0.9 mm). The reasons for a difference in sill values of CMV for different machine amplitude settings are attributed to the materials' response to different stress conditions and possibly different influence depths. Increasing amplitude increases the contact stresses under the roller drum and is also believed to increase the depth of influence under the drum.
- Geostatistical studies have shown the advantage of using spatial geostatistics for a better characterization of non-uniform conditions than using univariate statistics. E.g. for the Texas TB7 flexible base, the ICMVs for vibration amplitudes of 1.1 mm and 0.9 mm have similar COV values though with very different semi-variogram sill values, which differentiate the uniformity of compacted area with different machine settings.
- Results also show that the uniformity variation is not consistent with pass number. With more pass number, uniformity may increase (e.g. semivarigram sill value decreased for caterpillar MDP80 of KS and NY demonstration projects), or decrease (e.g. sill value increased for Sakai CCV of lift 6 of NY project, see Figure 88). The range values may decrease slightly with more pass counts (e.g. range decreases from 2 m to 1.6 m as seen in Figure 87), which suggests a decrease in spatial continuity.
- Geostatical semi-variograms also differentiate the uniformity of different materials or with various treatments. E.g. for the KS project (see Figure 87), MDP80 on weathered shale fill was more uniform compared to MDP80 on lean clay fill with lower sill values. Their range values are also different indicating their different spatial continuity.
- No consistent proof to show whether manual mode or AFC mode achieves a higher uniformity. E.g. for the NY project TB8, the manual model shows higher uniformity (with lower sill value), while for the TB3 the manual model shows lower uniformity (with higher sill value).
- Curing seems to increase non-uniformity of both ICMV and in-situ measurements (e.g. KS TB8 2-day curing results in higher non-uniformity compared to TB3 no curing). This increasing non-uniformity is attributed to various factors such as non-uniform application of cement, water content, mixing, compaction delay time, and compaction energy across the test bed area, etc.

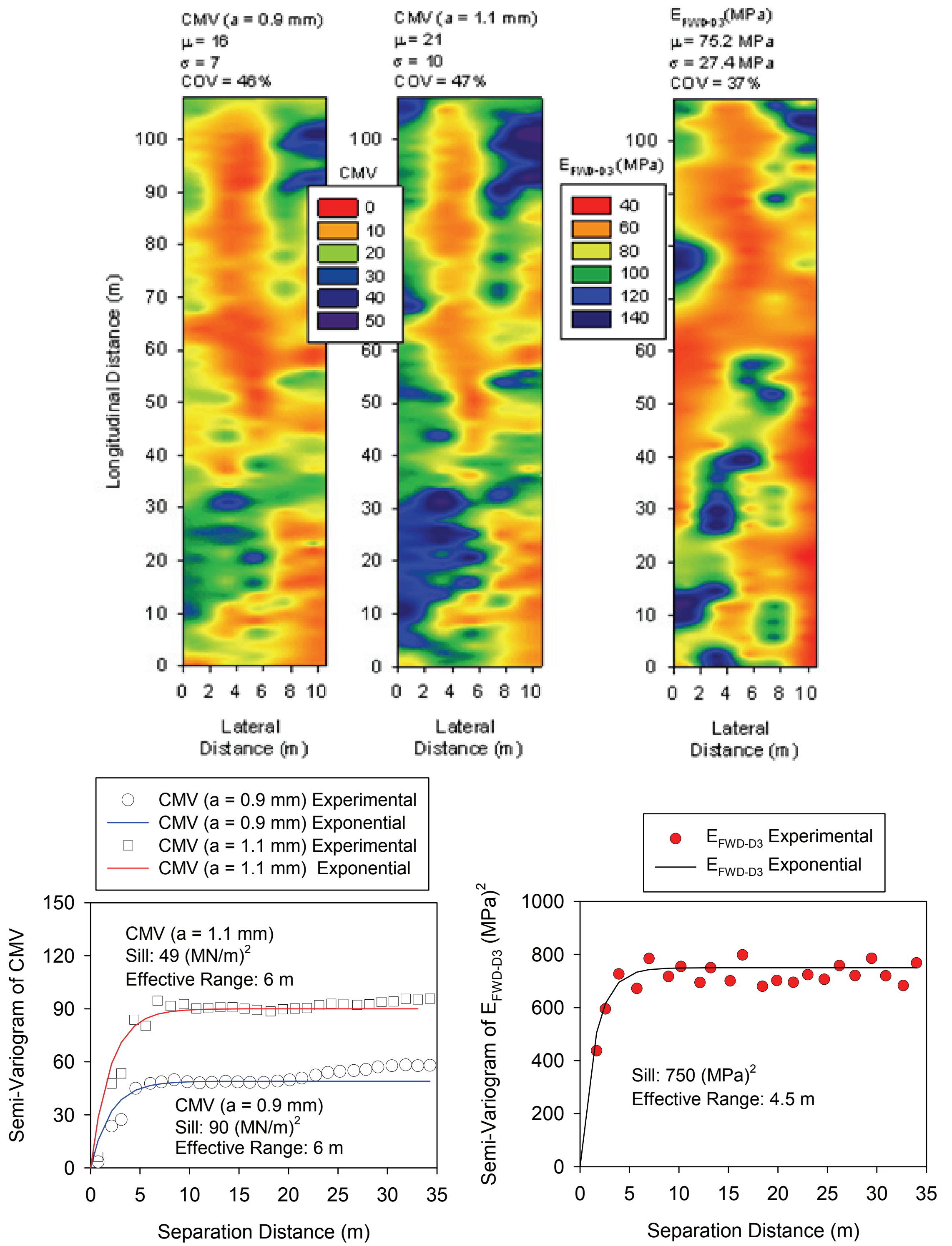
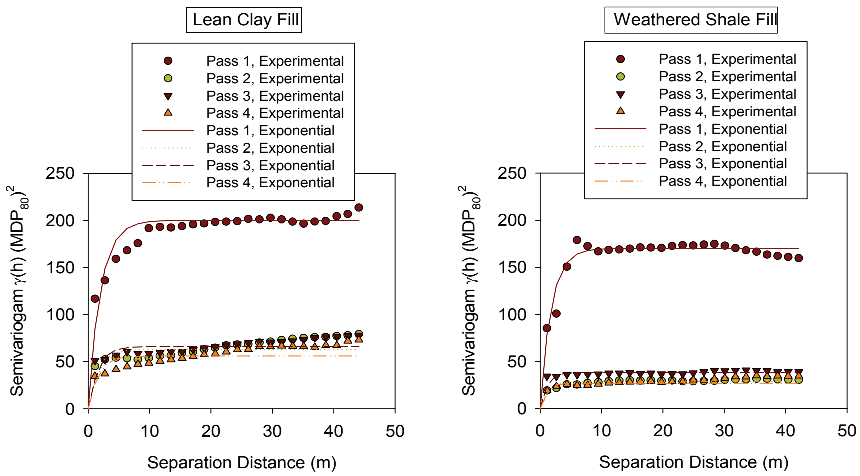
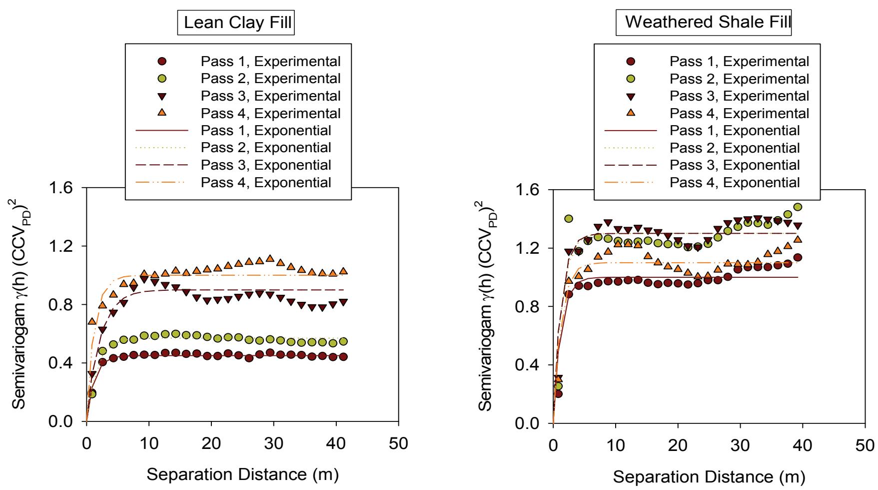


Figure 86. Texas Kriged contour maps and semi-variograms of CMV and E_{FWD} on TB 7 flex base material.



KS: TB3 – lift 3 lean clay and weathered shale fill materials, Caterpillar MPD



KS: TB3 – lift 6 lean clay and weathered shale fill materials, Sakai CCV

Figure 87. KS project: change in semi-variograms, spatial statistics of Caterpillar MDP and Sakai CCV with pass.

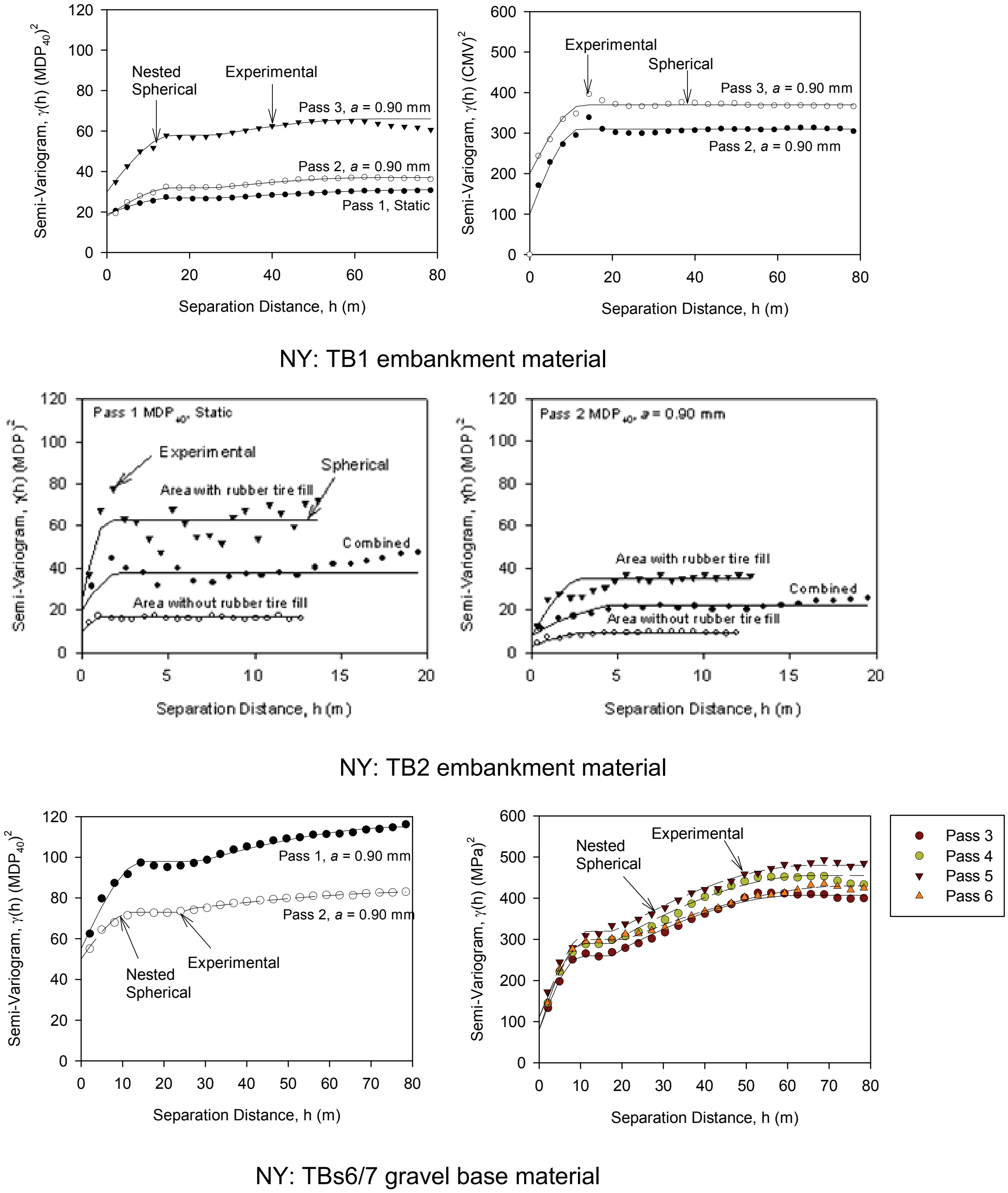


Figure 88. NY project: semi-variograms of ICMV for different passes.

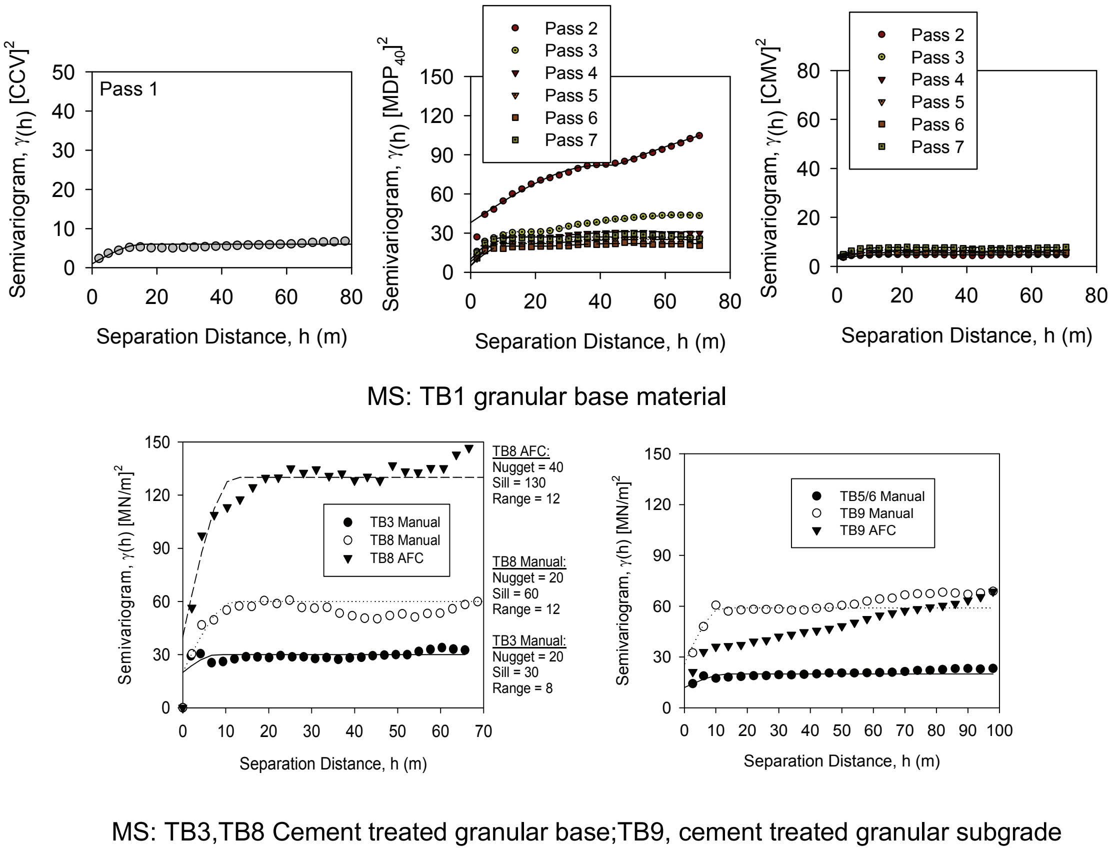
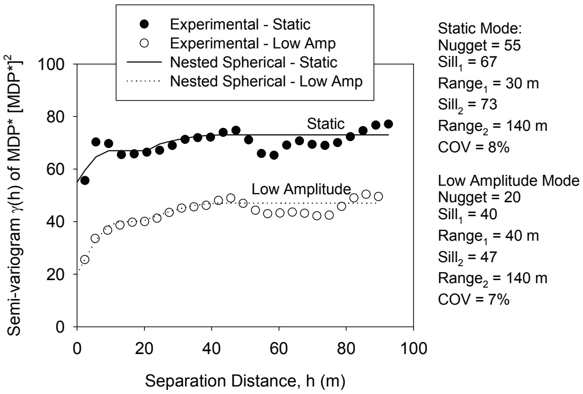
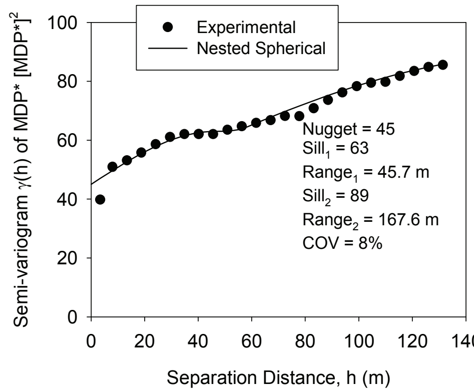


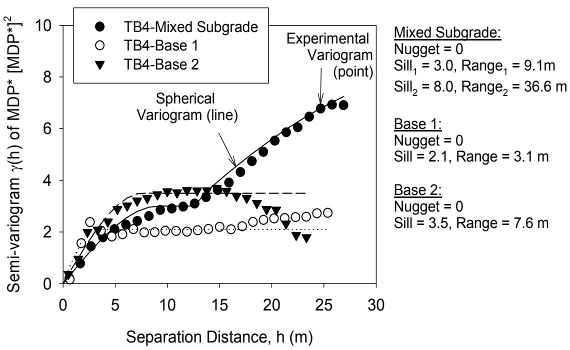
Figure 89. MS project: semi-variograms of ICMV for different passes and manual/AFC controls.



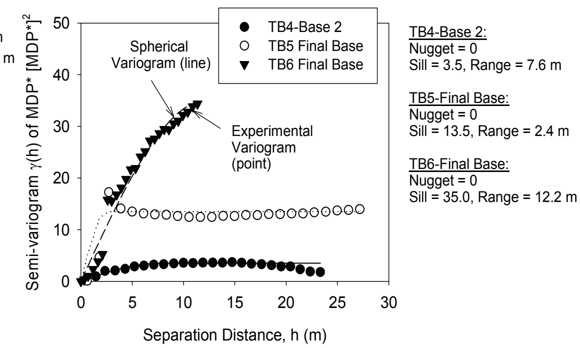
MDP* from static and low amplitude mapping passes – TB3



MDP*mapping pass – TB7

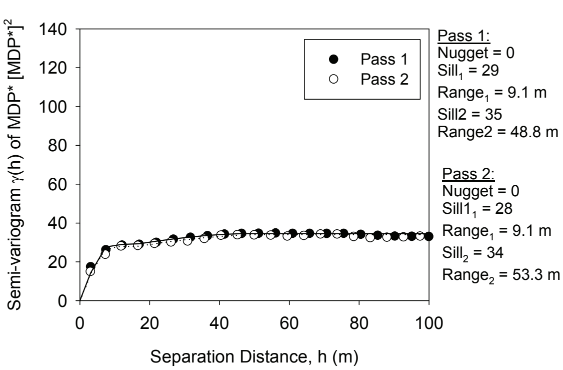


Comparison of MDP semivariograms on TB 4 mixed subgrade, base 1, and base 2 layers,

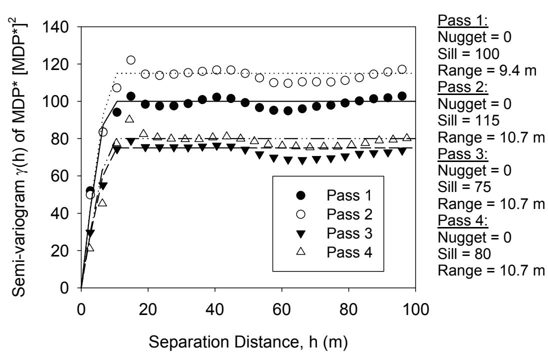


Comparison of MDP semivariograms on TB4, 5, and 6 base layers

Figure 90. ND project: semi-variograms of roller MDPs.



Granular embankment fill base lift 1



Granular embankment fill base lift 2

Figure 91. INDOT project: semi-variograms of roller MDPs (granular embankment fill).

Correlation Study

Univariate correlation

The univariate linear or logarithmic-scaled linear regression method is used to correlate ICMVs with in-situ measurements, which includes four types: 1) direct linear to linear correlation; 2) linear correlation of ICMV vs. logarithmical scaled in-situ measurements, presenting in a log function of ICMV vs. in-situ measurement; 3) linear correlation of logarithmic scaled ICMV vs. in-situ measurements, presenting in a exponential function of ICMV vs. in-situ measurement; and 4) linear correlation of logarithmic scaled both ICMV and in-situ measurements, presenting in a power function of ICMV vs. in-situ measurement.

Correlation of ICMV to LWD Moduli

Figure 92 present the correlation results between ICMVs and E_{LWD} from LWD measurements. The main conclusions are summarized as follows:

- ICMV increases with increasing E_{LWD} as expected, and generally they have a good linear correlation (with $R^2 > 0.60$);
- Dependent on the specific test strip and materials used, either the direct linear, or the logarithmic scaled linear function may better represent their linear correlation;
- ICMVs under the machine static mode also shows good linear correlation with in-situ measurements (e.g. NY and KS MDP40);
- For some cases, the relatively poor correlation is obtained (e.g. NY TBs1 and 2, CMV), which could be due to the more narrow range of ICMVs and limited in-situ test points.
- No obvious evidence shows that the machine settings such as frequency, amplitude and speed will affect the correlation quality (e.g. TX TB1);
- The correlation and variation trend of ICMV with in-situ measurement are very dependent on materials used (e.g. KS TB3 foundation shale and clay materials; TX TB2 stabilized subgrade and flexible base); separate trends of the same project but with different materials could be a result of differences in the underlying support, material, and moisture conditions.

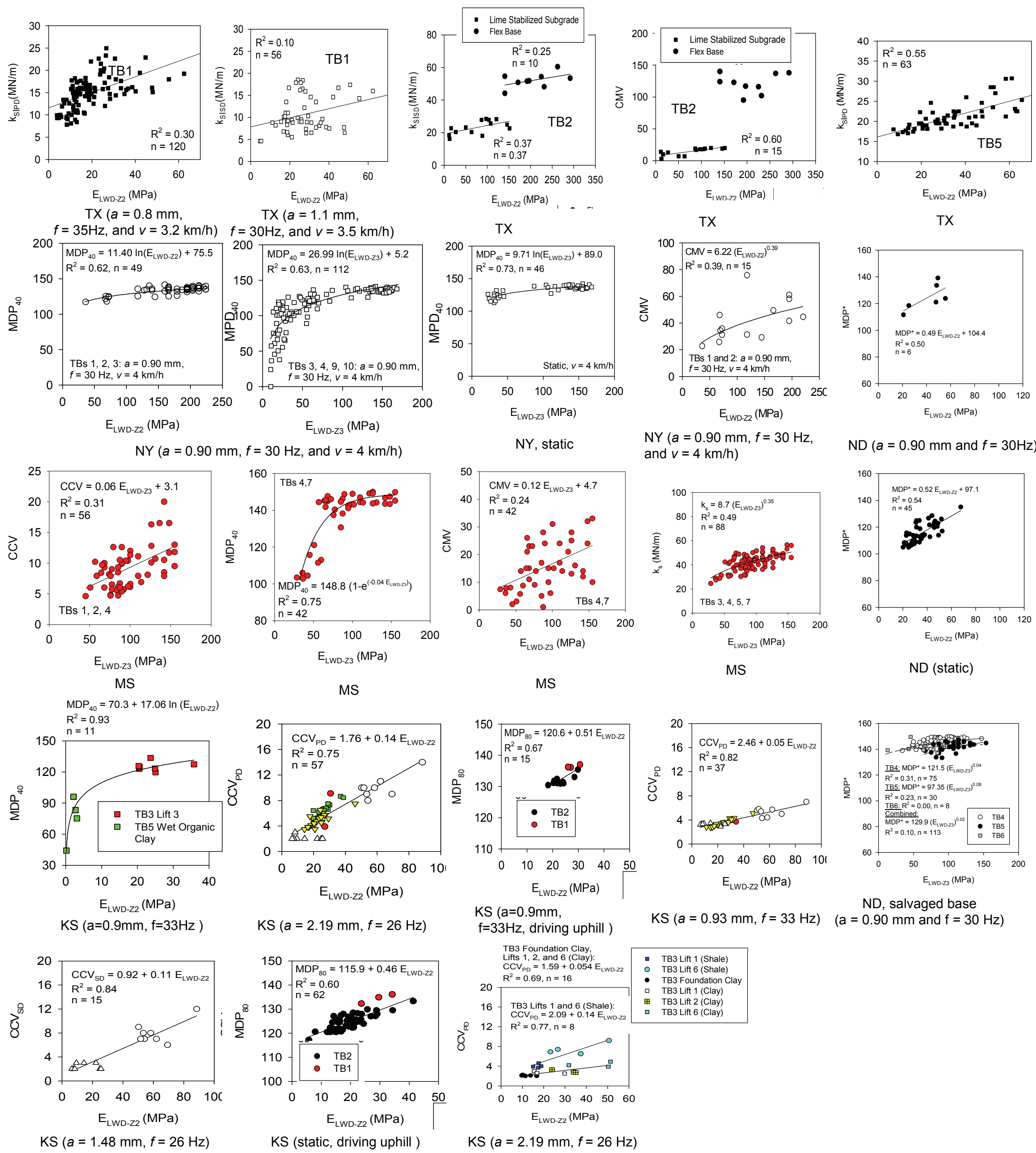


Figure 92. ICMVs vs. LWD measurements.

Correlation of ICMV to FWD moduli

Figure 93 present the correlation results between ICMVs and LWD measurement of ELWD. The main conclusions are summarized as follows:

- ICMV increases with increasing E_{FWD} as expected, and they have shown a good linear correlation (i.e. $R^2 > 0.66$);
- Dependent on the specific test strip and materials used, either the direct linear, or the logarithmic scaled linear function may achieve better correlation;

- ICMVs under the machine static mode also shows good linear correlation with in-situ measurements (e.g. KS MDP80);
- There are no evidences to show the influences of machine settings including amplitude and frequency on their correlation relationship;
- Separate trends are observed for different materials (e.g. TX TB2 lime treated subgrade and flexible base), which could be a result of differences in the underlying support, material, and moisture conditions, etc.

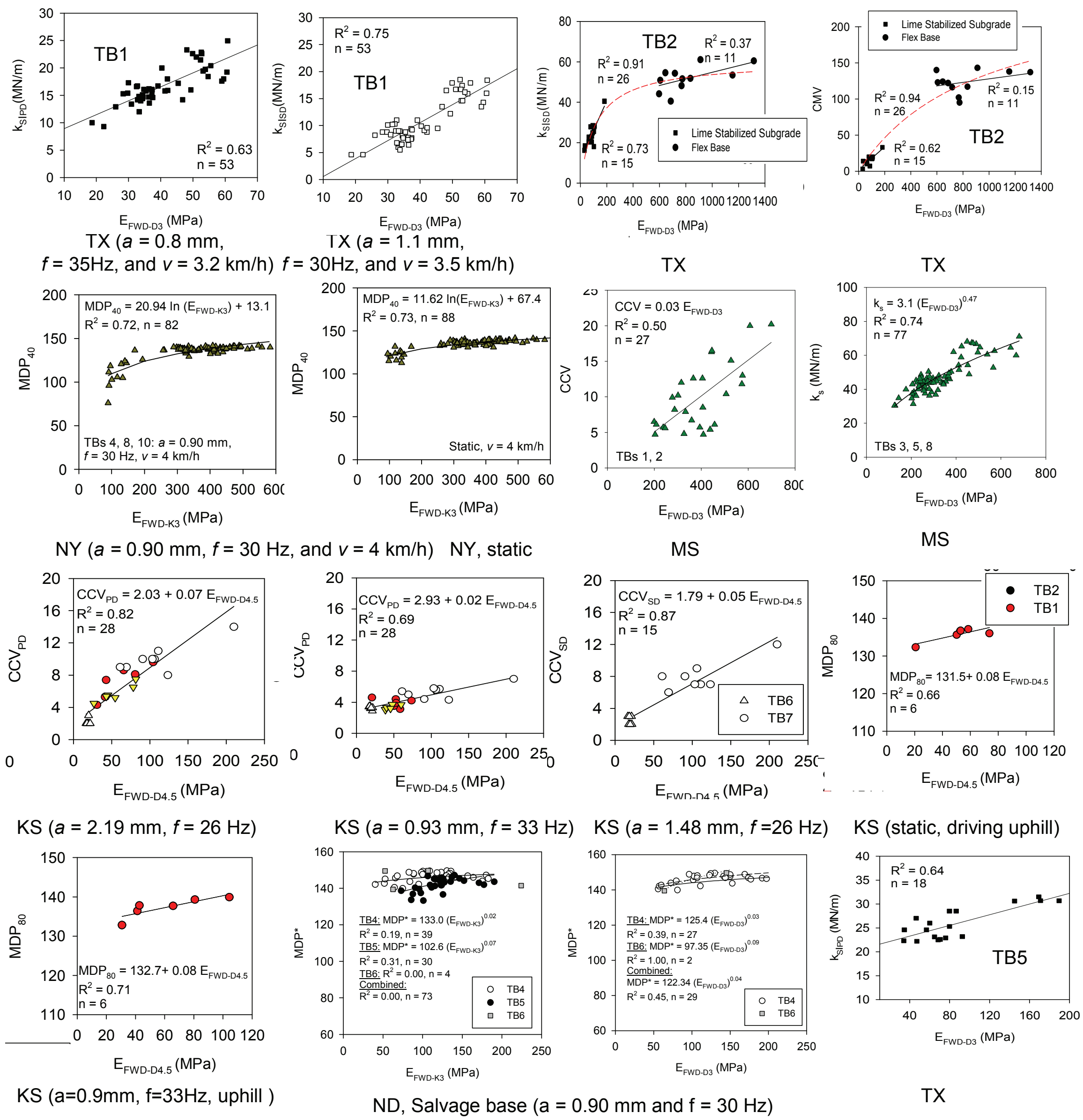


Figure 93. ICMVs vs. FWD measurements.

Correlation of ICMV to Ev1 and Ev2 of Plate Loading Tests

- Figure 94 presents the correlation results between ICMVs and LPD measurement of Ev1 and EV2. The main conclusions are summarized as follows:

- ICMV increases with increasing Ev1 and Ev2 as expected, but generally they shower a poorer correlation than that between ICMVs and LWD and FWD measurements (e.g. for the MS TBs 1,2, 4 CCV with a R^2 value of 0.18 only);
- Dependent on the specific test strip and materials, either the direct linear, or the logarithmic scaled linear function may achieve better correlation;
- There is no obvious evidence to show that the machine settings (vibration frequency, amplitude, operating speed) will affect the correlation quality;
- E_{v1} and E_{v2} have different correlation parameters with ICMVs.

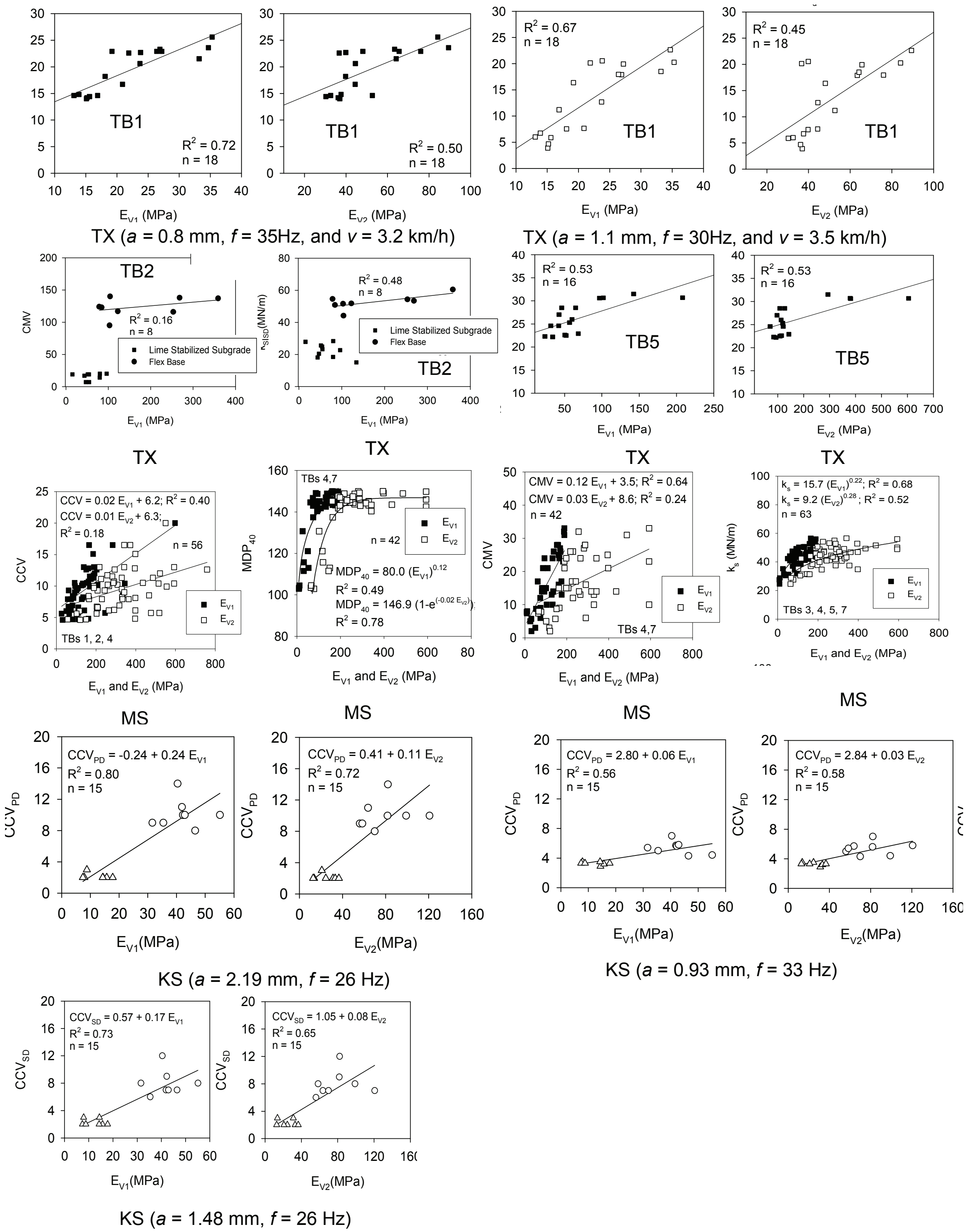


Figure 94. ICMVs vs. Plate Loading Tests.

Correlation of ICMV to DCP measured CBR

Figure 95 presents the correlation results between ICMVs and penetration measured CBR values. The main conclusions are summarized as follows:

- ICMV increases with increasing CBR as expected, and overall they show relatively poorer correlation than that between ICMVs and E_{LWD} and E_{FWD}. For some projects, relatively good correlations are achieved such as the MS TBs 4 and 7, while for some other projects relatively poorer correlations are achieved such as KS CCVPD (R^2 of 0.13);
- Dependent on the specific test strip and materials, either the direct linear, or the logarithmic scaled linear function may achieve better correlation than the other.

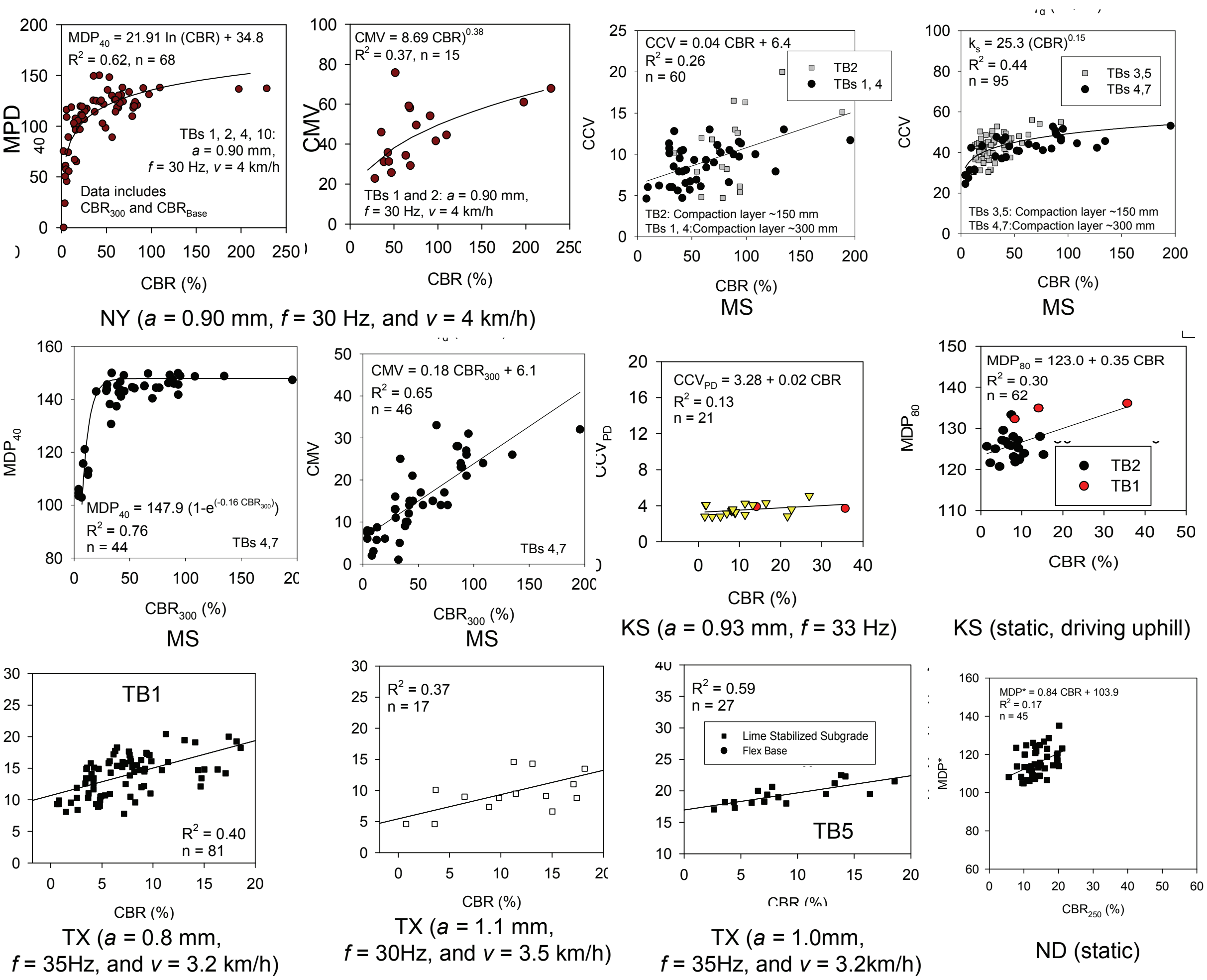


Figure 95. ICMVs vs. DCP tests.

Correlation of ICMV to NG dry unit density

Figure 96 present the correlation results between ICMVs and the NG dry unit density r_d. The main conclusions are summarized as follows:

- ICMV increases with increasing r_d as expected, and overall a poorer correlation is achieved than that of E_{LWD}, E_{FWD}, and E_{V1} and E_{V2};
- Dependent on the specific test strip and materials, either the direct linear, or the logarithmic scaled linear function may achieve better correlation;
- For some cases, significant scatter in the relationships is shown (e.g. MS TBs1, 2, 4 CCV, and KS TB1 and TB2 MDP80). These values are likely influenced by different material type encountered and narrow range of MDP80 values on each material type.
- Different materials show different correlation results and variation trends (e.g. KS TB3 foundation shale and clay materials). These separate trends could be a result of differences in the underlying support, material, and moisture conditions.

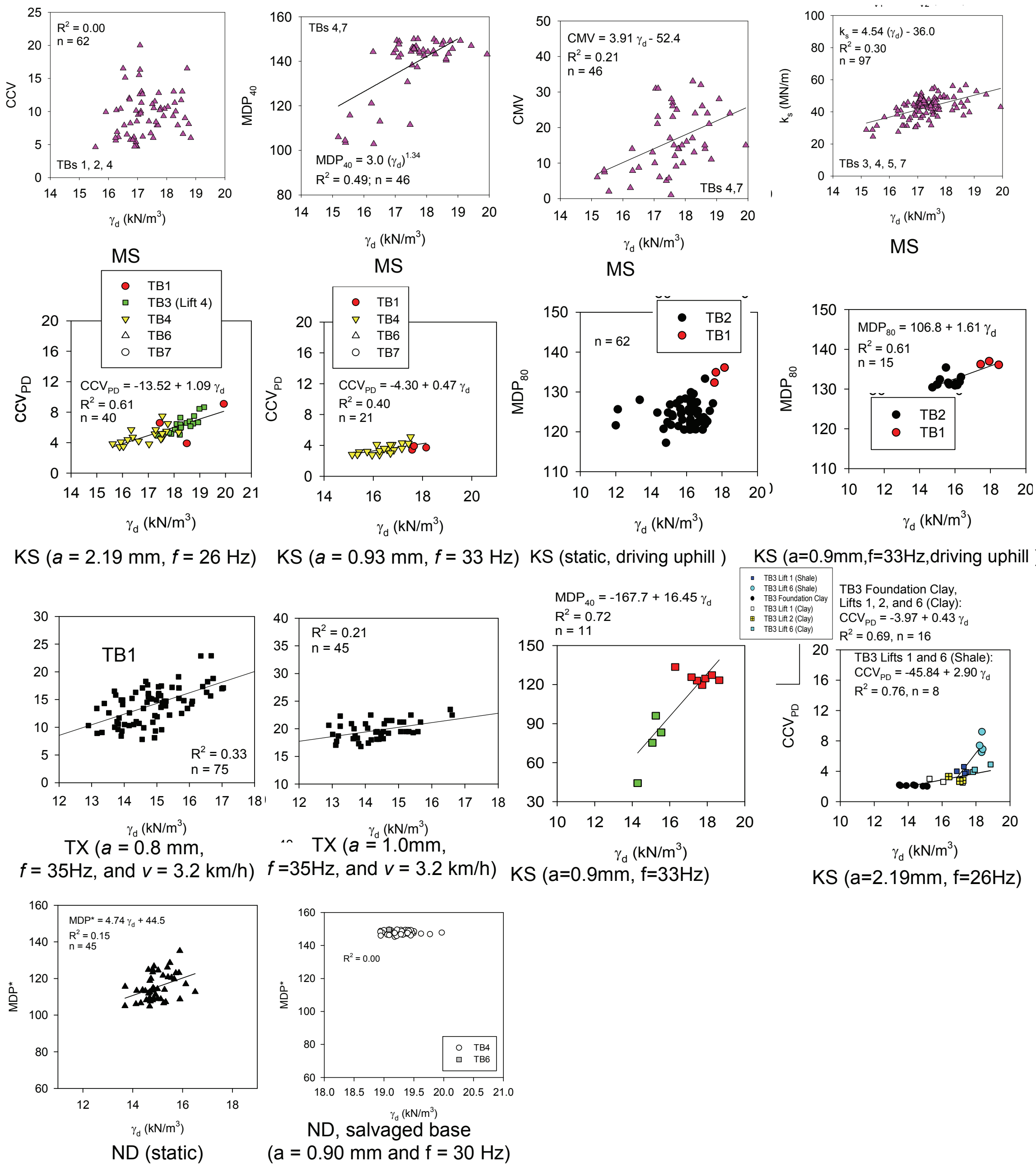


Figure 96. ICMVs vs. NG densities.

Multivariate Correlation

ICMV is potentially influenced by various factors, and therefore a multivariate analysis is warranted to study these effects. Here multiple regression analysis is performed to statistically assess the influence of soil moisture content and vibration amplitude.

The selected criteria for identifying the significance of a parameter included: p-value < 0.05 = significant, < 0.10 = possibly significant, > 0.10 = not significant, and t-value < -2 or $> +2$ = significant. The *p*-value indicates the significance of a parameter and the *t*-ratio value indicates the relative importance (i.e., higher the absolute value greater the significance).

Table 11 summarized the multiple regression analysis of CCV_{PD} and MDP_{80} for the KS demonstration project. Analysis results show that amplitude is statistically significant in relating all in-situ point measurement values (E_{LWD-Z2}, $E_{FWD-D4.5}$, γ_d, CBR, E_{V1}, and E_{V2}). For $CCV_{PD,}$ moisture content w is statistically significant for E_{LWD-Z2}, γ_d, and CBR (note that limited w measurements were available at other point measurement locations). For MDP_{80} w is statistically significant for γ_d. Table 12 summarized multiple regression analysis of E_{VIB} for the NY demonstration project. Results indicate that amplitude is significant for E_{VIB} relationships with in-situ measurements (E_{LWD-Z3}, E_{BCD}, and $\gamma_{d(H)}$) and also contribute to increased R^2 values.

However, it should be noted that the intercept of multivariate regression was not always statistically significant. Considering the NY project $E_{FWD-D4.5}$ for example, the R^2 value with amplitude incorporated in the model showed an $R^2 = 0.68$ which is lower than R^2 values obtained from the univariate linear regression analysis separating results from different amplitudes ($R^2 =$ 0.69 and 0.82). This is important to note and in such cases, it is appropriate to interpret the relationships separately for different amplitude settings, instead of combining the results. Nevertheless, it is recommended that all measurements obtained from calibration areas and production areas during QA should be obtained at a constant amplitude setting to avoid complication in data analysis and interpretation.

Table 11. KS, results of multiple regression analysis for influence of amplitude and moisture content on CCV_{PD} – TBs 1, 3(lift4), 4, 6, and 7 and MDP_{80} – TBs 1 and 2

Model	Term	Estimate	Std Error	*t* Ratio	*P* value	R^2
$CCV_{PD} = b_0 + b_1 E_{LWD\text{-}Z2} + b_2 a + b_3 w$	b_0	2.27	1.13	1.99	0.05	0.8
	b_1	0.1	0.02	5.97	<0.0001	
	b_2	1.36	0.2	6.89	<0.0001	
	b_3	-0.16	0.05	-3.09	0.0031	
$CCV_{PD}^{\dagger} = b_0 + b_1 E_{FWD\text{-}D4.5} + b_2 a$	b_0	-0.07	0.62	-0.11	0.92	0.7
	b_1	0.04	0.01	9.38	<0.0001	
	b_2	1.64	0.33	4.94	<0.0001	
$CCV_{PD} = b_0 + b_1 \gamma_d + b_2 a + b_3 w$	b_0	-10.47	3.16	-3.32	0.0016	0.8
	b_1	0.85	0.15	5.74	<0.0001	
	b_2	0.86	0.2	4.31	<0.0001	
	b_3	-0.06	0.06	-2	0.098	
$CCV_{PD} = b_0 + b_1 CBR + b_2 a + b_3 w$	b_0	3.6	1.36	2.64	0.012	0.6
	b_1	0.07	0.02	3.94	<0.0001	
	b_2	1.15	0.22	5.27	<0.0001	
	b_3	-0.13	0.08	-2.1	0.099	
$CCV_{PD}^{\dagger} = b_0 + b_1 E_{V1} + b_2 a$	b_0	-1.18	1.25	-0.95	0.35	0.6
	b_1	1.57	0.62	2.55	0.017	
	b_2	0.15	0.02	5.95	<0.0001	
$CCV_{PD}^{\dagger} = b_0 + b_1 E_{V1} + b_2 a$	b_0	-0.84	1.29	-0.65	0.52	0.6
	b_1	1.58	0.65	2.44	0.0217	
	b_2	0.07	0.01	5.47	<0.0001	
$MDP_{80}^{*} = b_0 + b_1 E_{LWD\text{-}Z2} + b_2 a$	b_0	115.32	1.07	107.5	<0.0001	0.7
	b_1	0.51	0.05	9.99	<0.0001	
	b_2	2.5	0.43	5.81	<0.0001	
$MDP_{80} = b_0 + b_1 \gamma_d + b_2 a + b_3 w$	b_0	89	9.21	9.67	<0.0001	0.4
	b_1	1.54	0.43	3.6	0.0006	
	b_2	2.45	0.62	3.96	0.0002	
	b_3	0.84	0.25	3.37	0.0011	
$MDP_{80}^{*} = b_0 + b_1 CBR + b_2 a$	b_0	123.21	1.22	101	<0.0001	0.5
	b_1	0.34	0.1	3.57	0.0016	
	b_2	4.45	1.75	2.55	0.0178	

a: amplitude, *w*: moisture content

Table 12. NY, Summary of multiple regression analysis – TB10 lane 2

Model	Term	Estimate	Std Error	*t* Ratio	*P* value	R^2
$E_{VIB} = b_0 + b_1 E_{LWD\text{-}Z3} + b_2 a$	b_0	61.69	21.17	2.91	0.0051	0.4
	b_1	1.19	0.22	5.51	<0.0001	
	b_2	-17.94	11.92	-3.51	0.0374	
$E_{VIB} = b_0 + b_1 E_{BCD} + b_2 a$	b_0	283.02	46.15	6.13	<0.0001	0.7
	b_1	1.27	0.35	3.66	0.0008	
	b_2	-238.72	41.55	-5.75	<0.0001	
$E_{VIB} = b_0 + b_1 \gamma_{d(H)} + b_2 a$	b_0	-330.3	101.86	-3.24	0.0022	0.4
	b_1	24.72	5.42	4.56	<0.0001	
	b_2	-29.64	11.7	-2.53	0.0146	
$E_{VIB} = b_0 + b_1 CBR_{300} + b_2 a$	b_0	87.46	24.42	3.58	0.0009	0.3
	b_1	0.68	0.21	3.2	0.0027	
	b_2	-16.86	15.71	-1.07	0.2899	
$E_{VIB} = b_0 + b_1 E_{FWD\text{-}K3} + b_2 a$	b_0	133.55	36.63	3.65	0.0065	0.6
	b_1	0.29	0.09	3.25	0.0117	
	b_2	-47.35	33.51	-1.41	0.1954	

Chapter 7 Demonstration Projects for HMA IC

This chapter summarizes the results from HMA IC demonstrations under the FHWA/TPF IC project.

State Demonstration Results

Minnesota IC Demonstration

This is the first demonstration and HMA compaction project of this FHWA TPF project. The Sakai SW880 double-drum vibratory roller was used for three highway construction projects conducted in June 2008. The demonstration activities include mapping the subbase layer and paving new HMA base (see Figure 97). The following demonstrations of IC technology were conducted on these projects:

- TH 71 (Renville County) – mapping of asphalt overlay,
- Route 40 (Kandiyohi County) – mapping of asphalt overlay, and
- Route 4 (Kandiyohi County) – mapping of the subbase and asphalt base course and wearing course layers.

The goals of this demonstration project that were successfully accomplished included:

- Demonstration of Hot Mix Asphalt (HMA) IC technology (specifically, tracking rollers passes and HMA surface temperatures) to Mn/DOT personnel, contractors, etc.,
- Evaluation of the benefits and effectiveness of IC rollers vs. conventional rollers,
- Assisting Mn/DOT in the development of IC quality control (QC) specifications for HMA pavement materials, and
- Identification and prioritization of needed improvements and further research for IC equipment.

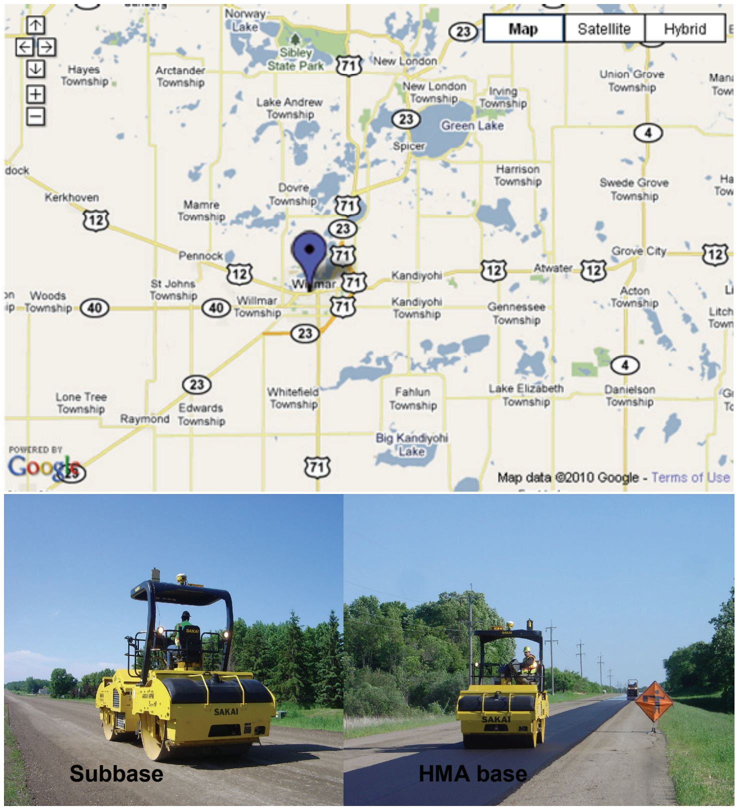


Figure 97. Minnesota HMA IC demonstration.

Major Findings

- IC mapping of the existing base for new HMA construction was shown to be crucial in identifying weak areas prior to the compaction of the asphalt layers.

TH 71 Asphalt Overlay

- This project successfully demonstrated the capabilities of the Sakai IC roller to track roller passes and asphalt surface temperatures using the Sakai CIS system with the Trimble GPS base station for an asphalt overlay.

Route 40 Asphalt Overlay

- This project demonstrated how the roller operator was able to significantly improve the rolling pattern by monitoring the color-coded map on the Sakai CIS display, then adjusting the passes to meet the requirements. Figure 98 shows the rolling pattern before and after the roller operator was trained to make use of the Sakai CIS.

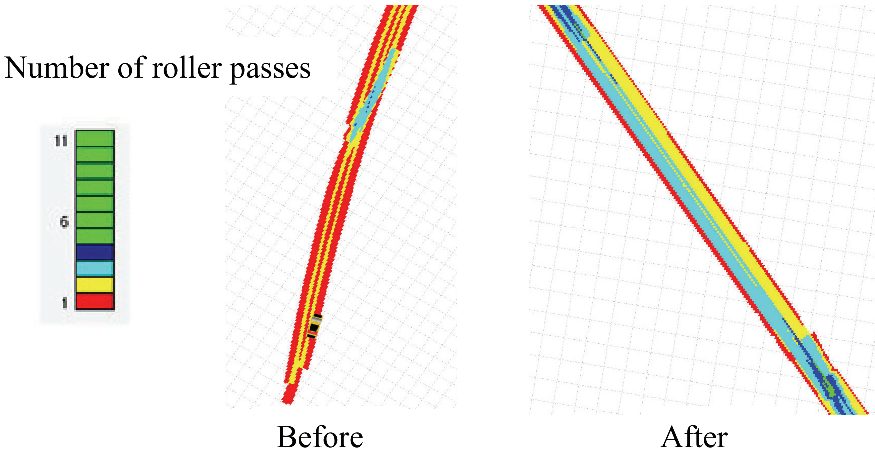


Figure 98. The rolling pattern before and after the roller operator made use of the Sakai CIS.

Route 4 New Asphalt Pavement Construction

This project successfully demonstrated the ability of the IC roller to map the compaction of the subbase, asphalt base course, and asphalt wearing course. The important findings of this project included:

- The Sakai Compaction Control Value (CCV) displayed on the screen allowed the operator to see in real time the relatively softer and stiffer areas of the entire roadway during compaction.

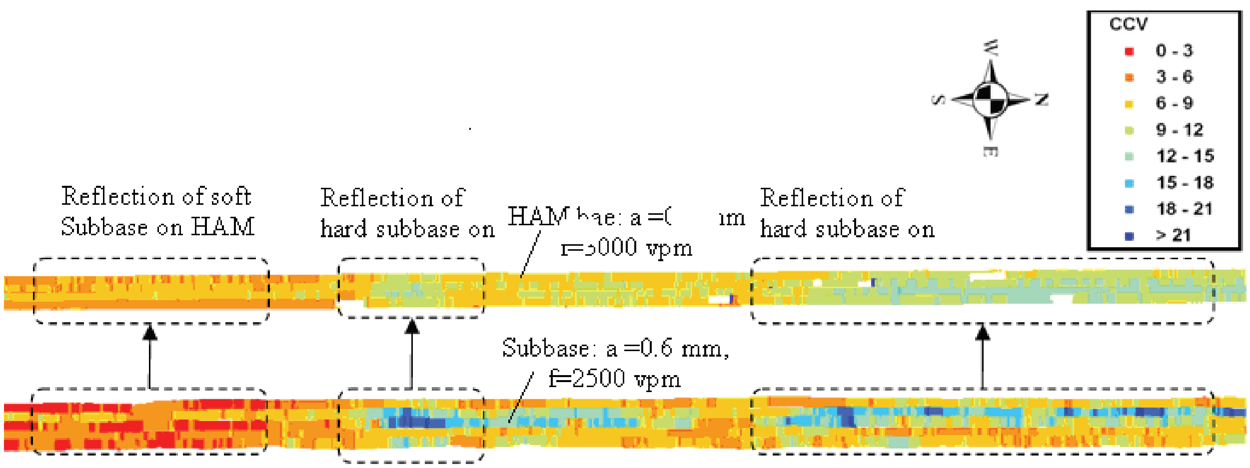


Figure 99. Comparison of CCVs of HMA base course layer and subbase layer mapping.

- The roller operator was able to identify changes in the asphalt mixture when noticing changes in the values shown on the display.
- CCV measurements obtained on the subbase layer at the 0.6 mm (0.024 in.) amplitude setting better distinguished the hard/soft spots compared to CCV measurements obtained at 0.3 mm (0.012 in.) amplitude setting.

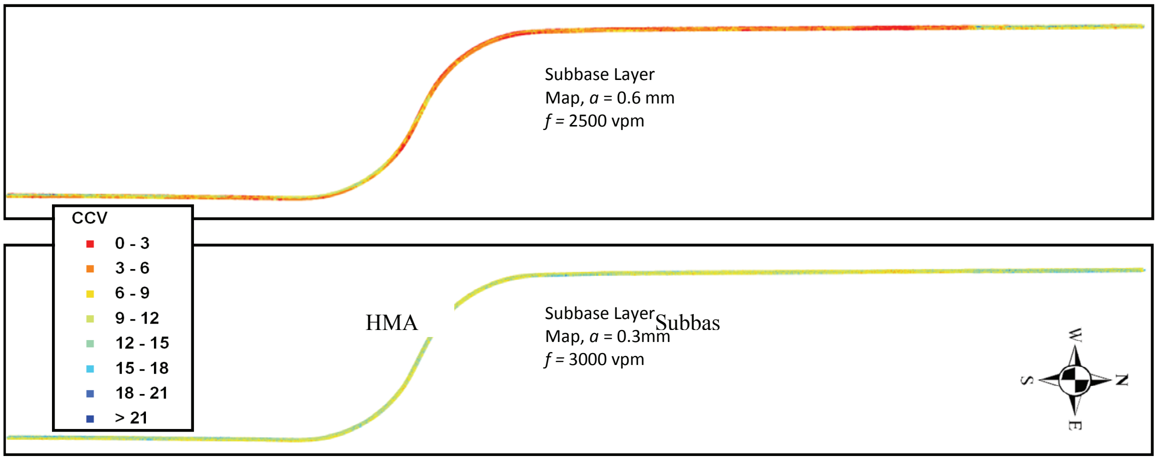


Figure 100. CCVs of HMA base course layer and subbase layer mapping.

- The surface temperature measurements from the roller dot sensor and thermal camera are consistent.
- A pavement section with premature failure of the asphalt base course was verified to be within a weak spot identified during mapping of the subbase using lower frequency (2,500 vpm) and higher amplitude (0.6 mm). This area is located within the area where the subgrade layer reportedly "failed" under the test rolling in summer 2007, and is an area identified on NRCS soil survey maps consisting of peat/muck soils.

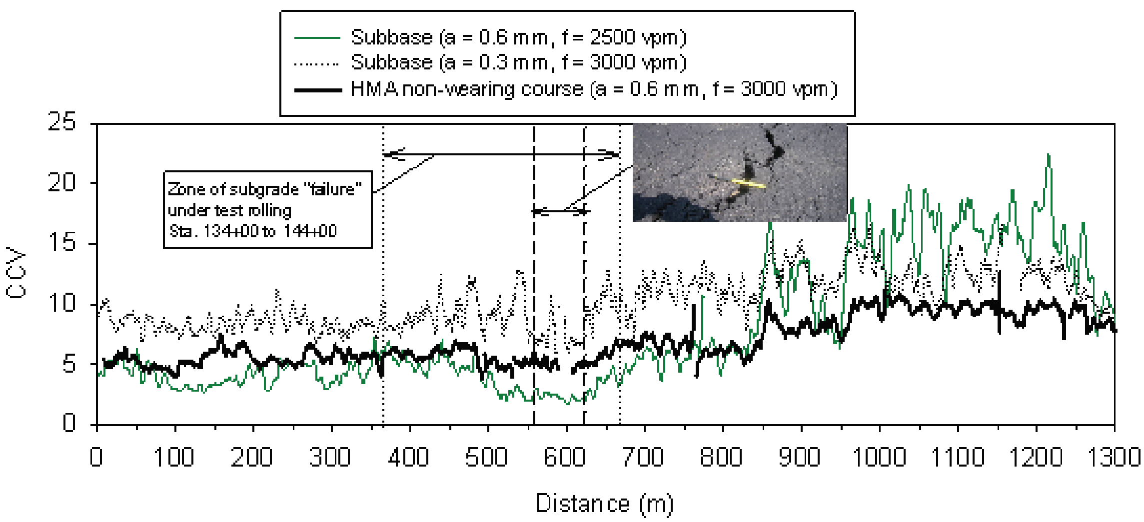


Figure 101. Comparison of CCV measurements on HMA base course layer and subbase layer (5m moving average).

- The lower frequency and higher amplitude settings for mapping the existing base were found to be highly correlated (reflected) to the asphalt mapping on top of the asphalt base course layer.

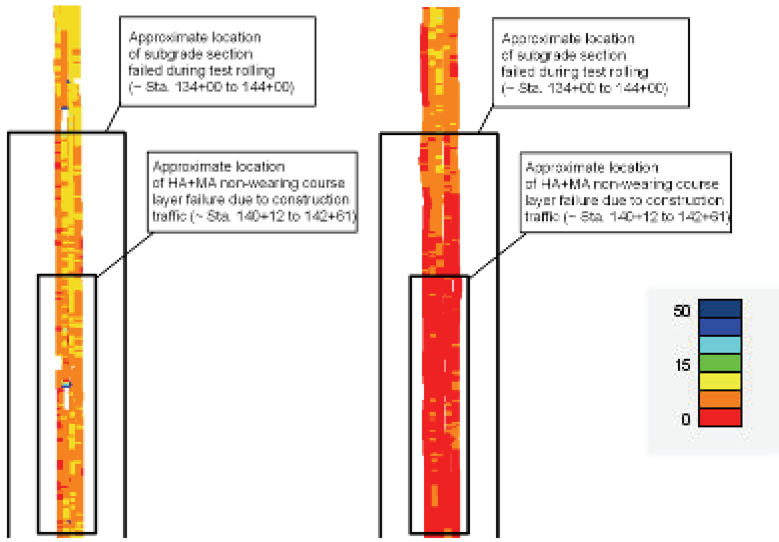


Figure 102. Comparison of CCV maps of the HMA base course and subbase.

- A strong natural logarithmic relationship between CCV measurements of subbase and HMA base layers at a vibration amplitude of 0.6 mm with R^2-value of 0.69. CCV measurements obtained on the subbase layer at an amplitude of 0.3 mm show relatively poor correlation to CCV measurements on the HMA layer with a linear relationship; A strong linear correlation is found for the CCVs between the HMA base course and wearing course (in-situ test spots were used);

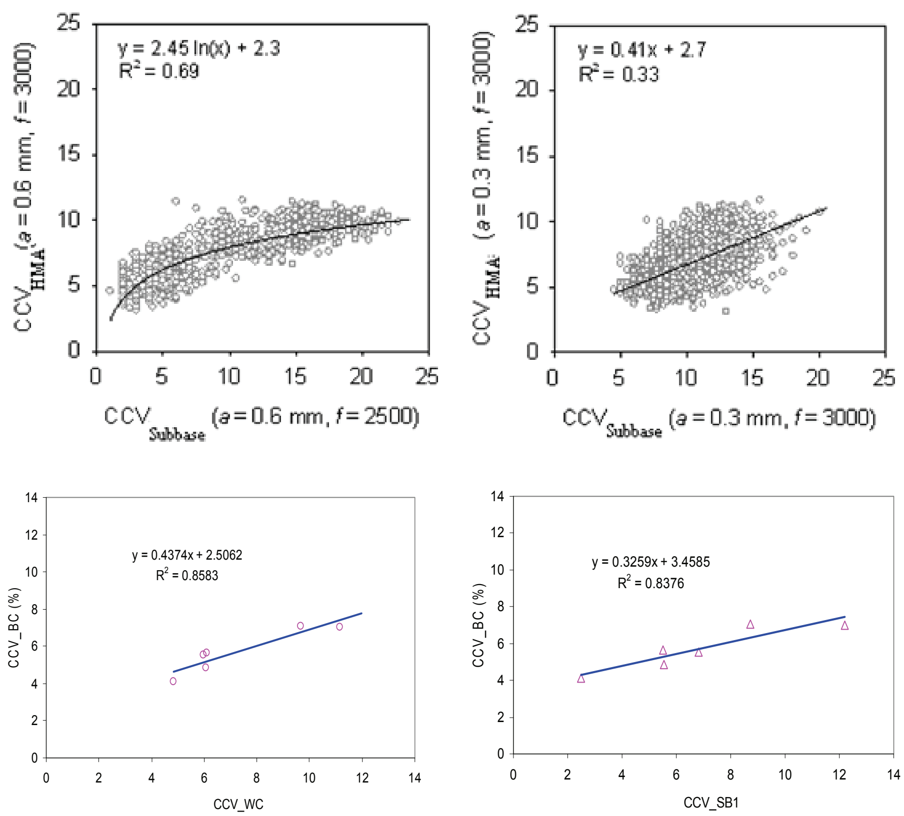


Figure 103. Correlation of CCVs between different layers.

- For the subbase layer, the machine setting at lower frequency and higher amplitude (i.e., 2,500 vpm, 0.6 mm) produces a wider range of CCVs (thus covering a wider ranges of conditions, such as softer and harder spots) and higher correlation with LWD and DCP. Note that the correlation between LWD and DCP (R^2 = 0.48) is at a similar level as those for CCV vs. LWD (R^2 = 0.59) and CCV vs. DCP (R^2 = 0.43). The correlations between DCP and CCV at high frequency and lower amplitude are particularly poor (the IC mapping was performed one day prior to the LWD and DCP tests, and the on-site moisture contents at the correlation test locations ranged from 4.3% to 6.1% which corresponded to soil moduli from 150 to 60 MPa).

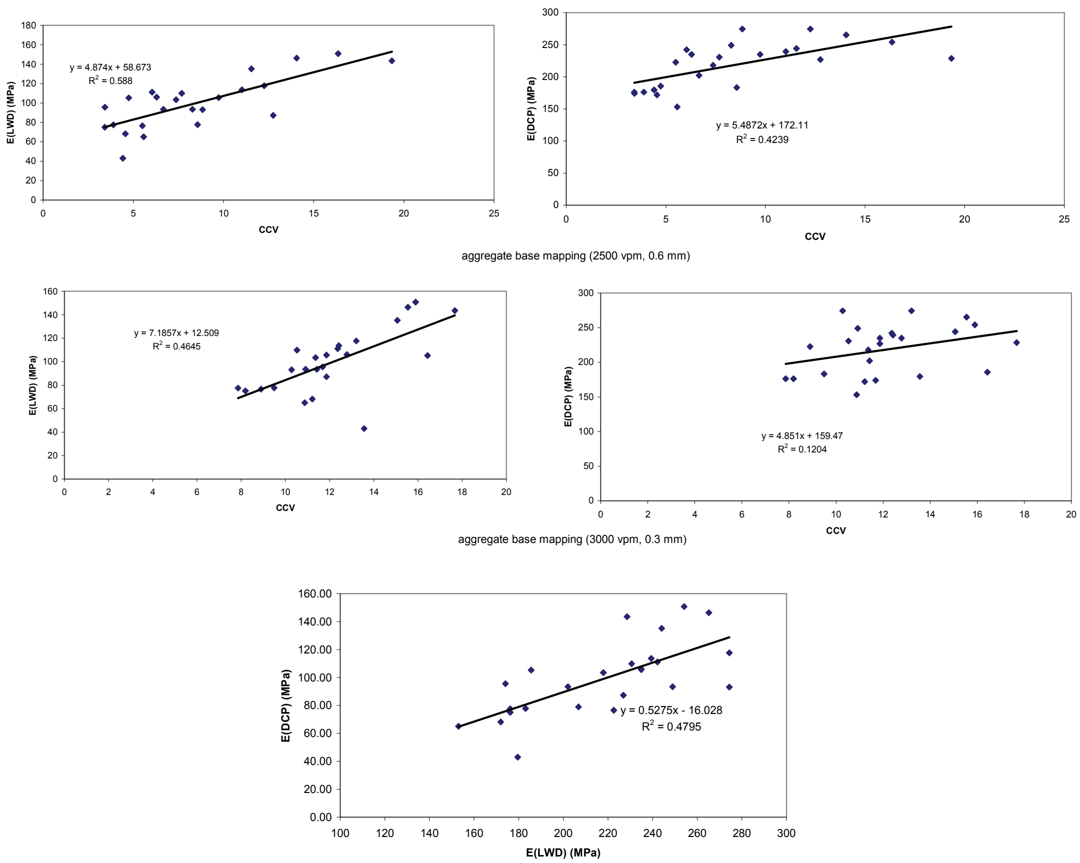


Figure 104. Correlation of CCVs with LWD and DCP tests on subbase.

- Both core density and lab density results (expressed in % G_{mm}) and the nuclear gauge readings correlate well (R^2 = 0.94). Lab density (% G_{mm}) and nuclear gauge readings vs. CCV correlate well (R^2 = 0.99 and 0.90 respectively) based on a 1 m (3.3 ft) radius averaging of the roller data (the latter is based on a second order polynomial fit). A linear or non-linear relationship may exist when correlating the material density with modulus (or modulus-type values). However, the above "correlation" is based on a fairly limited number of data points and one should be cautious to the interpretation of the results.

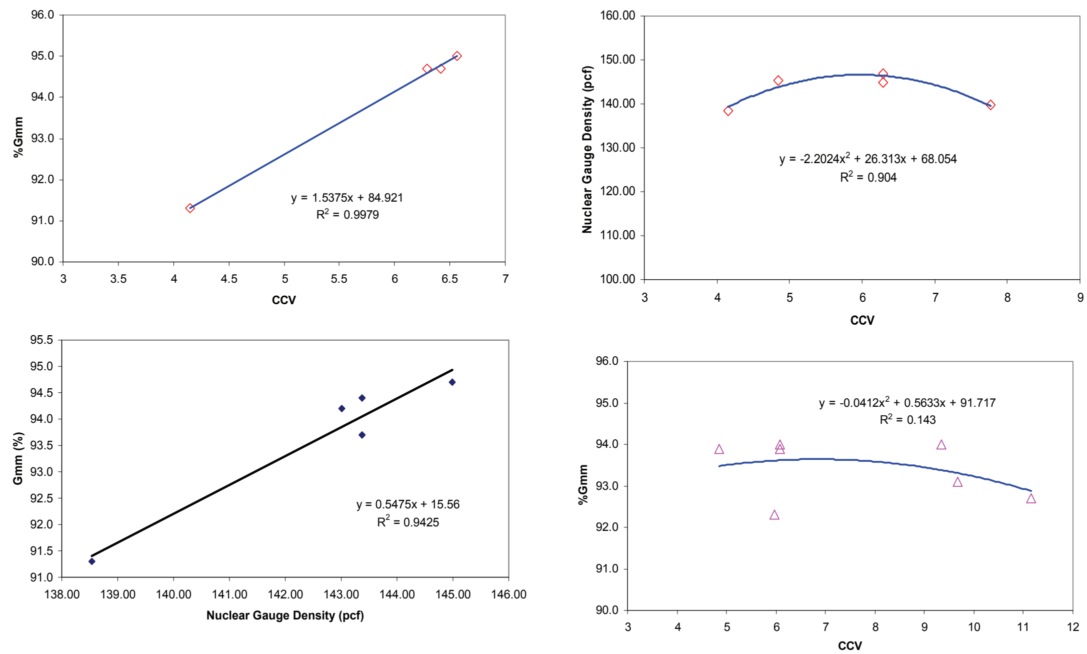


Figure 105. Correlation between nuclear gauge test, lab core density results, and CCV for the HMA base course (Route 4, SB).

Mississippi IC Demonstration

The field IC demonstration was performed from July 13 to July 17, 2009 on US 84, Wayne county, MS (see Figure 106). The materials include the stabilized subbase and HMA base.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to MSDOT and contractors who may not have prior experience with IC. The project was intended to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

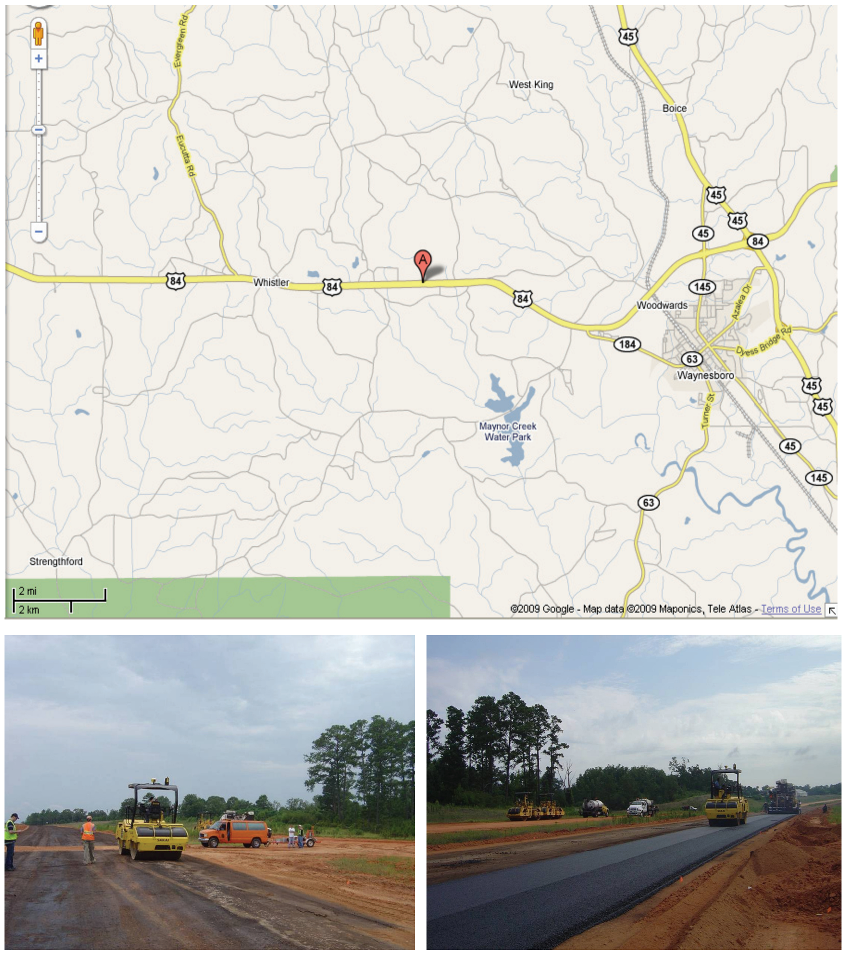


Figure 106. Mississippi HMA IC demonstration.

Main findings

- The Sakai IC double drum roller was used to successfully map the existing, tack-coated cement-stabilized subbase at different cured stages. Relatively soft spots were easily identified with the IC maps.

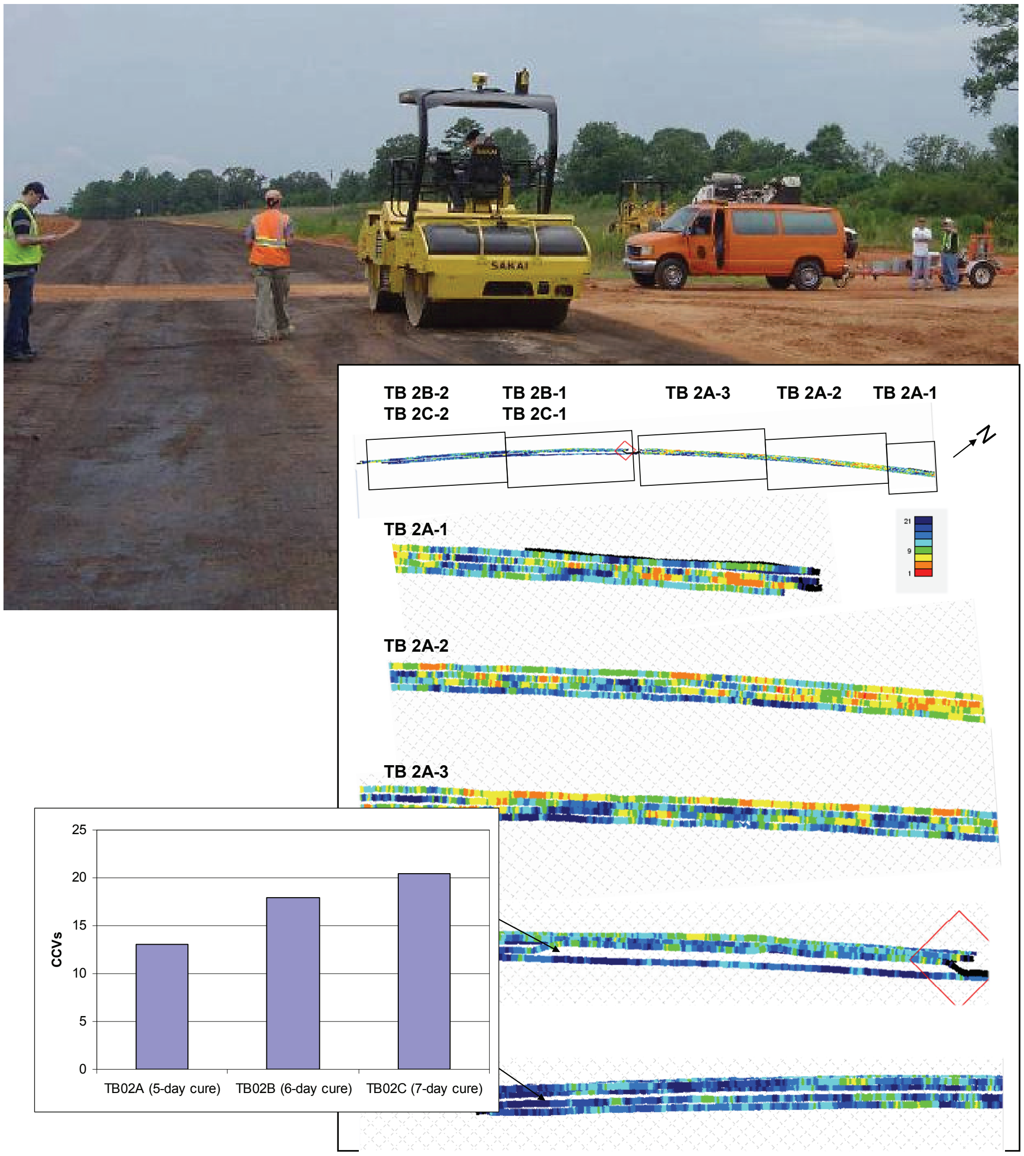


Figure 107. Mapping of tack-coated, stabilized subbase with the Sakai double-drum IC roller.

- The Sakai Compaction Control Value (CCV) displayed on the screen allowed the roller operator to observe real time information that identify relatively softer and stiffer areas of the roadway during compaction.

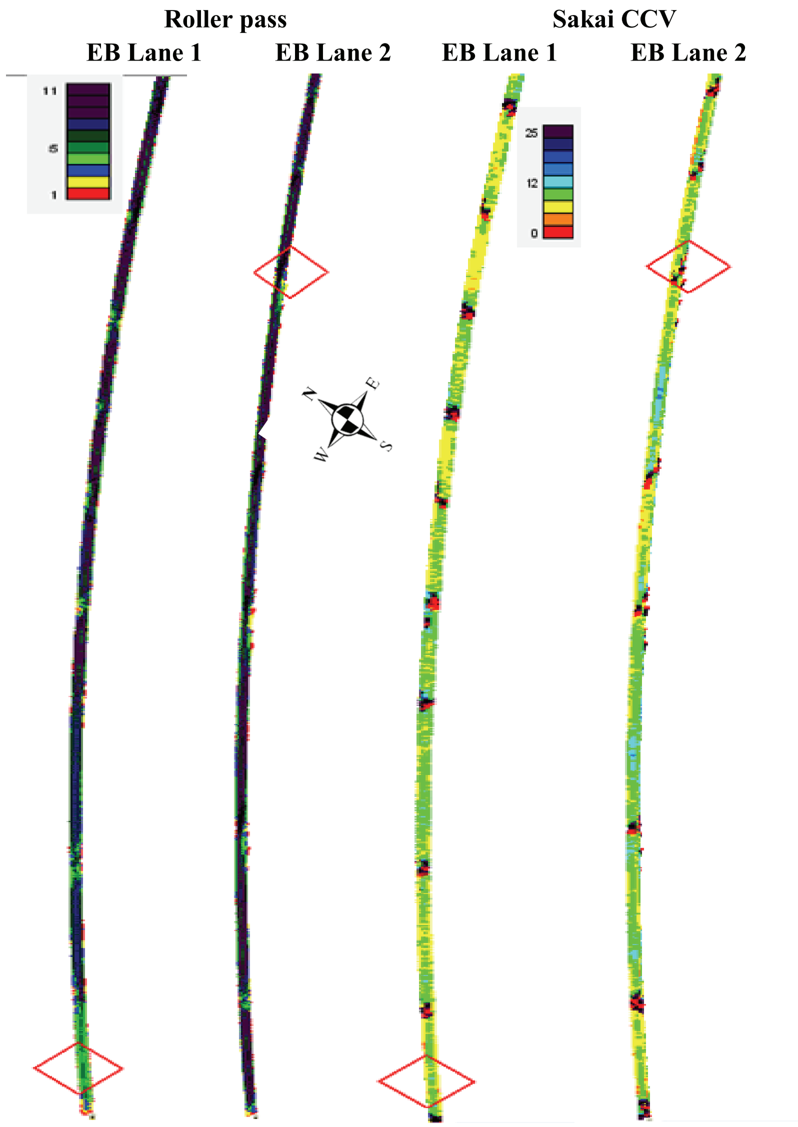
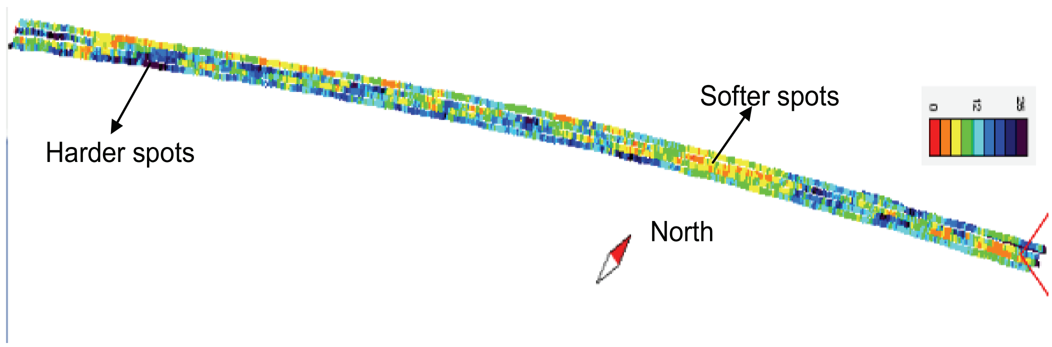
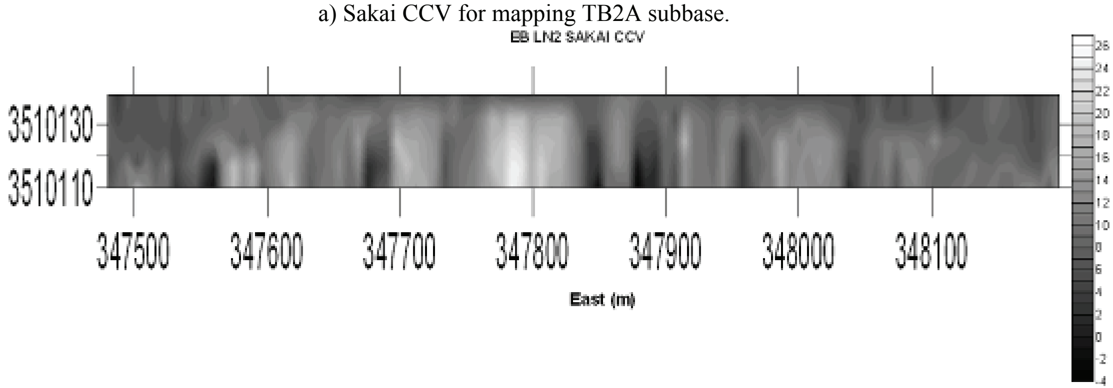


Figure 108. Roller pass No. and Sakai CCV of HMA base.

- The roller measurement values, ICMV, can be used to identify the weak or stiff areas of the pavement layers and the underneath support.



a) Sakai CCV for mapping TB2A subbase.



b) Kridging contour of surface temperature and Sakai CCV (TB24, HMA base course)

Figure 109. Sakai CCV of mapping subbase and paving HMA base course.

- Temperature plays an important role in determining the measurement values on HMA material.

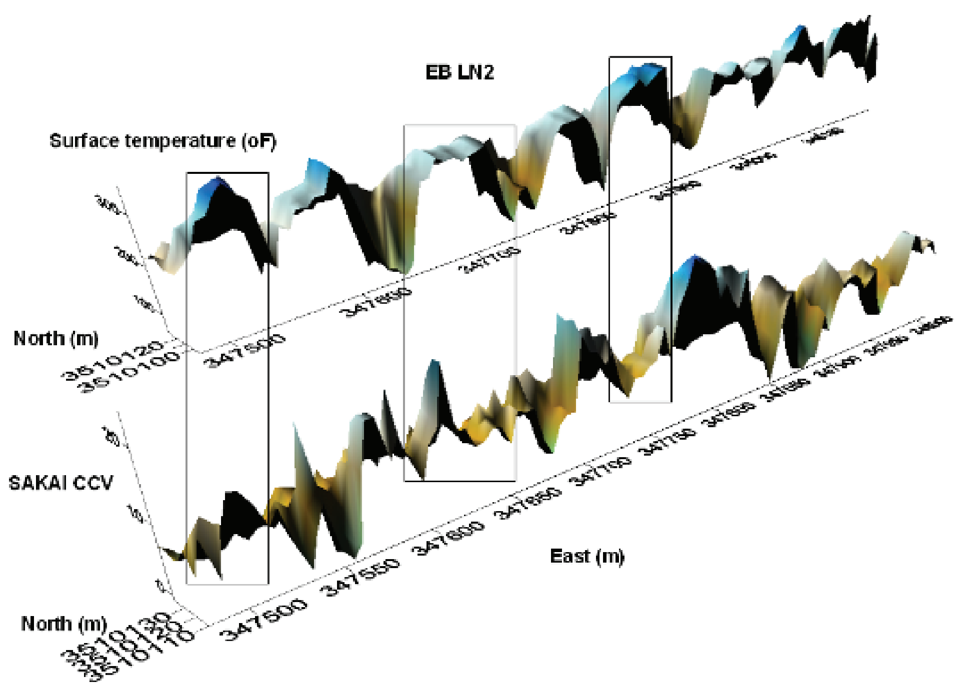


Figure 110. Surface temperatures and Sakai CCVs of HMA base course (EB Lane 2).

- The ICMV of mapping subbase correlates well with that of fresh HMA base paving, which indicates that a stiff or soft layer underneath could significantly affect the compaction results for the upper layers and reflected by the ICMV values.

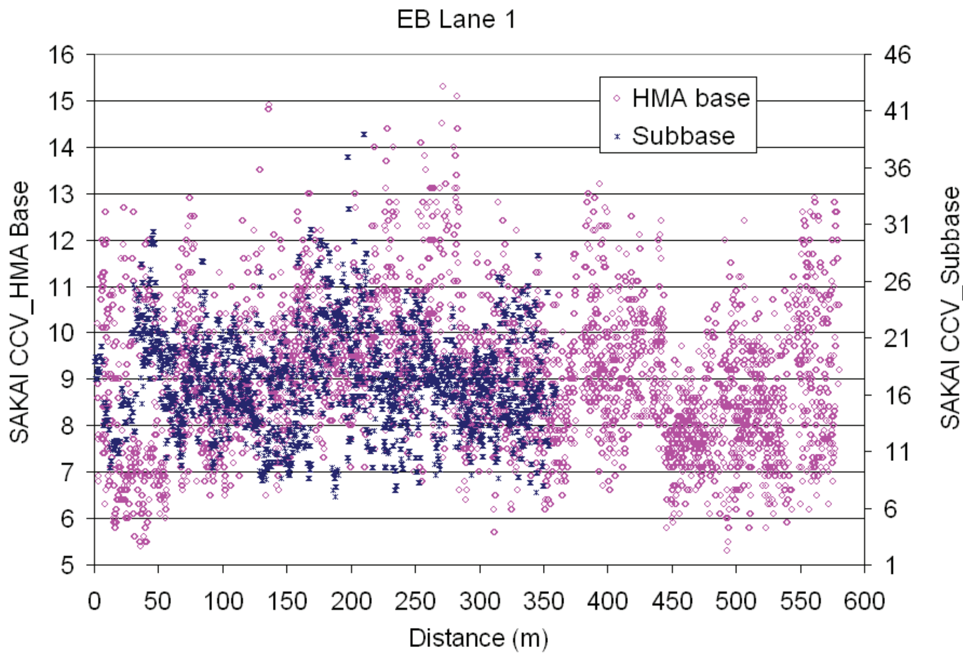
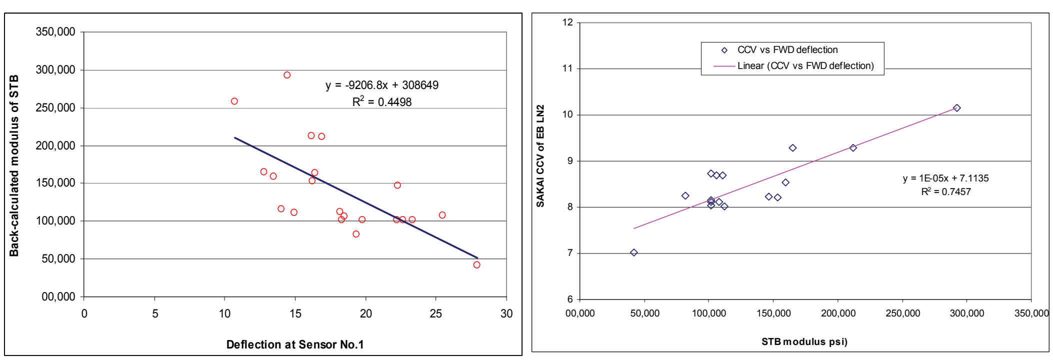


Figure 111. Comparison of Sakai ICMV among different layers (EB Lane 1, HMA base vs. Subbase).

- The FWD measured deflection and modulus correlate well with the ICMVs of subbase and HMA base course, indicating the reflecting effect of underneath layer on the stiffness of the upper layer.



FWD deflection vs. Sakai CCV of subbase FWD modulis vs. Sakai CCV of HMA base

Figure 112. Sakai CCV vs FWD measurements.

- The ICMVs and nuclear gauge test results of asphalt density seem to have linear relationships while with relatively low correlation. It may be interpreted with multiple reasons including the influence zone of ICMV (the whole pavement system rather than a single HMA layer), effective temperature variation, roller passes, vibration amplitude and frequency, etc. Note that the factors affecting (achieving) HMA density may also include the mixture properties, construction machines, and etc., in additional to compaction.

- The Geostatistics of semi-variogram analysis indicates that the HMA base course has higher compaction uniformity than that of the subbase layer, which sounds reasonable since the compaction was improved from the lower subbase course to the upper HMA base course in order to achieve a more uniform compaction.

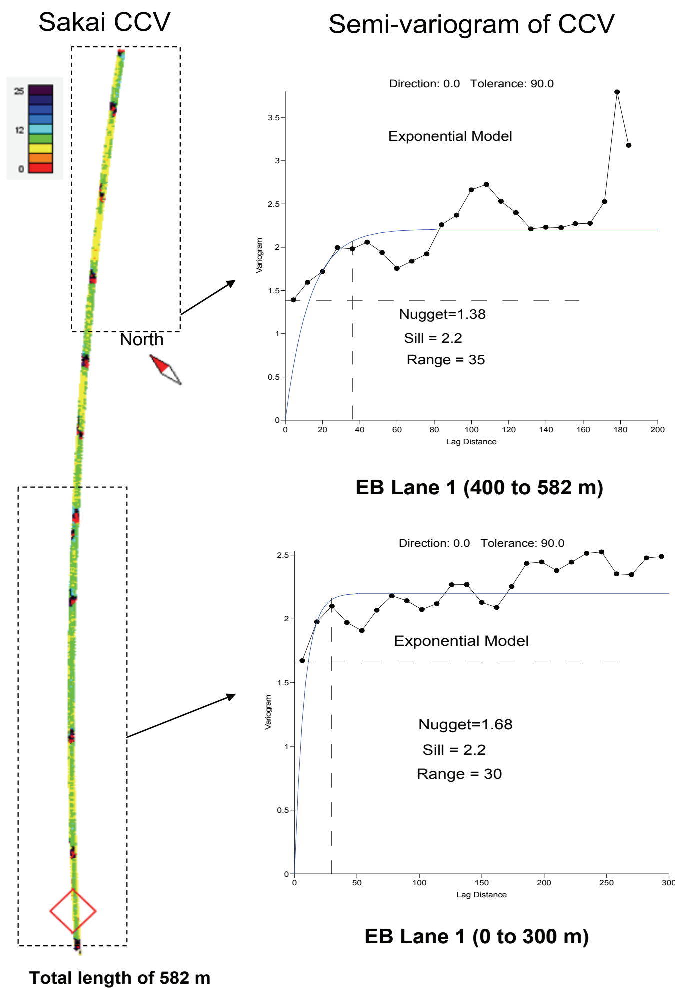


Figure 113. Geostatistic semi-variogram to access uniformity of asphalt pavement (US 84, EB Lane 1, Base course).

Findings confirming previous demo sites

The IC roller can effectively track the roller pass, HMA surface temperature, and the Roller Measurement Value (ICMV), which provide useful information for operators to control and adjust compaction efforts toward a more uniform compaction.

New York State IC Demonstration

The field IC demonstration was performed from May 17 to May 22, 2009 on US 219. The compaction layer and materials include the permeable HMA base, 2nd lift HMA base, and then the HMA binder course. The Sakai double-drum IC roller is used in this HMA demonstration project.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to NYSDOT and contractors who may not have prior experience with IC. The project was intended to demonstrate the benefits of IC for improving the compaction process by achieving more uniform density/modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Figure 114. New York State HMA IC demonstration.

Major Findings

- This project successfully demonstrated the ability of the IC roller to map the compaction of the subgrade, subbase, permeable asphalt base course, and asphalt binder course. The important findings of this project included:
- The roller measurement values, ICMV, can be used to identify the weak or stiff areas of the pavement layers and the underneath support.

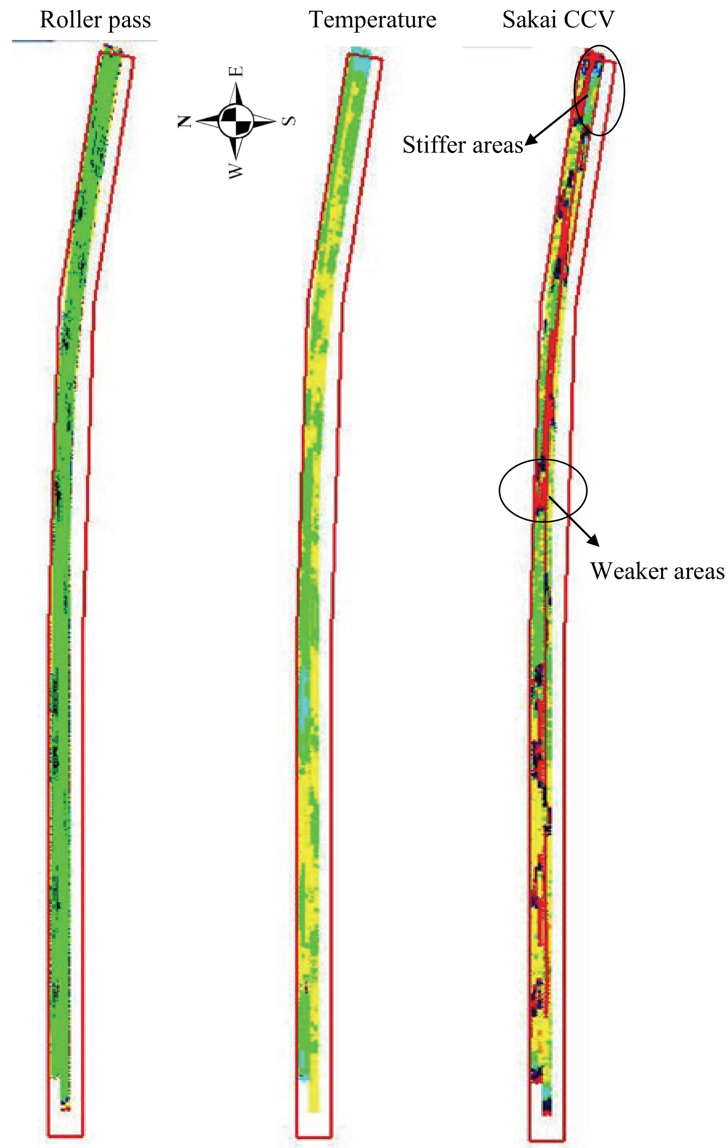


Figure 115. Roller measurement values of HMA 2nd lift base.

- The ICMVs are affected by the vibration frequency, roller pass, amplitude, and HMA material temperatures.
- For the asphalt mixture compaction, the temperature plays an important role in determining the measurement values.

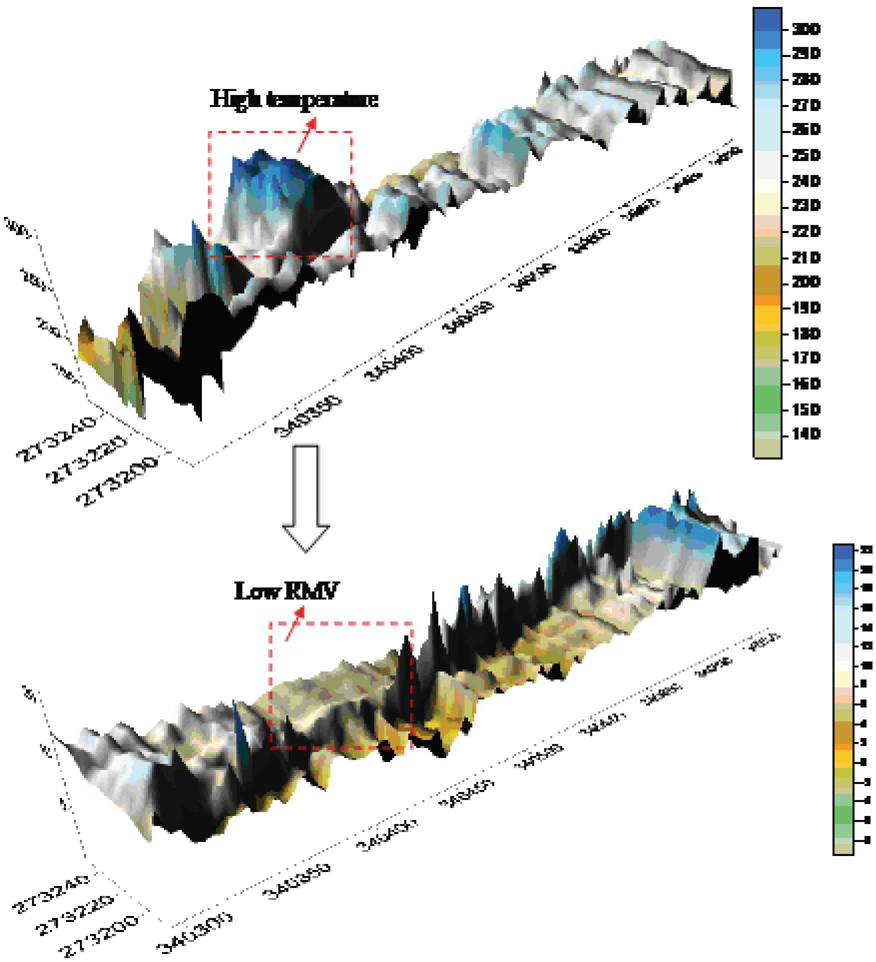


Figure 116. Sakai ICMVs and HMA temperatures of TB 15 - HMA base course (second lift).

- The measurement values between different pavement layers correlated well and have similar trends, which indicates that a stiff or soft layer underneath could significantly affect the compaction results for the upper layers and reflected by the ICMV values.

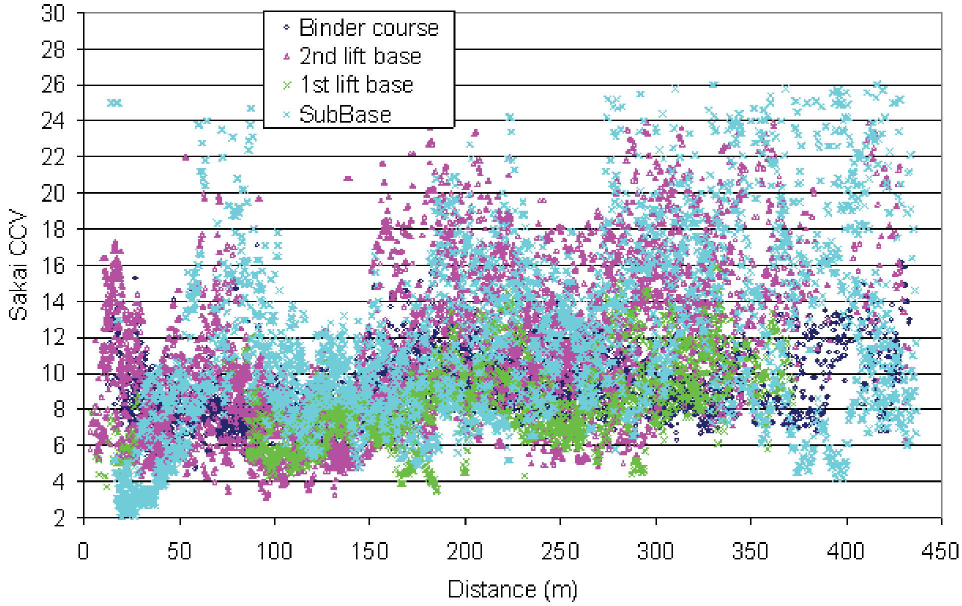
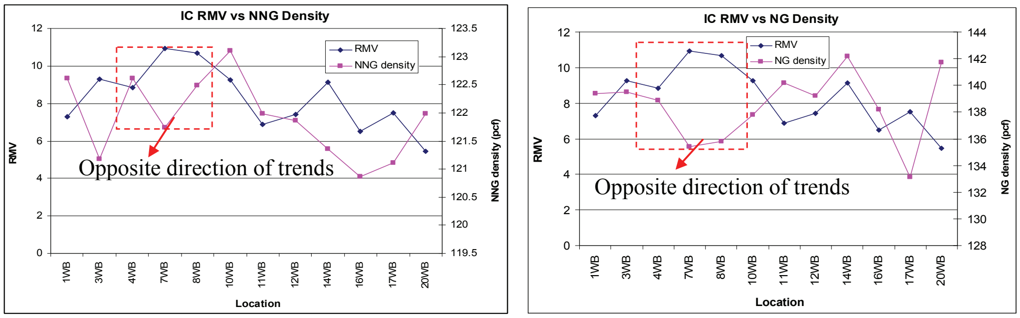
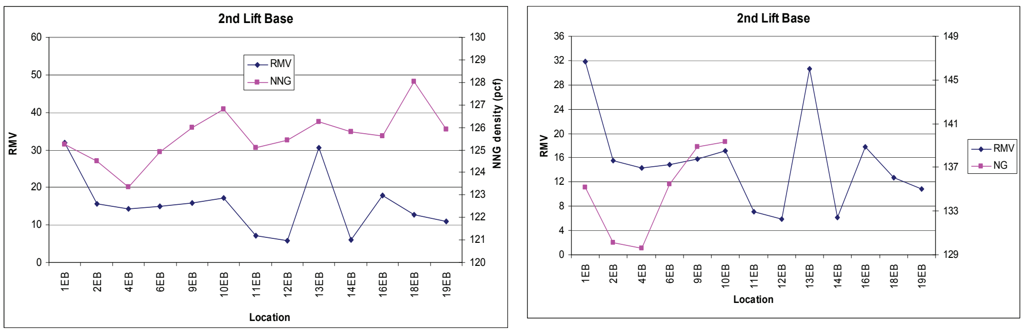


Figure 117. Comparison of Sakai ICMV among different layers.

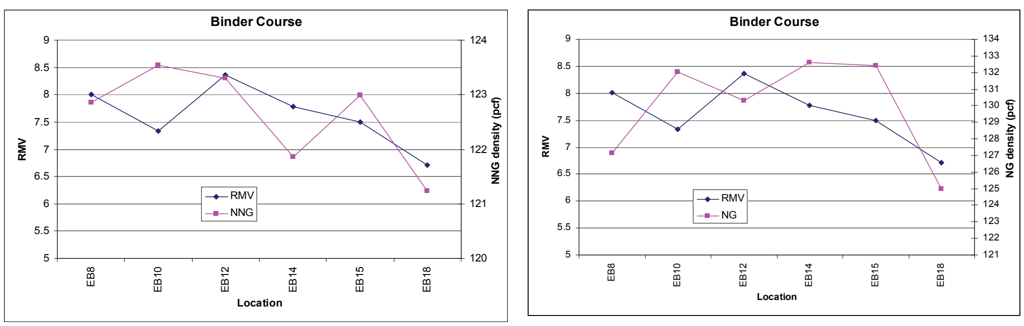
- The ICMVs and nuclear/non-clear gauge test results of asphalt density have inconsistent trends. It may be interpreted with multiple reasons including the effective temperature variation, roller passes, vibration amplitude and frequency, and etc. Note that the factors affecting (achieving) HMA density may also include the mixture properties, construction machines, and etc. in additional to compaction.



1st permeable HMA base course



2nd life HMA base course



HMA binder course

Figure 118. Sakai ICMV vs. NNG (left) and NG (right) density.

Maryland IC Demonstration

This test site is located on US 340 EB in Frederick County, MD (see Figure 119). This project is a grinding of existing HMA and then paving overlay with stone matrix asphalt (SMA). The objectives of this demonstration project were short-term goals for introducing HMA IC technology to MD SHA and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

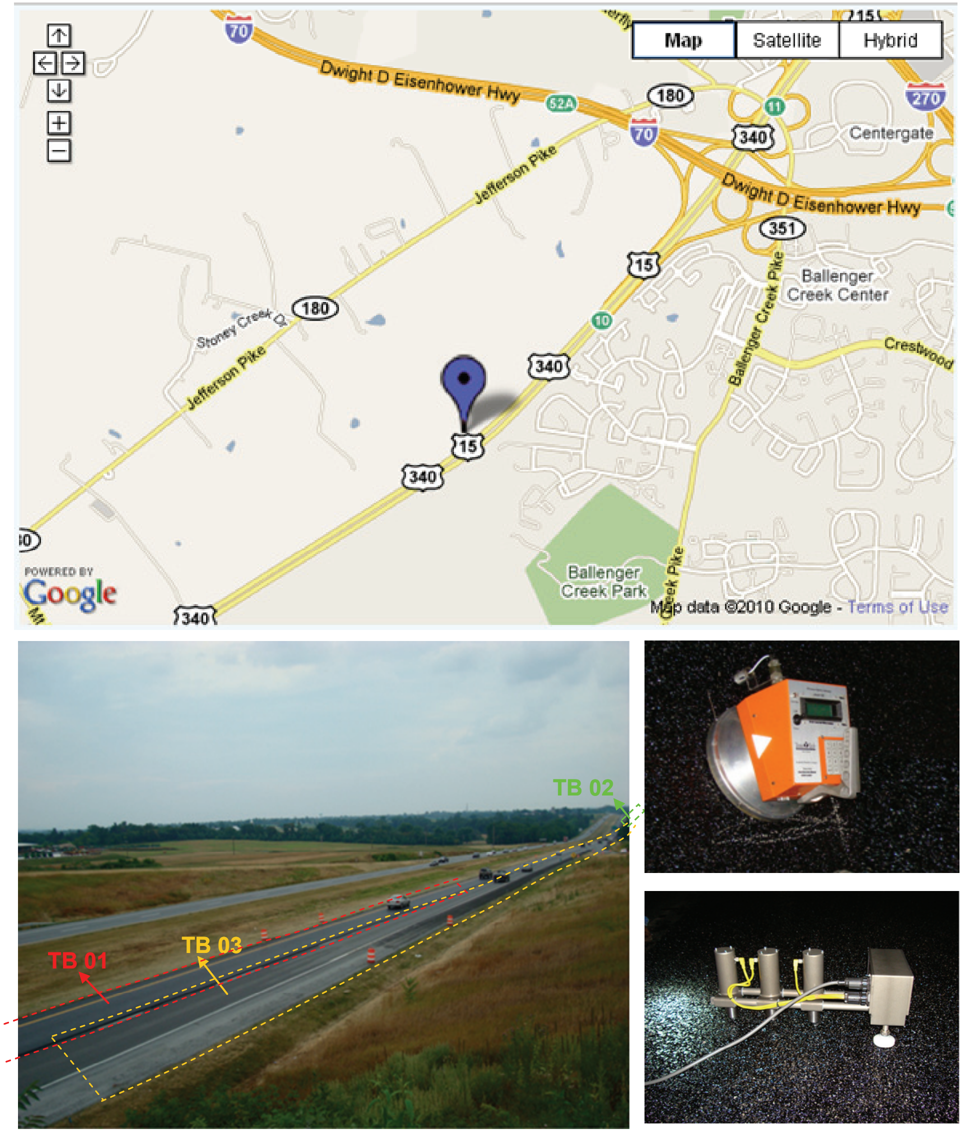


Figure 119. Maryland HMA IC demonstration.

The unique features of this demonstration project included the following:

- The first night-paving project for the IC demonstration;
- Te first SMA overlay project for the IC demonstration;
- The first time to map the existing HMA pavements using IC rollers;
- The first time to use two IC rollers (Sakai and Bomag) to map the same existing HMA pavements;
- The first time to use Portable Seismic Pavement Analyzer (PSPA) to measure the seismic modulus of HMA pavement for correlation purpose;
- The first time to instrument the RFID device to measure the HMA overlay temperatures at different depths.

Major Findings

- This project has successfully demonstrated the ability of the IC roller to map the compaction of HMA overlay on the existing HMA pavements. The important findings of this project included:
- Night paving has been successfully implemented. IC technology helps the night paving by offering the visible roller measurements to the operator;

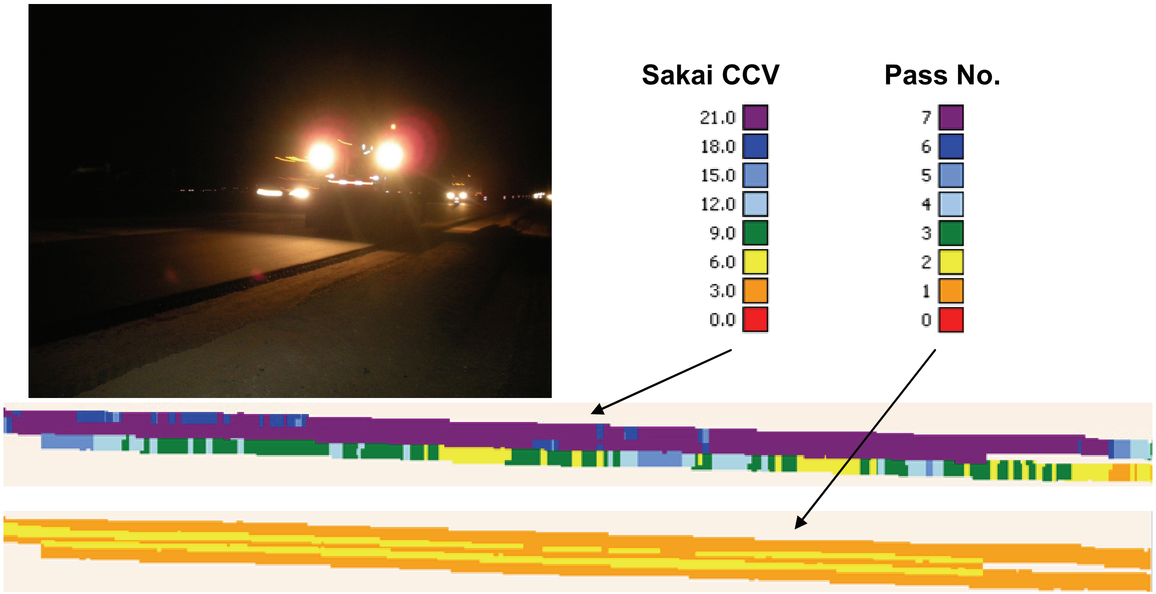


Figure 120. Night paving of SMA overlay.

- Both Sakai and Bomag mappings of the existing HMA pavements have shown that the shoulder has much lower ICMVs (relative stiffness) than that of the pavement lane, and ICMVs from both machines can consistently identify soft or stiff support;

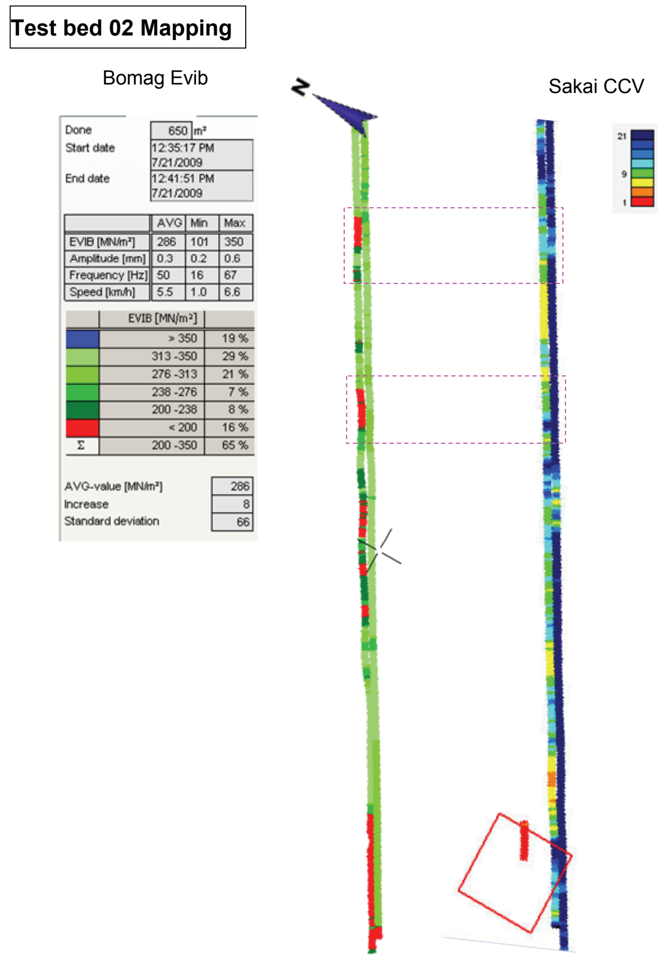
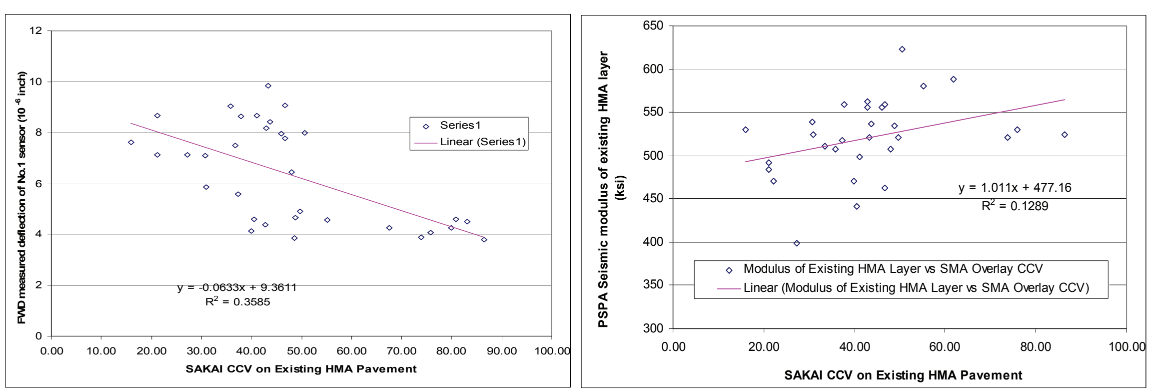


Figure 121. Mapping results - Bomag Evib and Sakai CCV - TB 02.

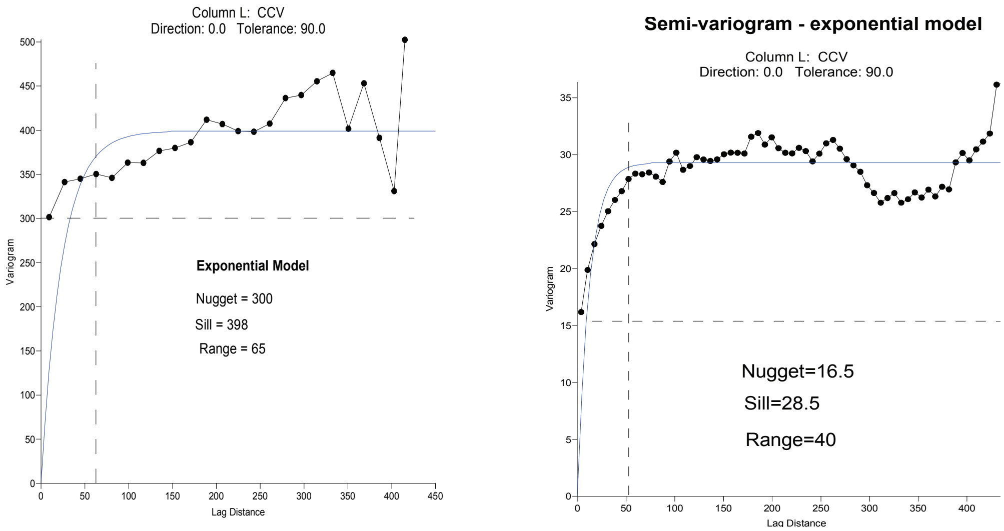
- ICMVs correlate with the FWD measured deflection better than with PSPA seismic modulus;



Sakai CCV *vs* FWD deflection Sakai CCV *vs* PSPA moduli

Figure 122. Sakai CCV vs. FWD deflection and PSPA seismic modulus.

- The compaction uniformity has significantly improved from the existing HMA pavements to the fresh SMA overlay as approved by the ICMV map and the geostatistics semi-variograms;



TB 03A Mapping (0-416m) TB 03B Mapping (0-684m)

Figure 123. Semi-variograms of Sakai CCV for the mapping areas.

- The ICMVs and nuclear density gauge test results of HMA are shown to have a linear relationship with a relatively low correlation. Their relationship may be explained by the fact that a greater material stiffness under a higher compaction effort correlates to a greater material density, and vice versa. However, there are also other factors that may affect the above relationship. To name a few: HMA temperature variation, roller passes, vibration amplitude and frequency, etc. It should also be noted that the factors affecting HMA density may also include the mixture properties, construction machines, etc. in additional to compaction.

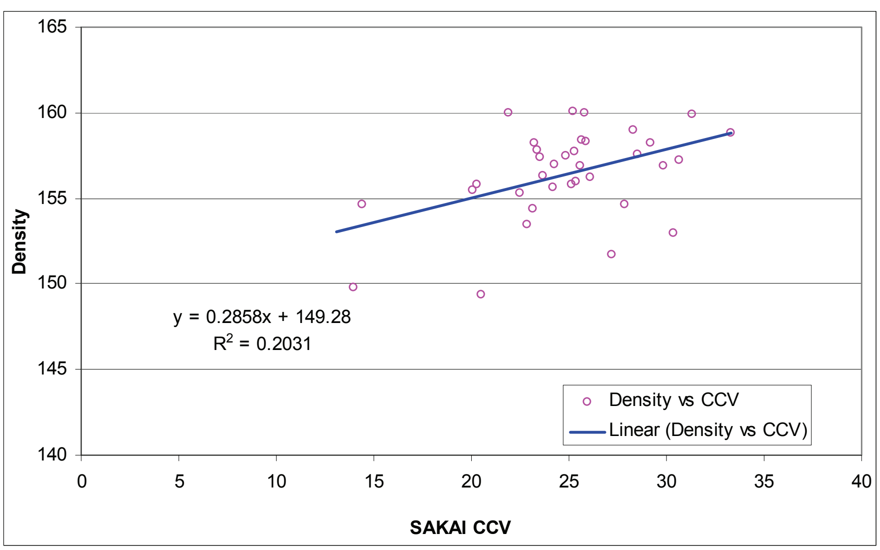


Figure 124. NG density vs Sakai CCV of TB 03 SMA overlay at discrete test locations.

Findings confirming previous demo sites

- The IC roller can track well the roller pass number, HMA surface temperature, and the Roller Measurement Value (ICMV), which provides important proof for the compaction quality;

- With the real-time information of IC roller pass, ICMVs displayed on the screen, the roller operator can adjust rolling pattern to improve the compaction quality;
- The ICMV mapping on the existing pavement layers can identify relatively softer and stiffer areas of the roadway;
- The ICMV can also identify the weak or stiff areas of the constructed HMA overlay and the whole pavement layer system;
- The HMA temperature affects the ICMVs or stiffness due to the temperature-dependent viscoelastic property of HMA material.

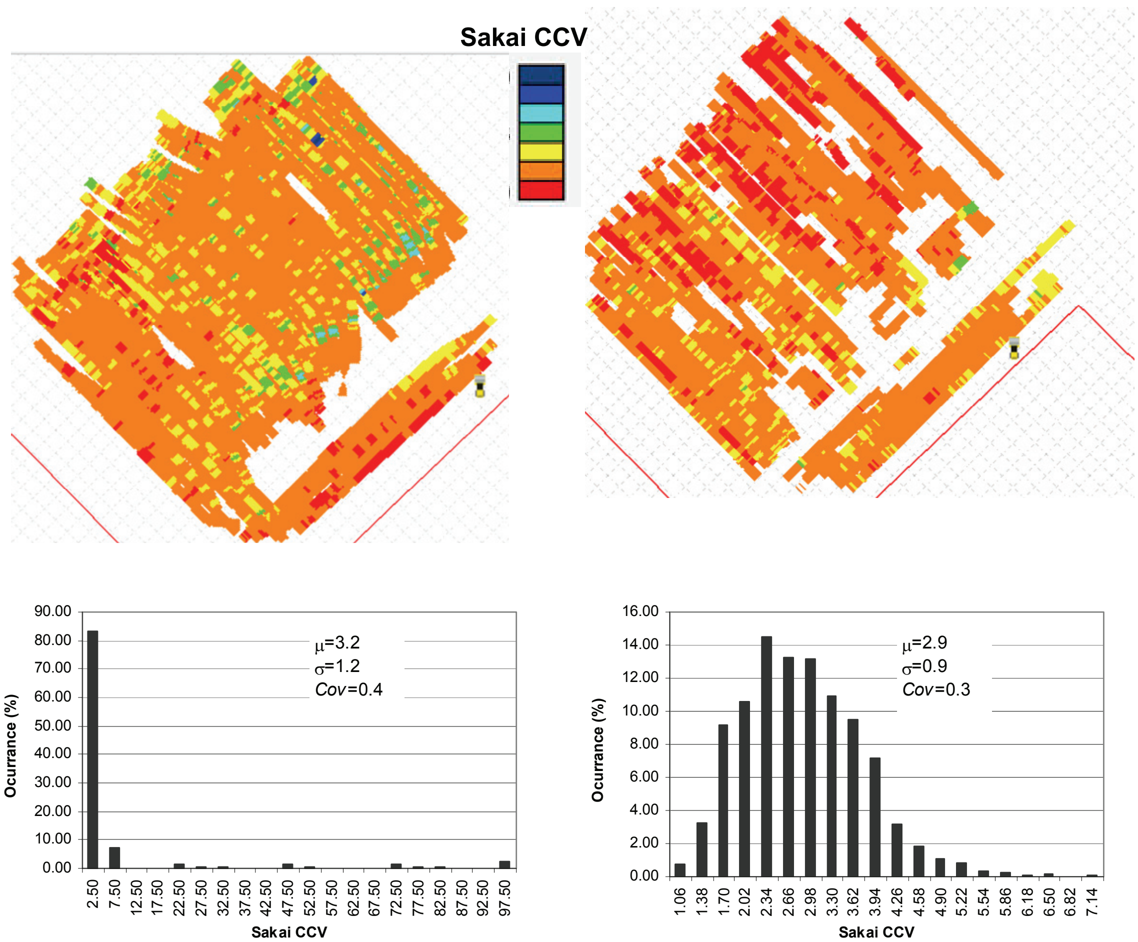
Georgia IC Demonstration

This is a demonstration of IC on the HMA overlay on the graded aggregate base using Sakai machine. The demonstration site is a parking lot close to the junction of highway 19, 41, and SR 3 in Clayton County, Georgia (Figure 125). The field IC demonstration was performed from Sept. 14 to Sept. 18, 2009. The objectives of this demonstration project were short-term goals for introducing HMA IC technology to GDOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Figure 125. Georgia HMA IC demonstration at the Park & Ride.

Major Findings

- Low Sakai compaction control values (CCVs) on the graded aggregate base (GAB) reflect on low CCVs on the HMA layer. Thus, it is strong evidence that one should construct a sound subbase/base course to achieve the integral strength of pavement layer system.



TB 01 GAB TB 01A HMA

Figure 126. Sakai CCV map and statistics.

- The moisture of GAB significantly affects the CCVs based on the mapping data. As shown in Figure 127, TB01 is the first test bed for mapping when moisture after rain is less dried than other test beds, resulting in lower CCV. Therefore, it is recommended to pave the HMA layer when the GAB is in "drier" condition.

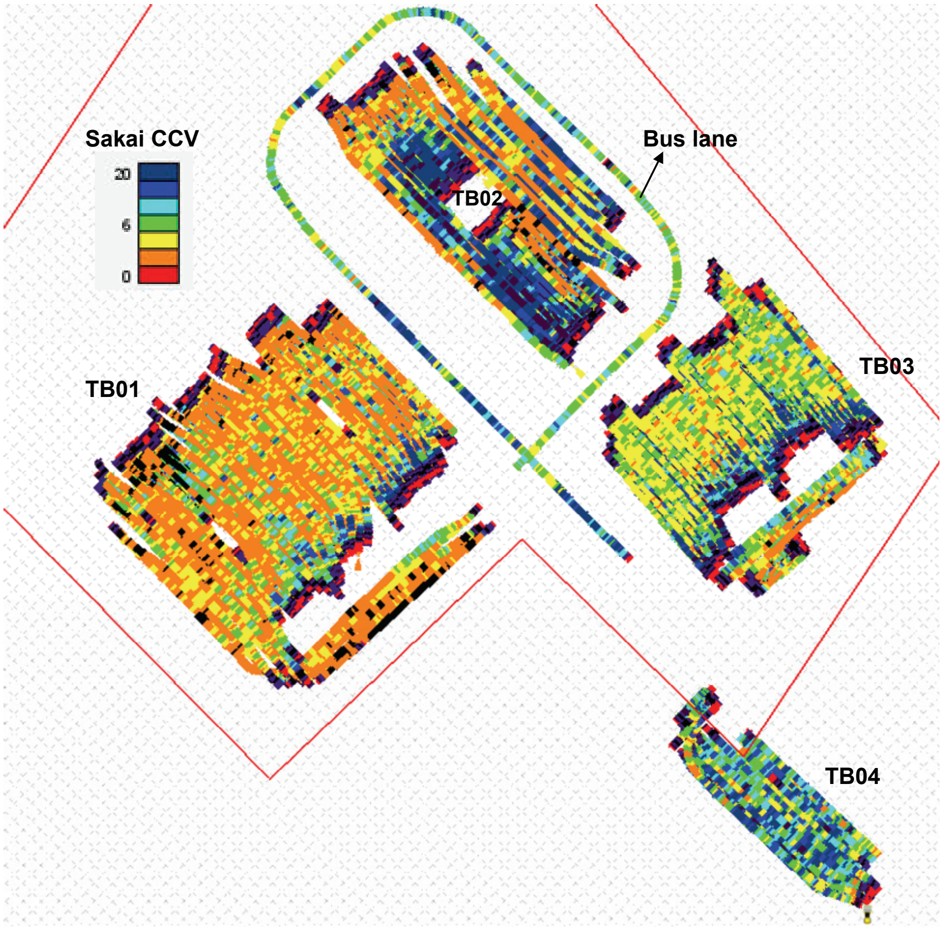


Figure 127. Sakai CCV of GAB.

- The curing and treatment help improve the stiffness of materials. E.g. the TE04 GAB base has been applied the prime, which results in higher Sakai CCVs than other GAB test beds (see Figure 127);
- The mapping of subbase using the Sakai double drum IC roller can be correlated to conventional in-situ nuclear-gauge density measurements.

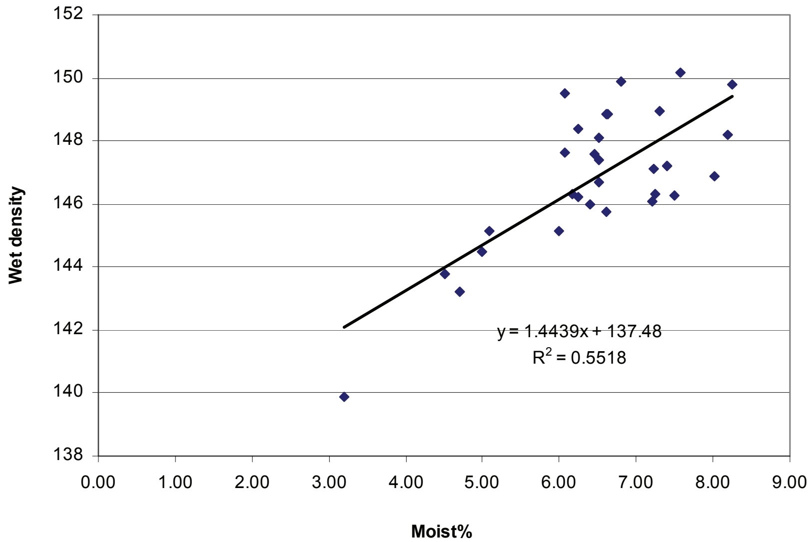
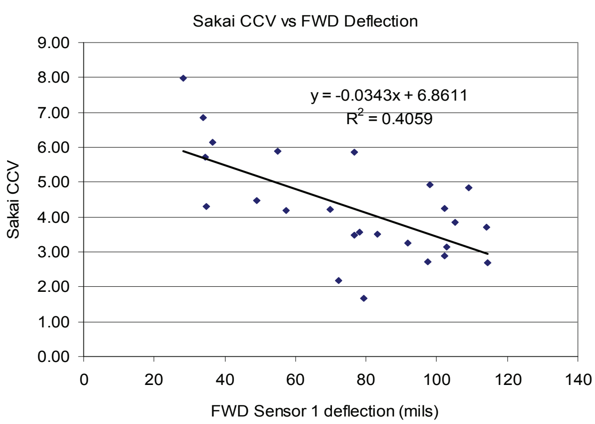
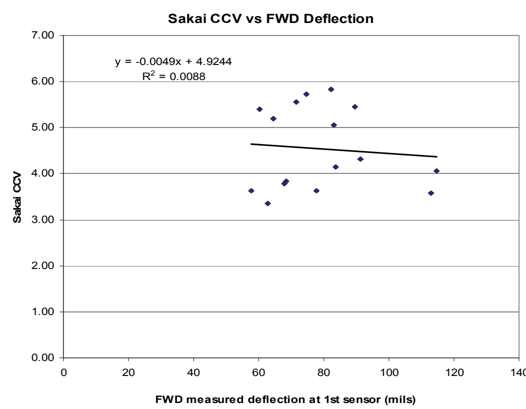


Figure 128. Sakai CCV vs NG density of GAB material.

- The FWD measurements of the GAB layer are correlated to CCVs at some test beds but not at others. Further investigation is wanted.



TB 02 GAB Sakai CCV vs. FWD deflection



TB 03 GAB Sakai CCV vs. FWD deflection

Figure 129. Sakai CCV vs FWD measurements.

- The densities of HMA core samples are correlated to CCVs on the HMA layer, but in a reversed trend. However, it should be noted that only limited (5 in this case) core samples are available while more samples may be required to reach a solid conclusion.

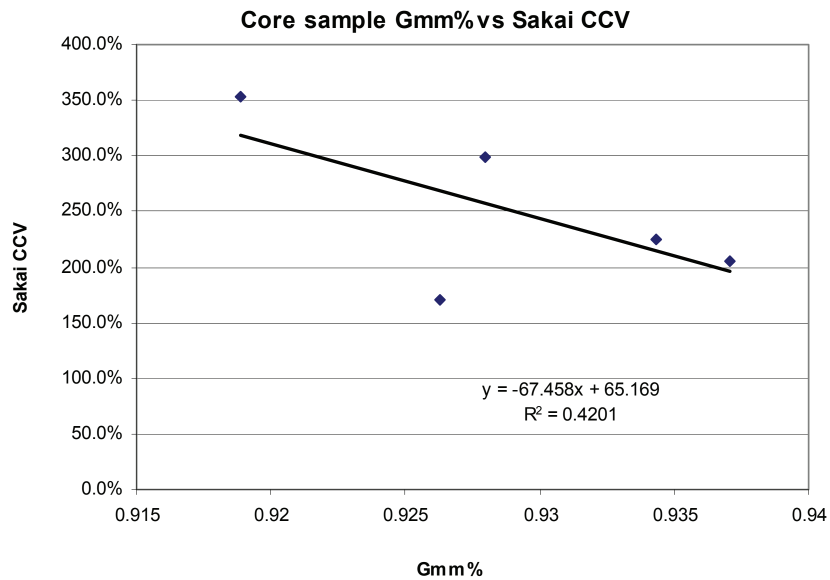


Figure 130. Sakai CCV vs Gmm% of HMA.

- The measured LWD deflections and derived CBR values are not correlated to CCVs on the HMA layer based on the available and yet limited data.

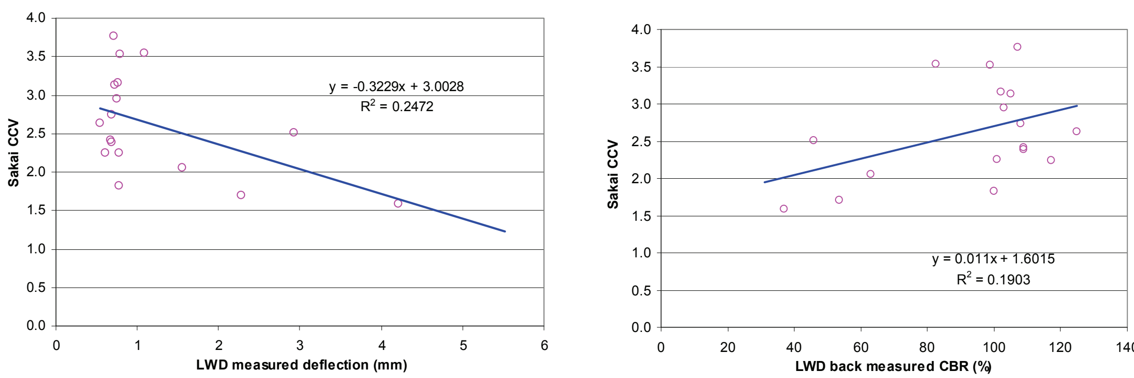


Figure 131. Sakai CCV VS LWD measurements of HMA.

Findings confirming previous demo sites

- The Sakai IC system can track roller passes, HMA surface temperatures, and the CCVs in real time - which provides essential tools for improving compaction quality;
- HMA temperatures affect the CCVs due to the temperature-dependent viscoelastic property of HMA materials. Note that CCVs' measurement depth is approximately 6 feet.

Indiana IC Demonstration

The test site is located on US 52 between the junction with US 231 and Cumberland Ave, Lafayette, IN (Figure 132), on September 21 2009 to September 23 2010, using both the Sakai and Bomag double-drum IC rollers. The length of the project is about 5 miles long with two lanes on each direction. The existing pavement structure is 6" of HMA on top of 7" of concrete pavements. The existing pavements were firstly milled for about 2", then overlaid with a 2.5" of intermediate HMA layer (19-mm max. nominal aggregate size) and 1.5" HMA surface layer (9.5-mm max. nominal aggregate size). The objectives of this demonstration project were short-term goals for introducing HMA IC technology to INDOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

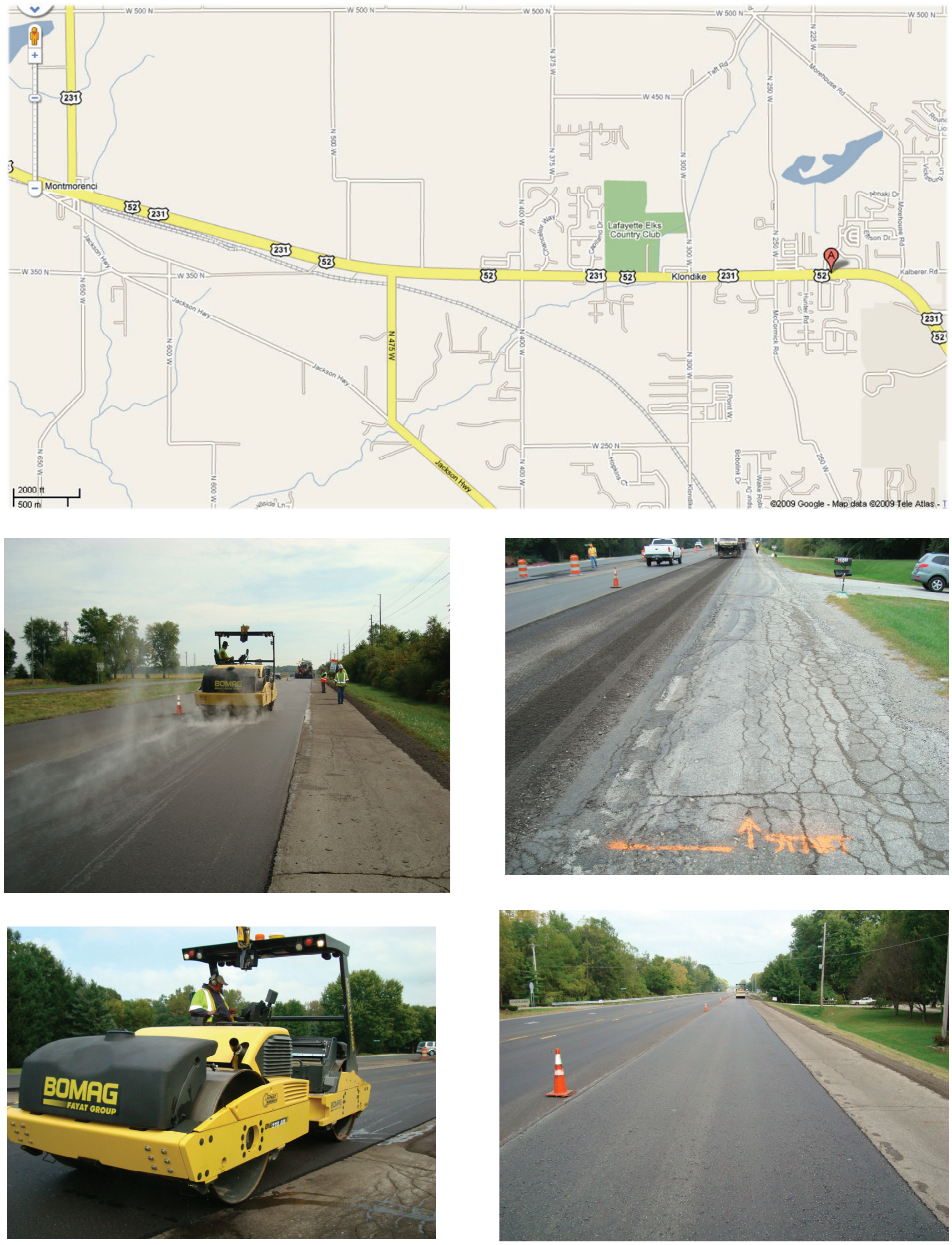


Figure 132. Indiana HMA IC Demonstration.

Major Findings

- Double-drum IC rollers can be used to map the milled asphalt pavements prior to the paving of HMA overlay.

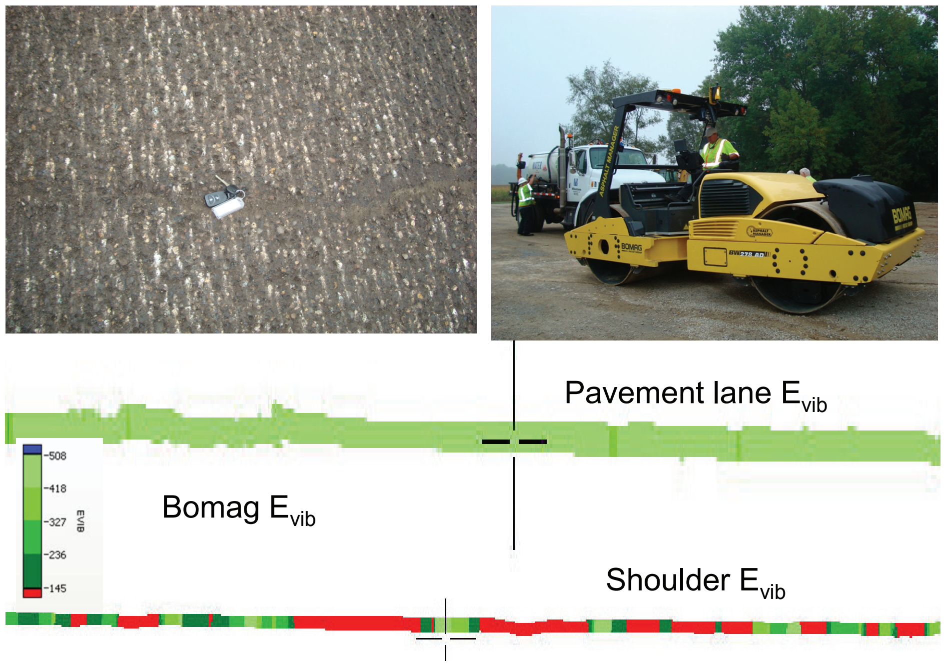


Figure 133. Mapping of milled HMA on PCC slabs using Bomag.

- From the Bomag IC mapping of the existing asphalt shoulders, lower vibration amplitude setting results in higher vibration modulus values (E_{vib}) due to its shallower influence depth that concentrating on the asphalt layers;

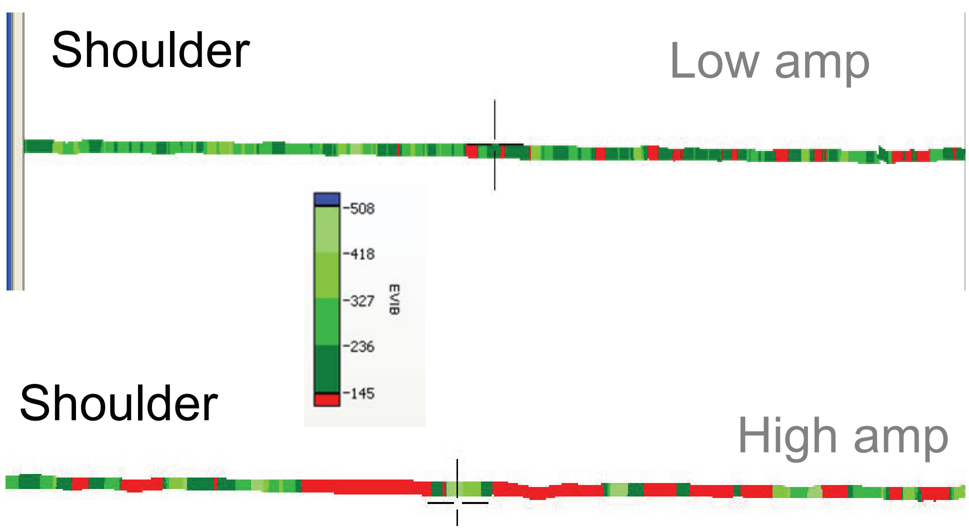


Figure 134. Mapping of milled HMA shoulder on PCC slabs.

- The Bomag E_{vib} values on the milled HMA surface is higher than that of the HMA shoulder, indicating the former is a stronger pavement structure (see Figure 133);
- For both the Bomag and Sakai IC compactions, the non-nuclear density gauge measurements

increase with increasing roller pass numbers, but the increase rate reduces;

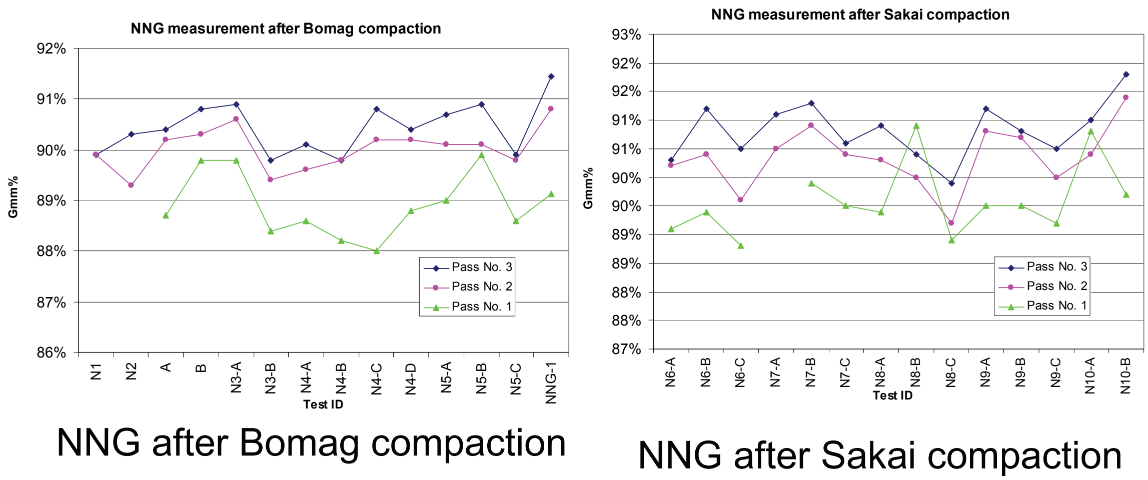


Figure 135. NNG density of each breakdown roller pass following Bomag and Sakai compaction, respectively.

- The non-nuclear density was measured for each roller pass, which was found to correlate well with the Sakai CCV;

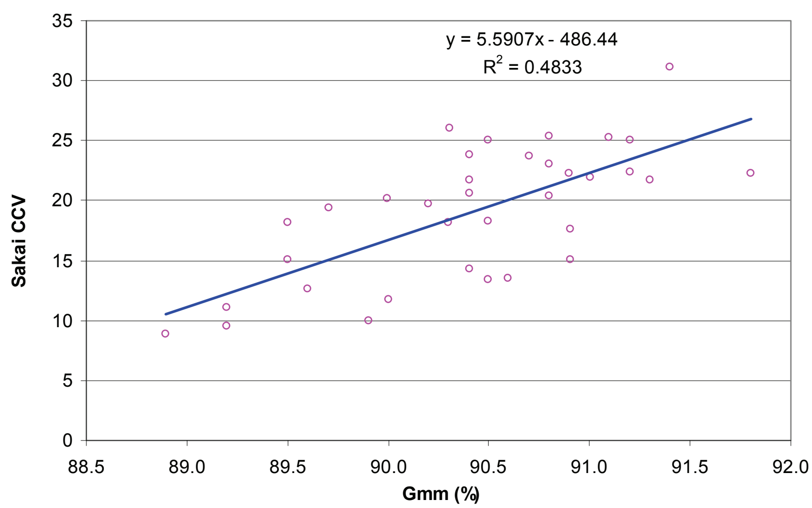


Figure 136. Sakai CCV vs. NNG gauge measured Gmm% for combined single passes.

- The FWD deflections at HMA surfaces corresponding to the underlying concrete slab joints is higher than those at HMA surfaces corresponding to slab centers due to the weaker support at the concrete slab joints, and the FWD deflections at the milled HMA are higher than those at the HMA surface overlay due to the improved structure and material strength;

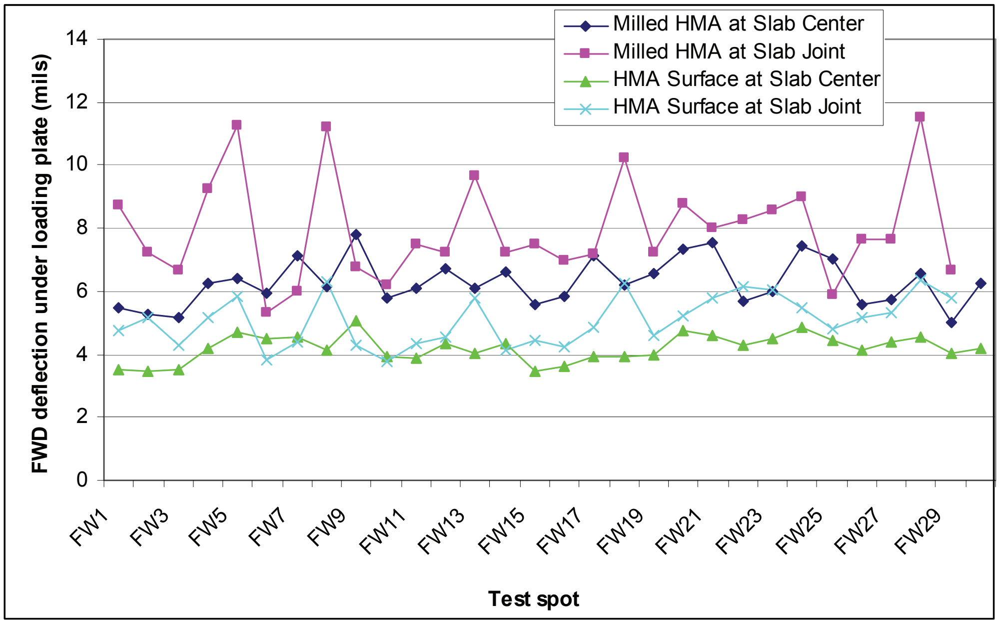


Figure 137. FWD measured deflection under loading plate.

- The Bomag E_{vib} has a linear relationship with the FWD measured deflection under the loading plate, but with a relatively low correlation;

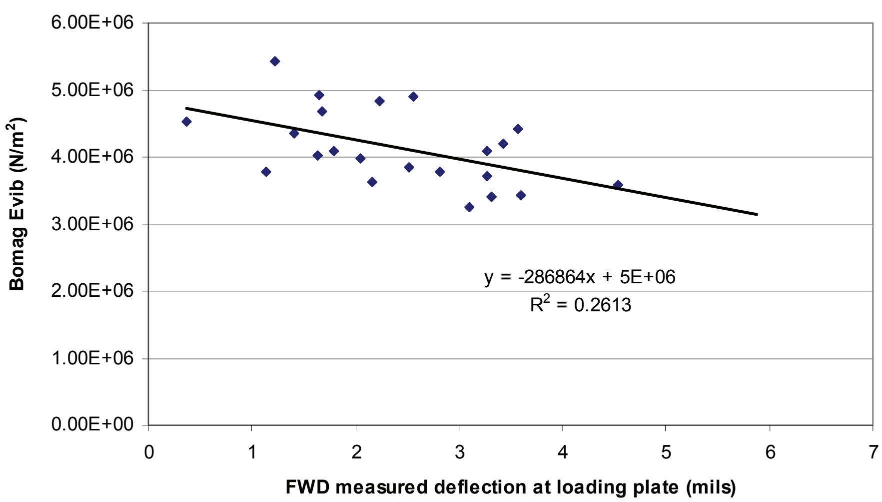


Figure 138. Bomag Evib vs. FWD measured deflection under the loading plate.

- The Bomag E_{vib} does not correlate well with cored sample density. One of the reasons can be that Bomag E_{vib} represents the stiffness of the pavement system rather than the single HMA layer. Also, IC measured surface temperatures at core locations are different as shown in Figure 139 and E_{vib} is not adjusted with asphalt temperature. IC measurements at some core locations can be influenced by the underlying PCC slabs or joints.

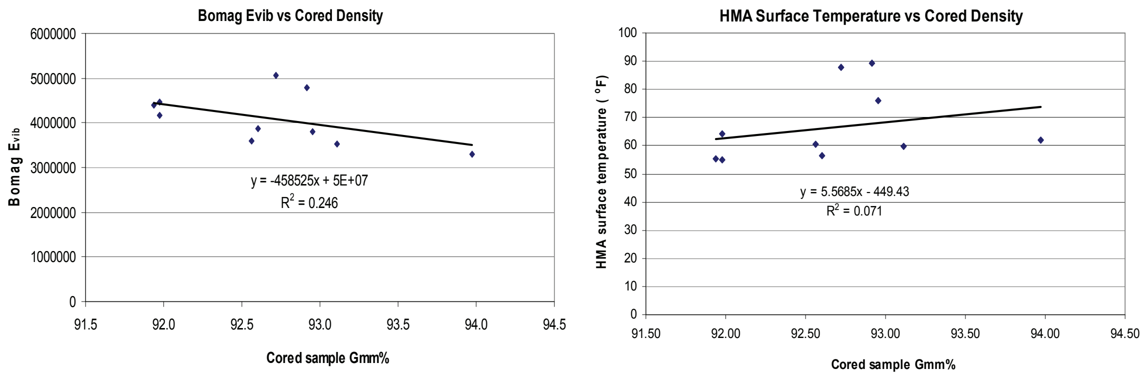


Figure 139. Bomag measurements vs. cored sample Gmm% of HMA intermediate layer (TB 03).

Findings confirming previous demo sites

- The IC roller can track the roller pass numbers, roller speed, HMA surface temperatures, and the ICMVs, which provides important metrics for the compaction quality;
- With the real-time information of IC roller passes, HMA surface temperatures and ICMVs displayed on the screen, the roller operator can adjust rolling patterns to improve the compaction quality;
- The HMA temperatures affect the ICMVs due to the temperature-dependent viscoelastic property of HMA materials;
- For the roller final pass (proof data), the non-nuclear density gauge measurements of HMA overlay do not correlate well with the Bomag Evib and Sakai CCV (they have linear relationships but with relatively low R^2 values like 0.25 and 0.27).

Wisconsin IC Demonstration

The test site is located on IH 39 at the junction of IH 39 and 153, Mosinee, WI (see Figure 140). The length of the project is about 5 miles long with two lanes on the South Bound (SB) direction. The layers and materials include the rubblized and crack-and-seat PCC base, HMA base course, intermediate HMA layer, and HMA surface layer. The Sakai double-drum IC roller was sued for all the mapping and compaction.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to WISDOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

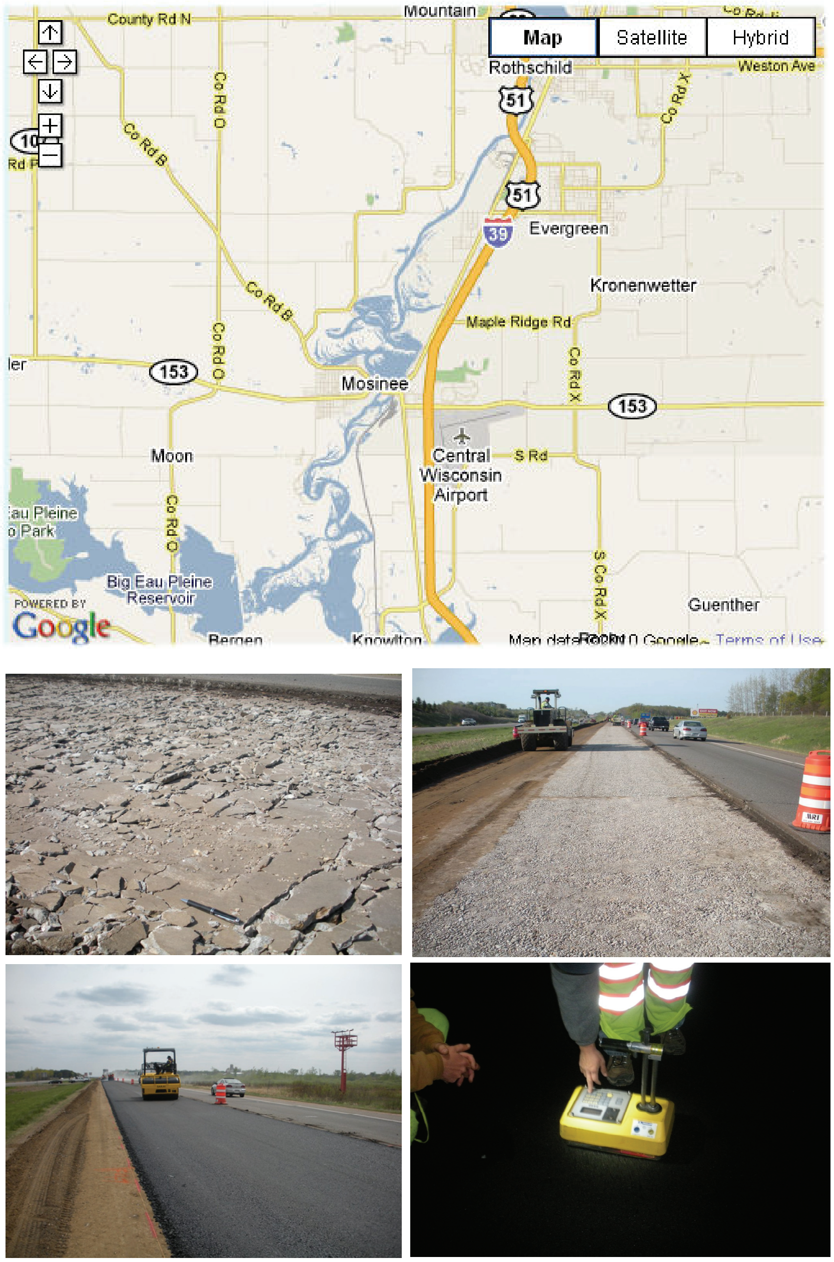


Figure 140. Wisconsin HMA IC demonstration.

Unique Features

- It is the first demo project to pave HMA courses on the rubblized PCC base;
- It is the first demo to use IC roller for multi-layers including mapping the PCC base, compacting on the HMA base, 2nd lift HMA intermediate layer, and HMA surface, which has provided a wealth of information and knowledge to share with the industry in order to accelerate the implementation of IC technologies;
- It is the first demo to perform FWD and LWD test on multi-layers from the PCC base, HMA base, 2nd lift HMA intermediate layer, and HMA surface;
- It is the first demo to use IC roller for both the breakdown and finishing compactions;

- It is the first demo to perform the LWD test following the breakdown compaction;
- Thermal bar was used for measuring HMA surface temperatures.

Major Findings

- One of the repeated evidence of immediate benefits is improvement of rolling patterns. See the significant difference between the "before" and "after" using of the IC technologies in **Error! Reference source not found.**.

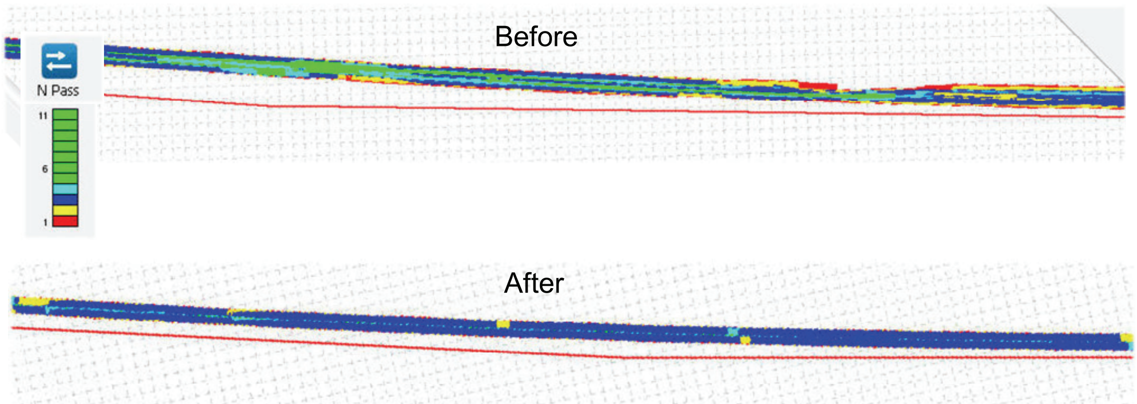


Figure 141. Improvement of rolling patterns using the IC technologies.

- Double-drum IC rollers can be used to map the rubblized and crack-and-seat PCC bases prior to the paving of HMA layer;

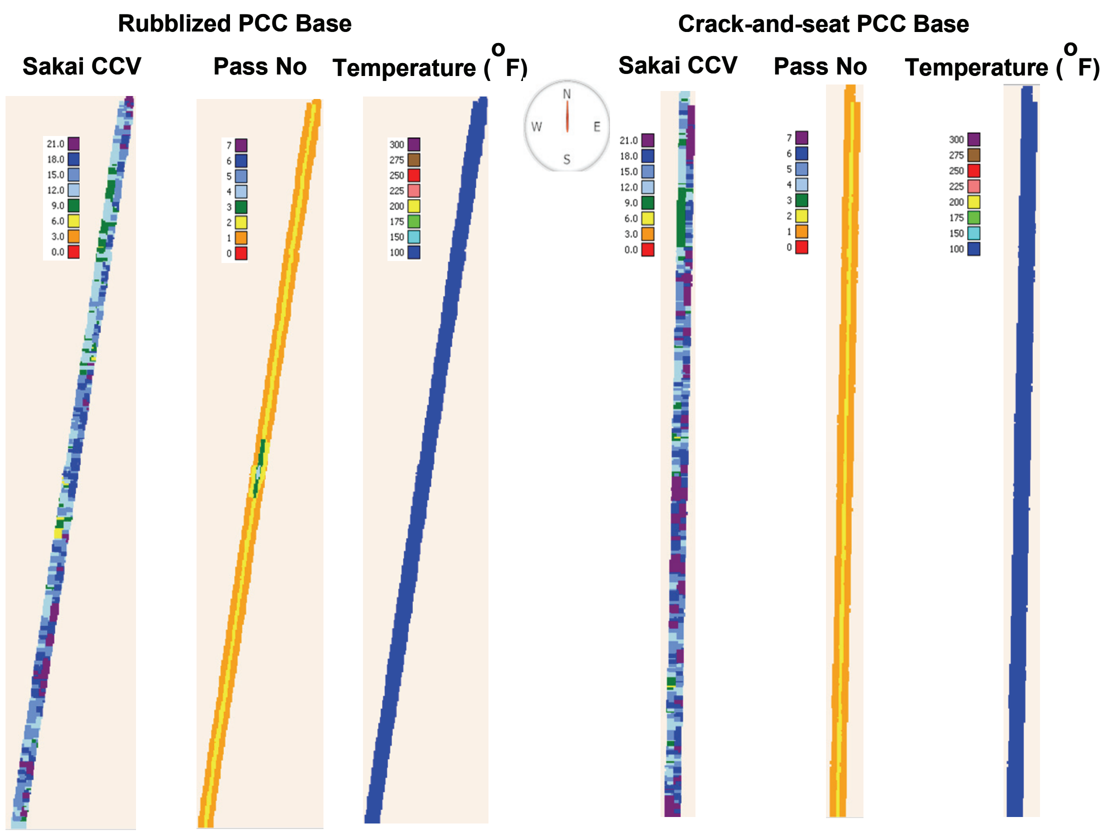


Figure 142. Sakai mapping existing rubblized and crack-and-seat PCC bases (TB2M).

- IC mapping of the rubblized and crack-and-seat PCC base was shown to be crucial in identifying the pavement conditions prior to the paving of the HMA base;

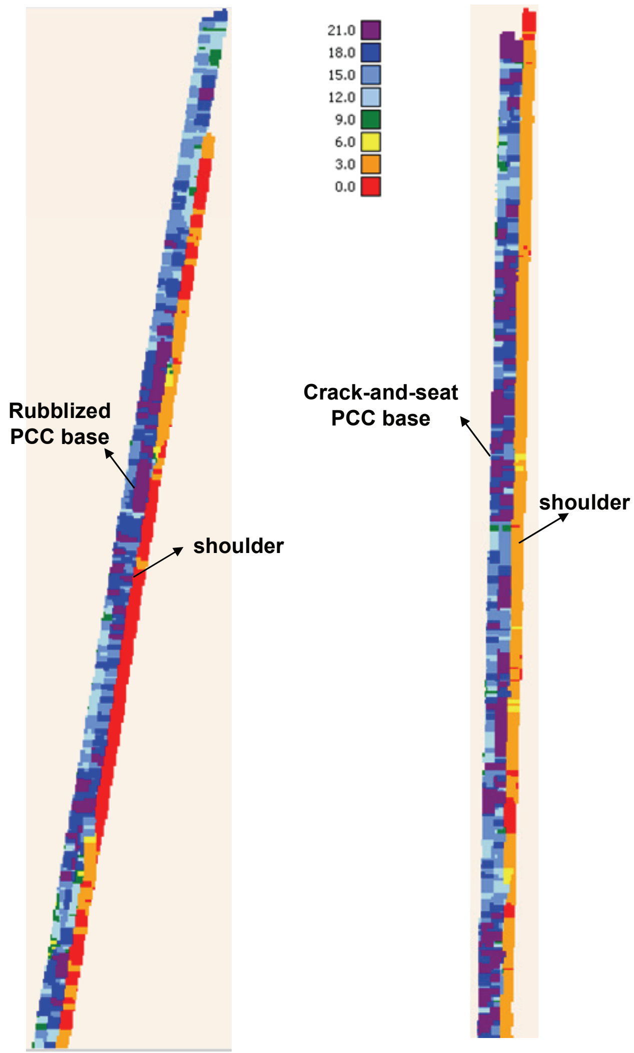


Figure 143. Sakai CCV of existing rubblized and crack-and-seat PCC bases (TB1M).

- The non-nuclear density was measured for each roller pass, which was found to correlate well with the Sakai CCV (R^2 value of 0.48);

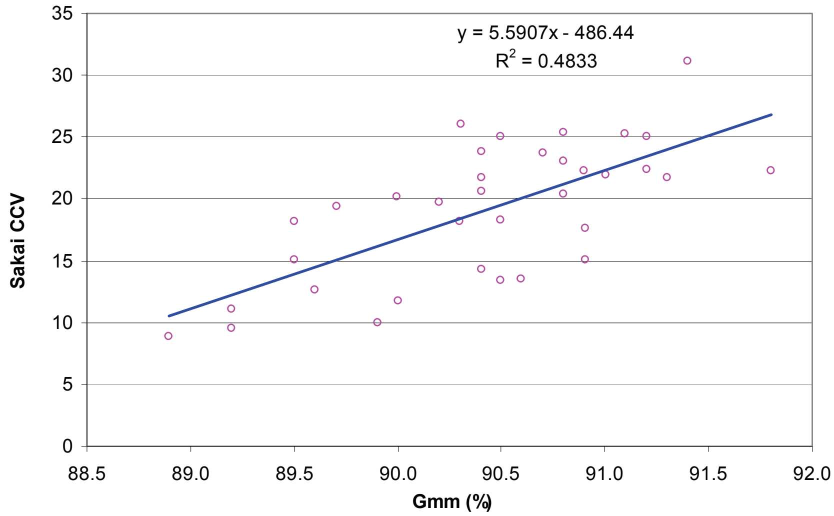


Figure 144. Sakai CCV vs. NNG gauge measured Gmm% for combined single passes.

- Night paving has been successfully implemented with the assistance of IC technology;

Figure 145. Night paving and HMA compaction.

- LWD measurements (deflection and moduli) and NG density have relatively good linear correlation with the roller measurement value (ICMV) for some test beds, and HMA temperature has significant effect on the correlation result (see examples below, ICMV vs. LWD on the left, and ICMV vs. NG density on the right);

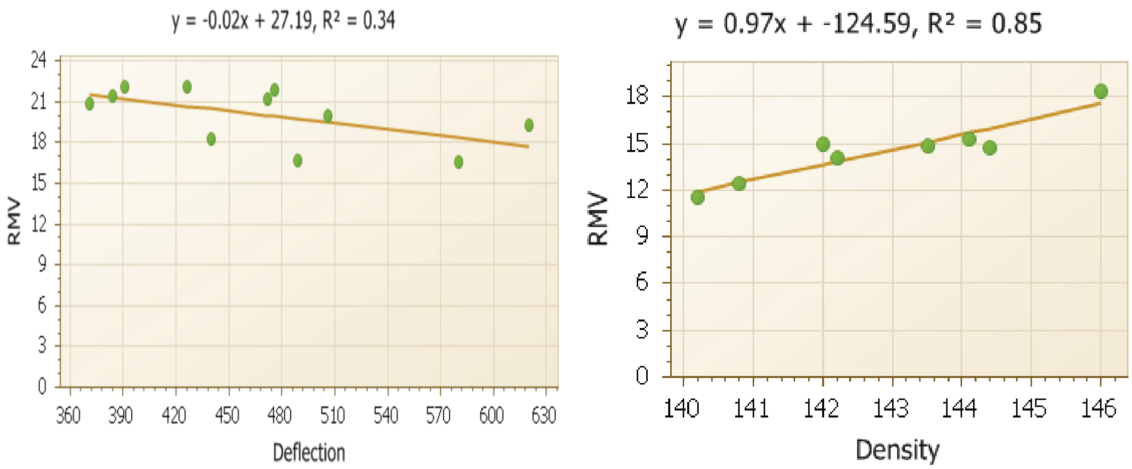


Figure 146. Roller MVs vs. FWD deflections and NG Densities.

- Generally compaction uniformity increases from the "ground up": i.e., from PCC base to the HMA base and then the 2nd lift HMA course and HMA surface, as indicated in the semi-variogram analysis (see below, semi-variograms for HMA base course and the second lift, intermediate course);

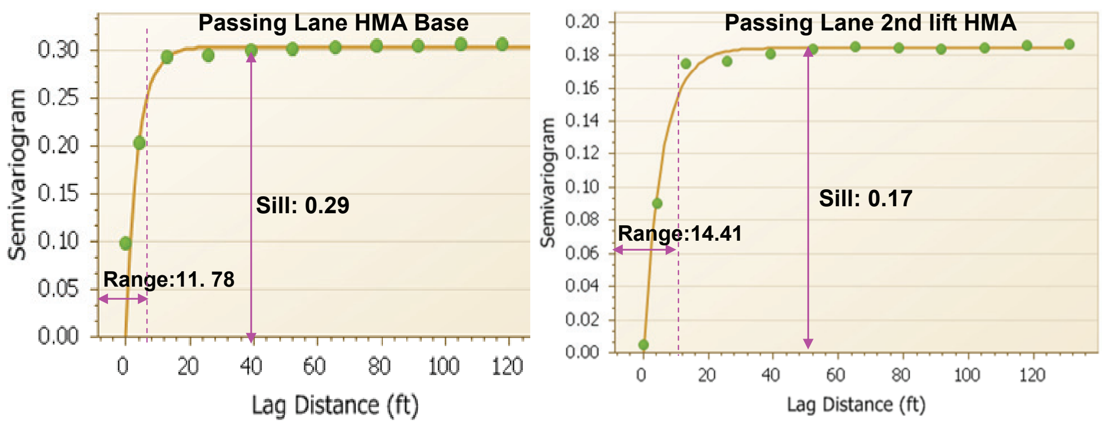


Figure 147. Semi-variograms of HMA base and 2nd lift HMA.

- Optimum roller passes can be determined by the "compaction curves" that help avoiding the over compaction or under compaction. (see below examples of compaction curves that indicate optimum pass as 4)

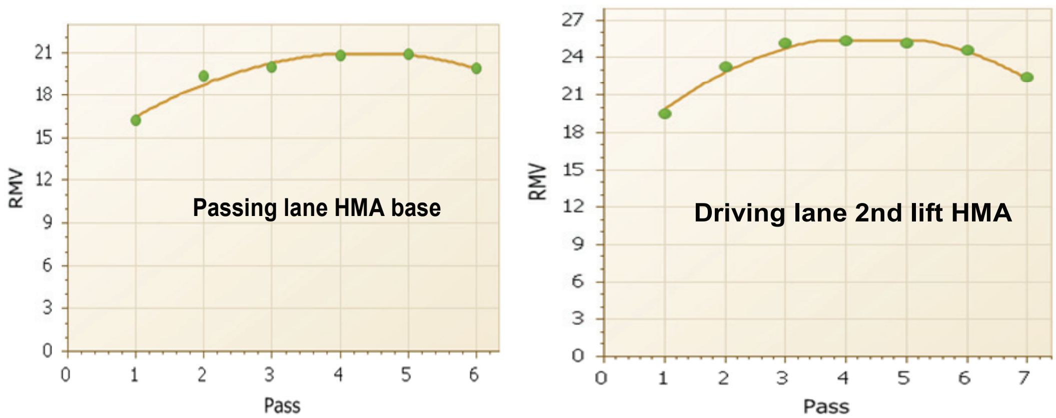


Figure 148. Compaction curves of HMA base and 2nd lift HMA.

Findings confirming previous demo sites

- The IC roller can track the roller pass numbers, roller speeds, HMA surface temperatures, and the ICMVs, which provides important metrics for the compaction quality;
- With the real-time information of IC roller passes, HMA surface temperatures and ICMVs displayed on the screen, the roller operator can adjust rolling patterns to improve the compaction quality.

Texas IC Demonstration

This report describes the FHWA/TPF mini intelligent compaction (IC) demonstration for the hot mix asphalt (HMA) materials in El Paso, TX, in May 2010. It is a new HMA construction project (CSJ 3451-01-027) on FM 1281. Project limits are from 0.3 miles east of IH-10 to 3.301 miles east of IH-10. The existing asphalt layer was milled and the top 4” of granular base was stabilized with 4% cement by weight. Then, a 2” of new HMA layer was paved on top of the cement stabilized base (CTB).

Figure 149. Texas HMA IC demonstration.

Major Findings

- Sakai double-drum IC rollers can be used to map cement stabilized bases prior to the paving of HMA layer that can differentiate performances from different cement mixing techniques;

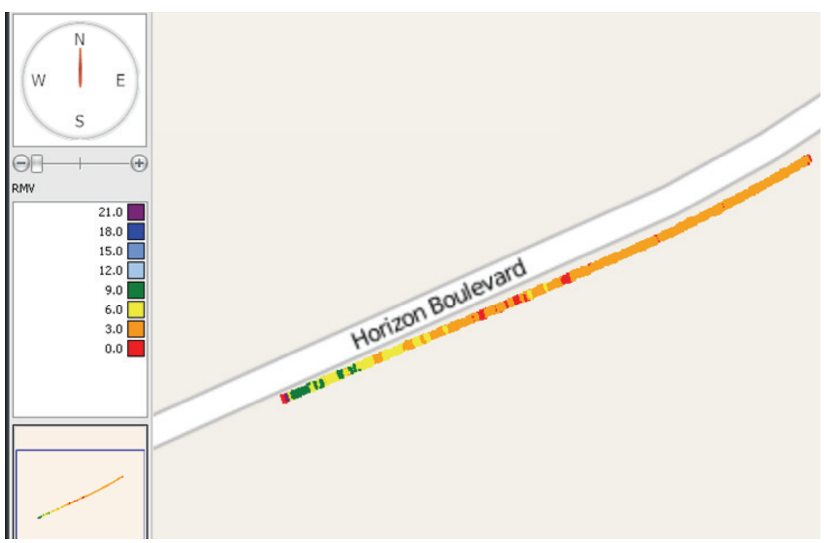


Figure 150. Sakai CCVs from the IC mapping on the cement stabilized base, TB 01M

- Falling Weight Deflectomer (FWD) and Non-Nuclear density Gauge (NNG) test data, when performed close to the IC mapping temperatures on HMA, can be correlated well with the Sakai CCV;

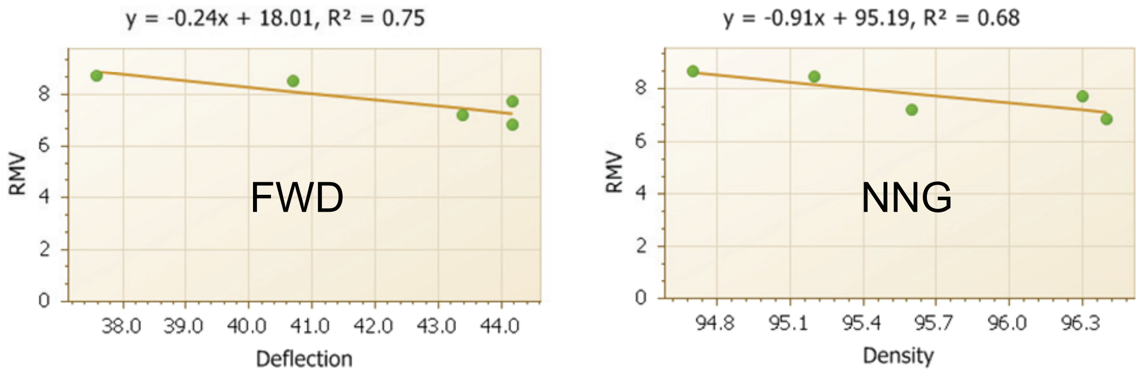


Figure 151. Correlation between Sakai CCVs (mapping run) and in-situ tests on HMA (FWD deflections normalized to 9,000 lb in mils, NNG in %Gmm), TB 01A.

- PSPA tests, when performed close to the IC mapping temperatures on HMA, can be correlated very well with the Sakai CCV;

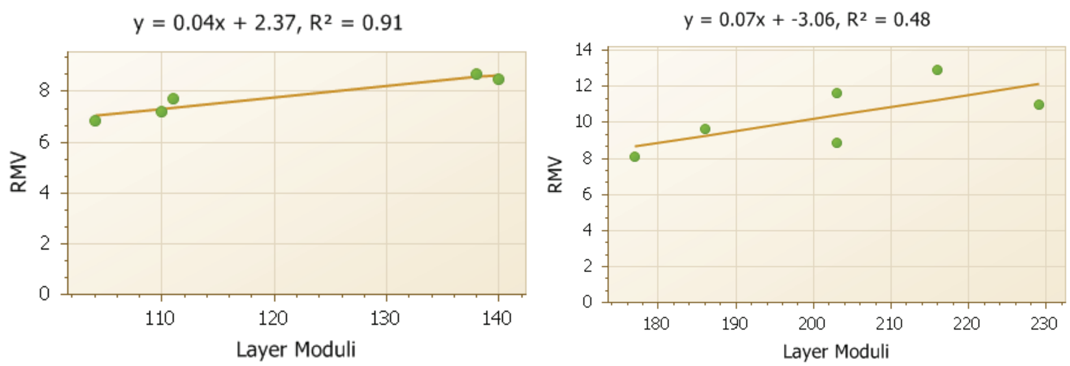


Figure 152. Correlation between Sakai CCVs (mapping run) and PSPA tests (normalized to 77 °F in ksi) on HMA, TB 01A (left) and TB 02A (right) at 1 and 2 hours after paving, respectively.

- The Sakai IC roller can track roller passes, roller speeds, HMA surface temperatures, and CCV successfully for HMA compaction;
- With the real-time information of IC roller passes, HMA surface temperatures and ICMVs displayed on the onboard Sakai CIS screen, roller operators can adjust rolling patterns to improve the compaction quality;
- Semi-variogram can be used as a metric for evaluating uniformity.

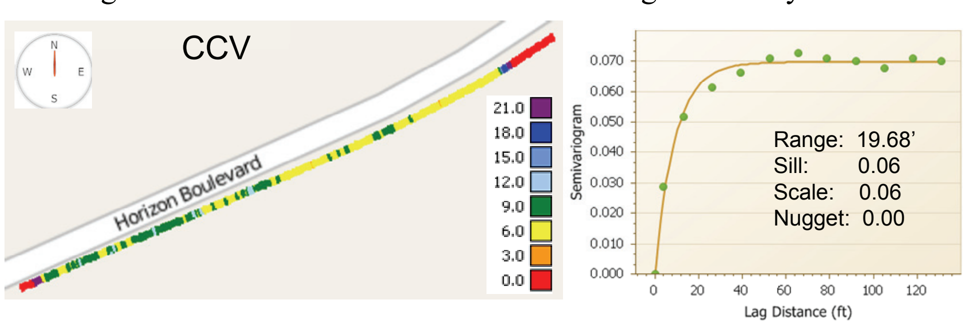


Figure 153. Sakai CCVs for mapping run on fresh HMA and it's associated semi-variogram, TB 01A.

Pennsylvania IC Demonstration

This is an HMA overlay project that the location is centered at the interchange of SR 53 and SR 219 in Summerhill, PA (Figure 154). The existing pavement is HMA on top of PCC slabs. During the demonstration, the existing HMA layer was milled and removed before paving HMA binder and wearing courses (9.5-mm mix). The Sakai and Volvo double-drum IC rollers were used for all the mapping and compaction.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to PennDOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

Figure 154. Pennsylvania HMA IC demonstration.

Unique Features

- It is the first IC demonstration project on mountainous areas that bring challenges to global position signals (GPS) signal transmission;
- It is the first IC demonstration project to conduct light-weight deflectometer (LWD) tests on hot mixture asphalt after breakdown or intermediate compaction;
- It is the first IC demonstration to map newly paved HMA binder course;

- It is the first IC demonstration to use Volvo IACA roller for measuring HMA densities in real time.

Major Findings

- One of the repeated evidence of immediate benefits is improvement of rolling patterns;
- Measurements of IC roller GPS can be verified by placing a GPS rover receiver on the top of roller GPS receiver unit to eliminate the potential error resulted from offset and direction angle;
- Relocation of GPS base station will cause roller GPS data shifting, therefore restarting the IC roller computer system as well as hand-held GPS rover is required under such condition;
- The Sakai compaction control value (CCV) of underneath layer reflects to that of the upper HMA layer (e.g. uniform CCV of the HMA binder course from mapping corresponds to relatively uniform CCV of HMA wear course paved on top as shown in the following figure);

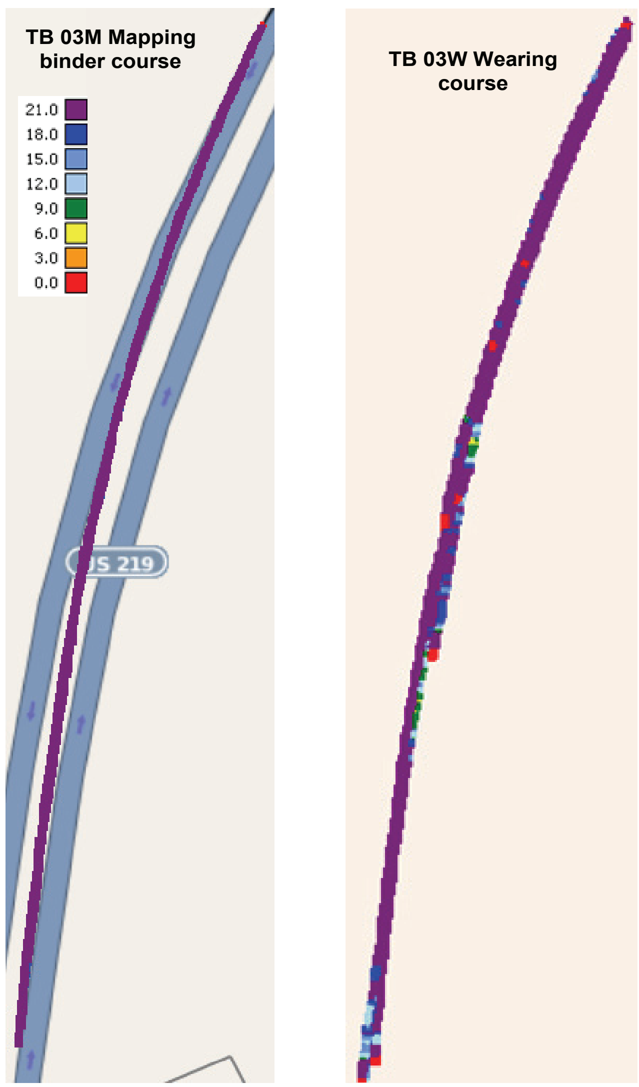


Figure 155. Sakai CCVs of mapping binder course and paving on wearing course.

- Compaction uniformity can be compared for different sections using semi-variogram analysis (e.g. Uniformity increases from sections 1 to 4 for TB 03W HMA wearing course. See the following figure);

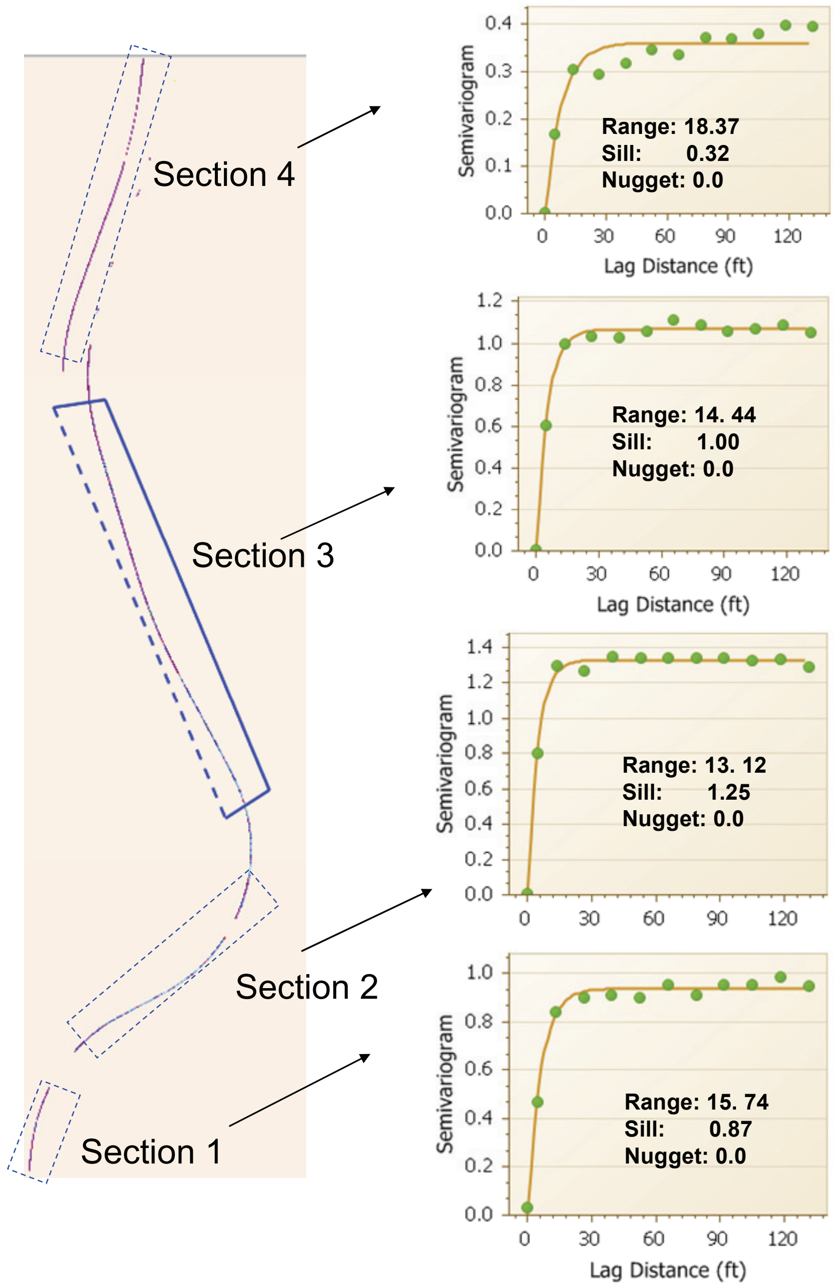


Figure 156. Semi-variograms of HMA wearing course.

- Compaction uniformity appears to increase from the "ground up" for the paving materials (i.e. from the hot HMA binder course paving to the hot HMA surface course paving);
- The newly paved HMA binder course exhibits good uniformity likely due to uniform temperature distribution. However, more research is needed to quantify the effects of temperature distribution on compaction uniformity;

- Optimum roller passes can be determined by the "compaction curves" to prevent de-compaction or under-compaction. (see the figure below for an example of compaction curves)

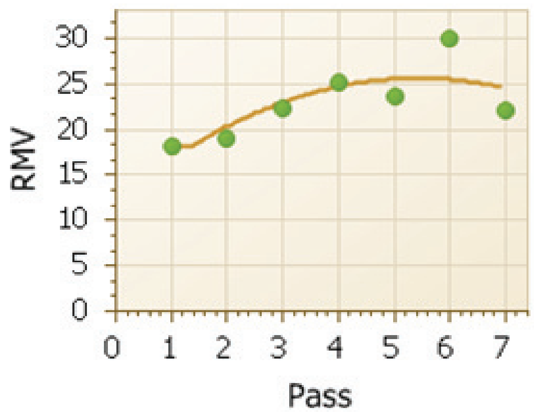


Figure 157. Compaction curve for HMA wearing course.

Confirming Past Findings

- The IC roller can track the roller pass numbers, roller speeds, HMA surface temperatures, and the ICMVs, which provides important metrics for the compaction quality;
- With the real-time information of IC roller passes, HMA surface temperatures and ICMVs displayed on the screen, the roller operator can adjust rolling patterns to improve the compaction quality.

Virginia IC Demonstration

It is an HMA overlay project on I-66, Markham, VA, conducted from September 27 to September 30 2010 (see Figure 158). The existing pavement is HMA pavement. During the demonstration, the existing HMA surface layer was milled and removed before paving HMA overlay.

The objectives of this demonstration project were short-term goals for introducing HMA IC technology to VADOT and contractors who may not have prior experience with IC technology. The project was intended to demonstrate the benefits of IC for improving the compaction process and quality by achieving more uniform density and modulus of the HMA material and providing roller operators (and superintendents) better feedback tools to make right decisions, and ultimately real-time quality control.

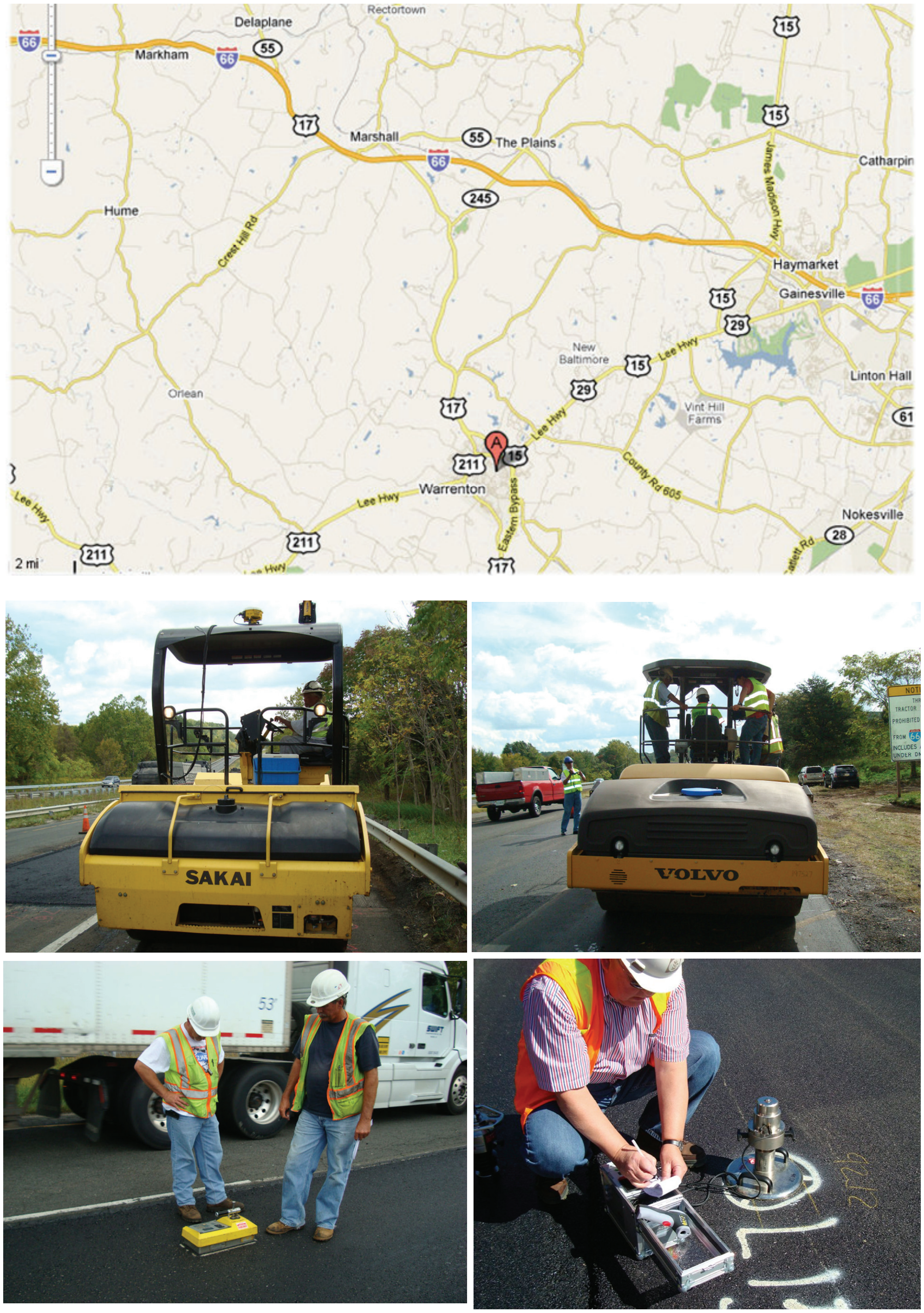


Figure 158. Virginia HMA IC demonstration.

New Findings:

- Measurements of IC roller GPS can be verified by placing a GPS rover receiver on the top of roller GPS receiver unit to eliminate the potential error resulted from offset and movement angles (see figure below);

Figure 159. Roller GPS validation.

- Mapping of exiting HMA surfaces can be used to evaluate pavement conditions in order to identify relatively weaker areas (see figure below that shoulder area –right hand side - has lower CCV than pavement lane –left hand side-);

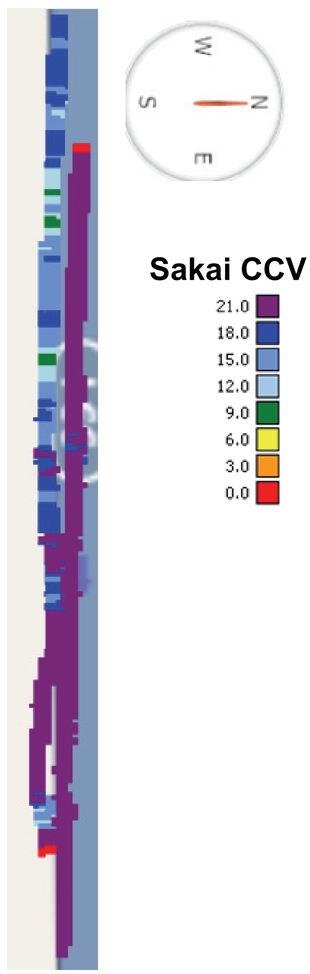


Figure 160. Sakai CCV of mapping HMA surface.

- Compaction uniformity for different construction sections can be compared using semi-variogram analysis (see figure below that higher range values indicates higher compaction uniformity);

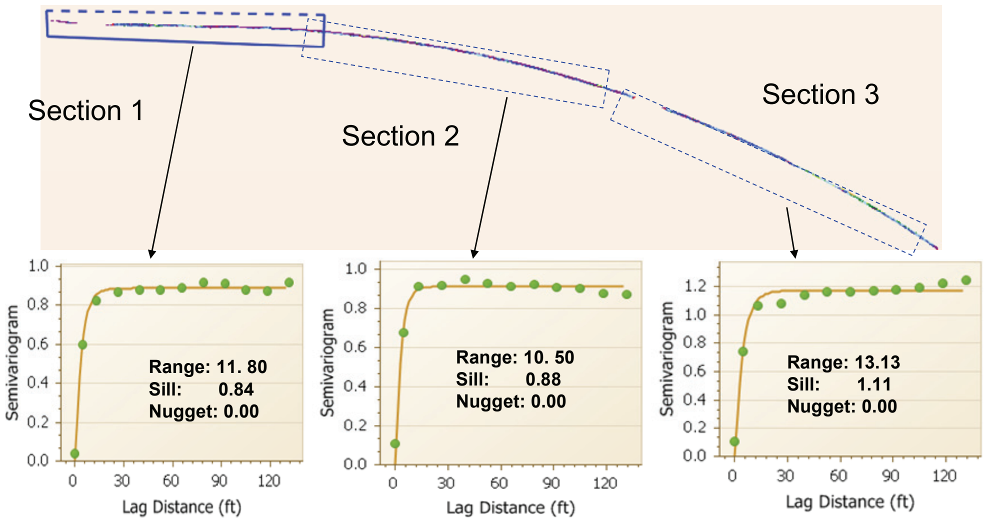


Figure 161. Semi-variogrqams of HMA overlay.

- Mapping of existing HMA pavement shows a relatively higher uniformity than that from compaction of hot mixture asphalt overlay. This observation may be due to the uniform (colder) temperatures of existing HMA. However, more research is needed to quantify the effects of temperature distribution on compaction uniformity;
- Compaction curve can be established using IC technology to determine optimum roller pass number (see figure below for compaction curves of three different sections of HMA overlay);

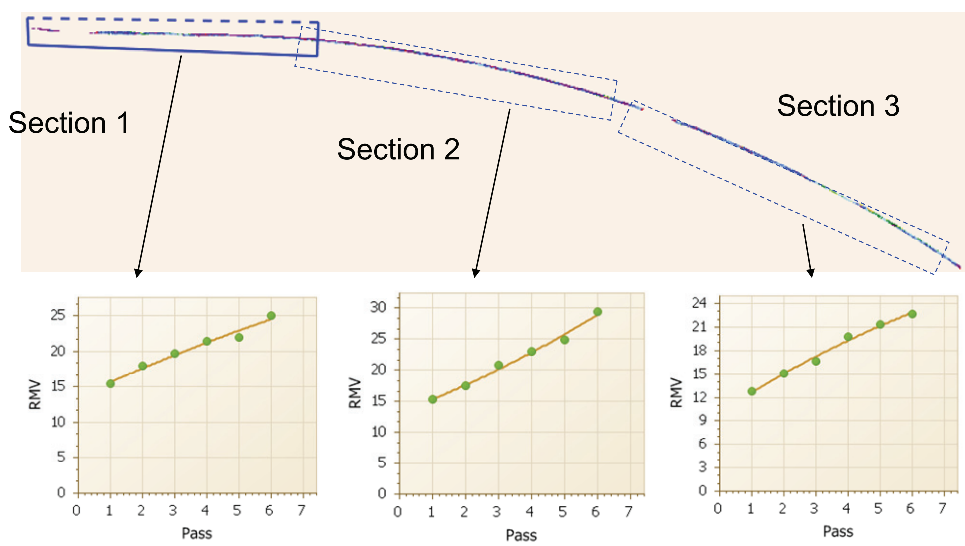


Figure 162. Compation curves of HMA overlay.

- Nuclear density gauge measurements of fresh HMA overlay behind the Volvo IACA roller forms a compaction curve within a narrow range of densities (see figure below);

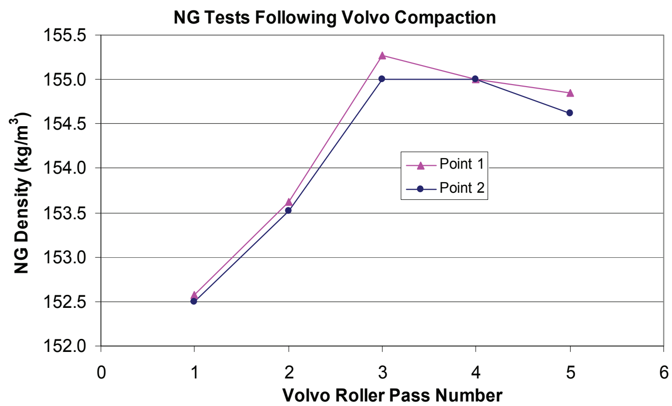


Figure 163. NG density at different Volvo roller pass.

Confirming Past Findings

- The IC roller can track roller pass numbers, roller speeds, HMA surface temperatures, and the ICMVs, which provides important metrics for compaction quality;
- With real-time information of IC roller passes, HMA surface temperatures and ICMVs displayed on the onboard screen, roller operators can adjust rolling patterns to improve the compaction quality.

Rolling Patterns and Mapping

All the FHWA/TPF demonstration projects have successfully demonstrated the use of IC rollers for tracking roller locations and passes, ICMVs, and surface temperatures for 100 percent coverage of compaction areas to facilitate decision making.

- Improvement of Rolling Patterns: IC technologies can be used to improve roller patterns as an immediate benefit. Figure 164 shows that roller passes become more consistent and uniform after using the IC technologies for the Indiana demonstration project. Knowing pavement temperatures in real-time helps operator determine compaction modes (static vs. vibratory) during the intermediate/finishing roller compaction, and avoid material premature failure (e.g. vibratory compaction at relatively low temperature will damage HMA materials).

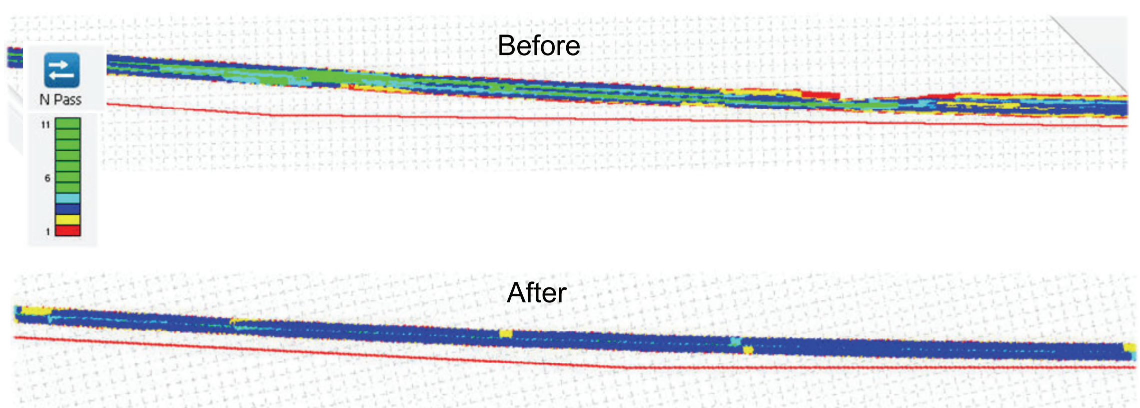


Figure 164. Roller Passes before and after using IC technology (Indiana IC demonstration)

- Mapping the Strength of Existing Support: IC rollers were also successfully used for mapping the underlying materials prior to HMA paving (IC roller drives on the existing pavement layer using the vibration mode), for just-in-time corrective actions. The Minnesota project identified weak spots on the grade prior and after paving.

- Monitoring the Strength Gains of Stabilized Base: IC mapping can be used to monitor strength gains of stabilized base as shown in the Mississippi project (Figure 165). IC technologies also help improve compaction quality during night paving as it tracks rollers in the dark.

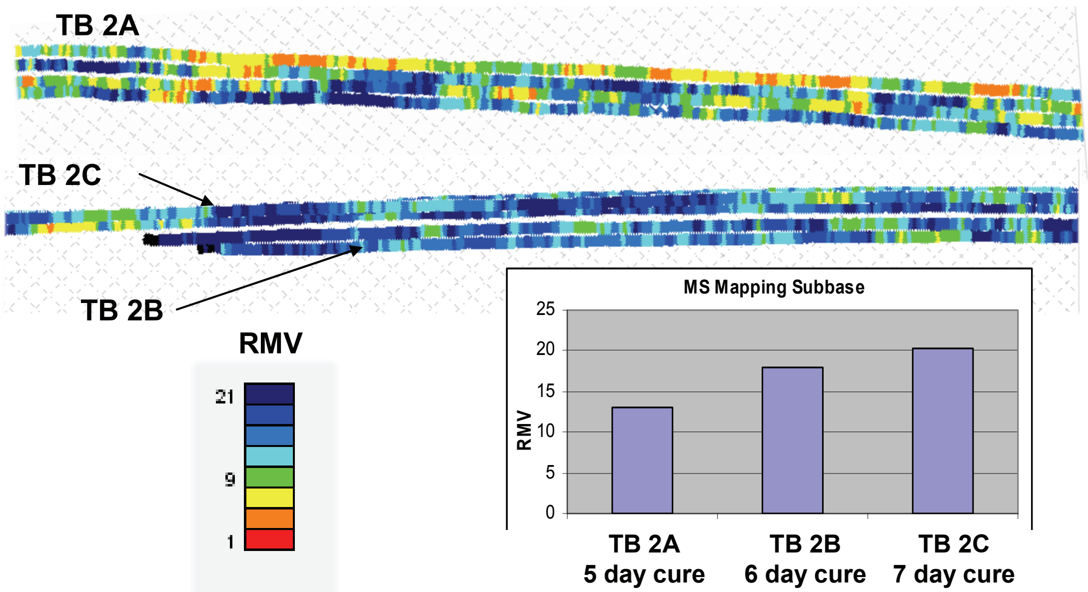


Figure 165. Sakai CCV of mapping existing stabilized subbase (Mississippi IC demonstration).

Compaction Curves

For a paving project with relatively uniform support, an optimum roller pass can be established from a test strip for a given HMA mix. Figure 166 shows compaction curves. Results show that for most highway projects the ICMV increase first and then decreases with increasing roller pass number, or ICMV continuously increases until being constant after a certain roller pass. E.g. for the Wisconsin demonstration, the optimum roller pass is 4 or 5. This finding offers very important information to help achieve the best compaction, while avoid under/over-compaction by using the IC technology.

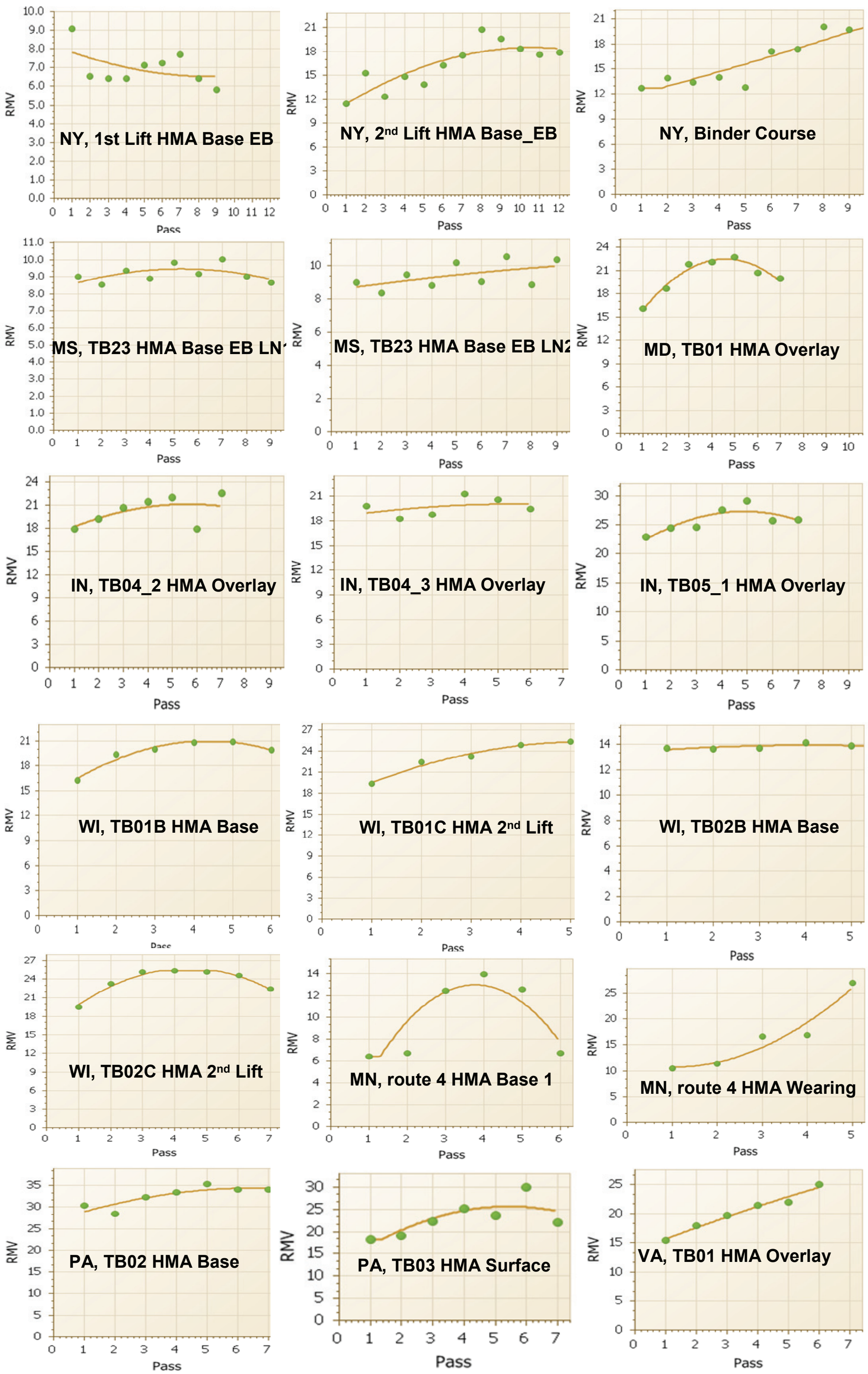


Figure 166. Compaction curves of TPF HMA IC Projects

Compaction Uniformity

Semivarigram parameters were derived using the geostatistical analysis. Table 13 summarizes the semi-variogram parameters of range and sill. Results have shown that generally compaction uniformity increases (with greater range while lower sill values) from the "ground up": i.e., from the base to the HMA base and then HMA surface courses (see results of the NY, MS, MD, and WI demonstrations). This is because that the adjustable compaction efforts on the upper layer have increased the compaction uniformity.

Table 13. Fitted Semi-variogram parameters.

State	Test bed	Roller	RMV Mean	Range	Normalized sill
MN	Route 4 HMA Base 1	SW880 Breakdown	7.25	5.22	3.28
MN	Route 4 HMA wearing course	SW880 Breakdown	10.64	15.67	2.94
NY	Mapping SB	SW880 Mapping	12.98	41	1.67
NY	1st Lift HMA Base EB	SW880 Breakdown	15.36	93	0.44
NY	2nd Lift HMA Base EB	SW880 Breakdown	14.05	92	0.70
MS	TB 2A SB Mapping	SW880 Mapping	13.7	28	1.53
MS	TB23 HMA Base EB Ln1	SW880 Breakdown	9.38	35	0.23
MS	TB23 HMA Base EB Ln2	SW880 Breakdown	9.78	37	0.40
MD	TB02 HMA Base Mapping	SW880 Mapping	24.33	27	10.39
MD	TB02 HMA Overlay	SW880 Breakdown	22.8	85	2.70
MD	TB03A HMA Base Mapping	SW880 Mapping	35.98	65	11.06
MD	TB03B HMA Overlay	SW880 Breakdown	24.11	40	1.18
IN	TB04-1 HMA Overlay	Bomag Breakdown	5,511,175	2.8	0.13
IN	TB04-2 HMA Overlay	Bomag Intermediate	5,682,027	4.4	0.09
IN	TB04-3 HMA Overlay	Bomag Breakdown	6,138,302	4.4	0.06
IN	TB05-1 HMA Overlay	Bomag Intermediate	5,784,951	2	0.07
IN	TB04-1 HMA Overlay	SW880 Intermediate	14.2	4	1.38
IN	TB04-2 HMA Overlay	SW880 Breakdown	19.4	4	0.76
IN	TB04-3 HMA Overlay	SW880 Intermediate	17.7	4	1.07
IN	TB05-1 HMA Overlay	SW880 Breakdown	22.8	6.4	0.04
IN	TB05-2 HMA Overlay	SW880 Breakdown	18.4	4	0.80
WI	TB01B HMA Base_1	SW990 Breakdown	17.49	11.78	0.29
WI	TB01C 2nd HMA lift_1	SW990 Breakdown	19.15	14.41	0.17
WI	TB01D HMA surface_1	SW990 Breakdown	13.07	17.05	0.08
WI	TB01B HMA Base_2	SW990 Breakdown	18.03	13.06	0.28
WI	TB01C 2nd HMA lift_2	SW990 Breakdown	21.07	15.68	0.15
WI	TB01D HMA surface_2	SW990 Breakdown	15.48	19.58	0.08
WI	TB02B HMA Base_1	SW990 Breakdown	13.58	18.36	0.10
WI	TB02C 2nd HMA lift_1	SW990 Breakdown	23.13	19.66	0.08
WI	TB02D HMA surface_1	SW990 Breakdown	21.99	19.68	0.07
WI	TB02B HMA Base_2	SW990 Breakdown	15.28	19.58	0.07
WI	TB02C 2nd HMA lift_2	SW990 Breakdown	24.35	15.67	0.10
WI	TB02D HMA surface_2	SW990 Breakdown	24.13	15.67	0.10
PA	TB01B HMA binder course	SW880 Intermediate	14.67	10.49	0.00
PA	TB02W HMA wearing course_1	SW880 Intermediate	27.15	15.74	0.00
PA	TB02W HMA wearing course_2	SW880 Intermediate	21.56	13.12	0.00
PA	TB02W HMA wearing course _3	SW880 Intermediate	24.9	14.44	0.00
PA	TB02W HMA wearing course _4	SW880 Intermediate	33.83	18.37	0.00
PA	TB03M HMA binder course (mapping)	SW880 Mapping	65.48	21	0.00
PA	TB03W HMA wearing course_1	SW880 Intermediate	28.48	13.12	0.00
PA	TB03W HMA wearing course_2	SW880 Intermediate	25.58	11.81	0.00
PA	TB03W HMA wearing course_3	SW880 Intermediate	21.22	14.43	0.00
PA	TB03W HMA wearing course_4	SW880 Mapping	19.72	14.44	0.00
VA	TB 01M	SW880 Mapping	26.33	14.42	0.00
VA	TB 01 HMA Overlay_1	SW880 Breakdown	22.12	11.8	0.00
VA	TB 01 HMA Overlay_2	SW880 Breakdown	21.88	10.5	0.00
VA	TB 01 HMA Overlay_3	SW880 Breakdown	17.79	13.13	0.00

Notes: For the Indiana demonstration, the existing HMA mapping data using Bomag was not exportable due to some technical issues and thus not analyzed in this table.

Correlation Study

Univariate Linear Correlation

Correlation of ICMV to NG/NNG density

Figure 167 presents the linear correlation of ICMV with density. Results show that mostly ICMV increases with increasing density, indicating that a higher stiffness corresponds with a greater material density. For some test beds, a good correlation was achieved (e.g. for the Indiana TB 04-2 test bed with NNG densities for all passes, and the Wisconsin TB02C test bed with NG for the proof data). However, for some test beds, the correlation is poor and the trend even reverses for rare ones like the NY HMA base. Those relatively poor correlations could be explained by at least the following reasons: 1) ICMV is a stiffness of the pavement system with an influence depth going through underlying layers and soil foundation, while density is measured only for the top HMA layer; 2) During the compaction HMA temperature and/or the vibration frequency are not constant at those in-situ test spots, which will affect ICMV much more significantly than density; however, the existing ICMV models are unable to convert ICMVs to that at reference temperature and decouple the stiffness to a respective pavement layer due to technical challenging.

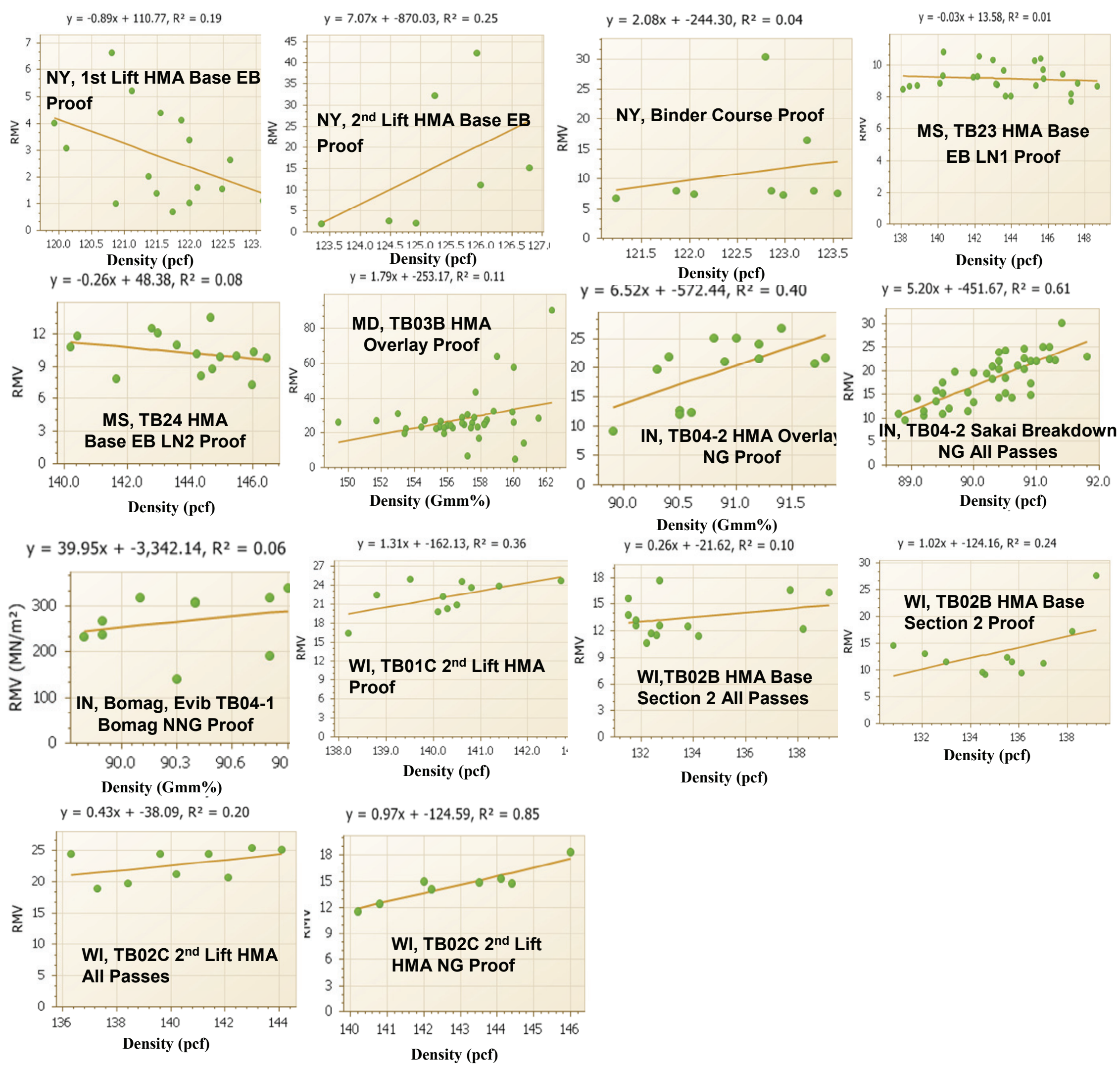


Figure 167. NG/NNG Density Correlation (NY, MS, MD, IN, WI)

Note: Only units of original research of in-situ measurements are presented as also required by the TRB guideline, and thus not converted to uniform one as the same for following figures.

Correlation of ICMV to cores density

Figure 168 presents the linear correlation between ICMV and cores density. Results show inconsistent correlations, as ICMV may increase or decrease with the increase of core density. This inconsistent correlation may be explained by at least the following reasons: 1) the cores were taken after the static finishing roller compaction when pavement cooled down, while the ICMV was measured from the vibratory breakdown roller compaction; 2) the test spot number was usually very limited (e.g. 4) due to the high cost for the destructive test; and 3) others include the inconsistent HMA temperatures and frequencies at test spots, and ICMV is measuring the pavement system rather than only a top HMA layer for cores.

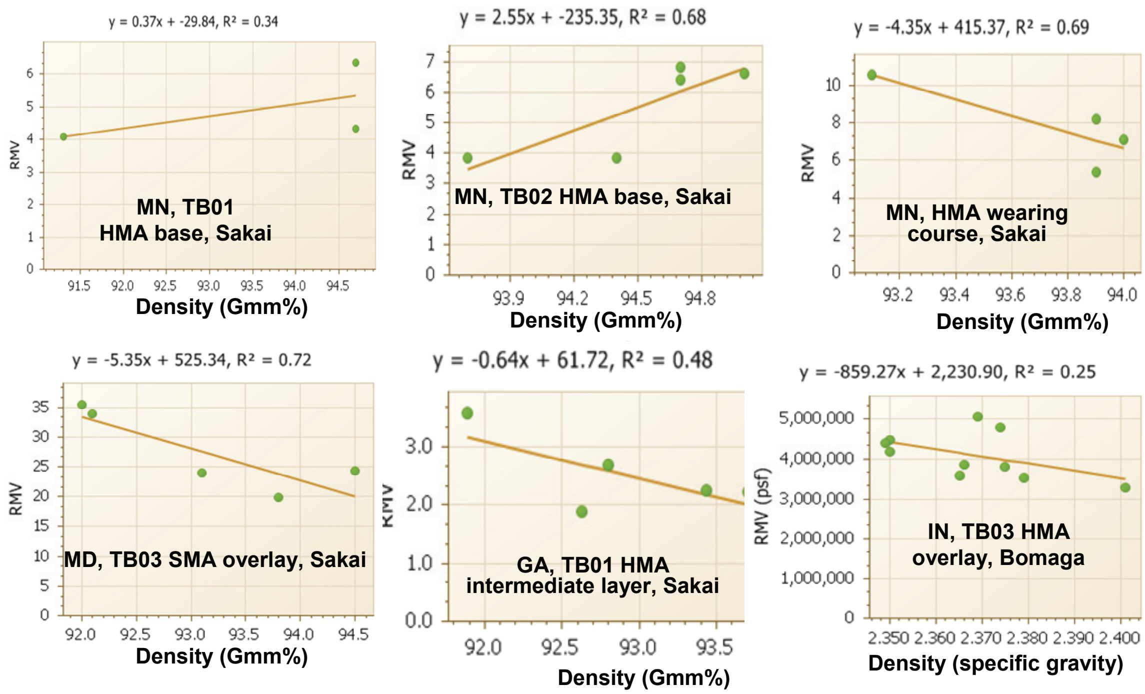


Figure 168. Cores density vs. ICMV (MN, MD, GA, IN)

Correlation of ICMV to FWD deflections and modulus

Figure 169 presents the linear correlation of ICMV with normalized FWD measured deflection (e.g. at 9000 lbs) or layer moduli (note that here only one project presents the layer moduli from FWD test). Apparently ICMV decreases with increasing FWD measured deflection as expected. Results show that they have more consistent and relatively good linear correlation compared to that of ICMV with density, which maybe due to that FWD measurement is for the integral pavement system as measured by ICMV. However, not very high R^2 values are achieved in these demonstration projects, which could be explained by following reasons: 1) ICMV and deflection are two different concepts and they may not have a linear correlation, though both of them indicate the stiffness of pavement; 2) the inconsistent HMA temperature and vibration frequency during construction at those spots affect the correlation results as discussed above; and 3) other factors include moisture variation of subbase/soil.

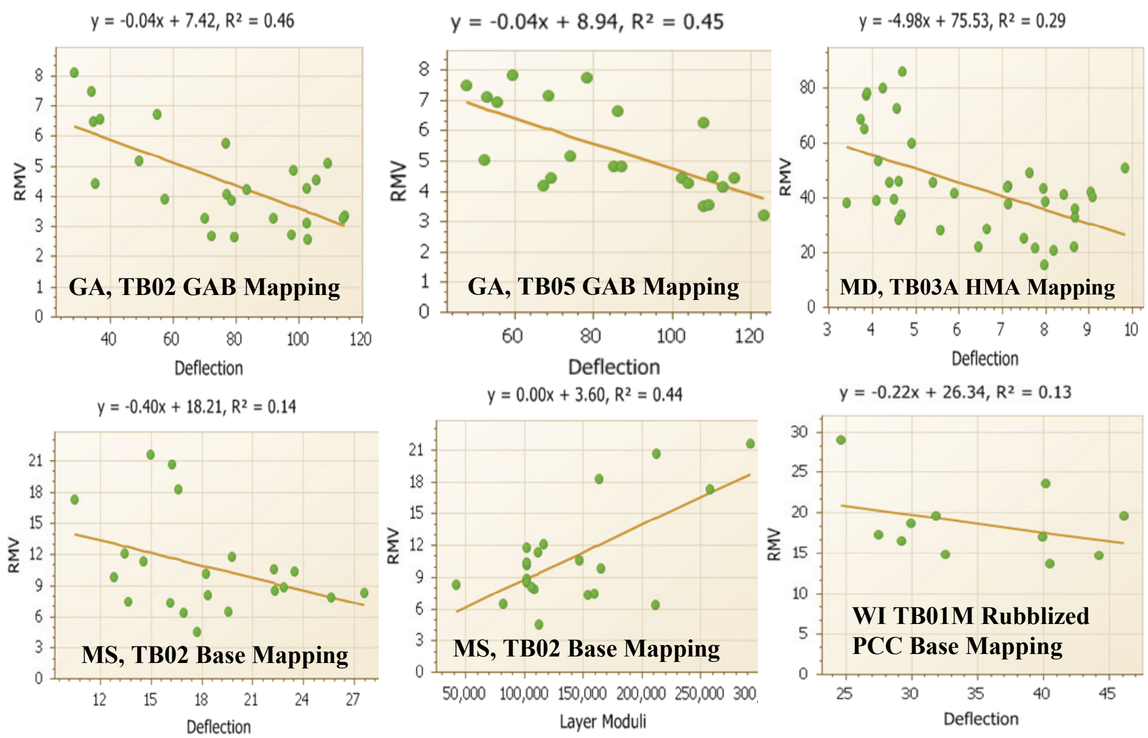


Figure 169. Correlation of Sakai CCVs with Normalized FWD Defections or moduli

Note: 1. deflection unit is 10-3 inch, layer moduli unit is psi; 2. GAB is granular aggregate base.

ICMV correlation with LWD measured deflection and moduli

Figure 170 presents the linear correlation of ICMV with LWD measured deflection and moduli or CBR. Apparently ICMV increases with increasing LWD moduli/CBR or decreasing LWD deflection as expected. Results show that they have more consistent linear correlation than that of ICMV and density discussed above. Nonetheless, no very high R^2 values are achieved, which maybe explained by the same reasons as that for the correlation between ICMV and FWD measurements.

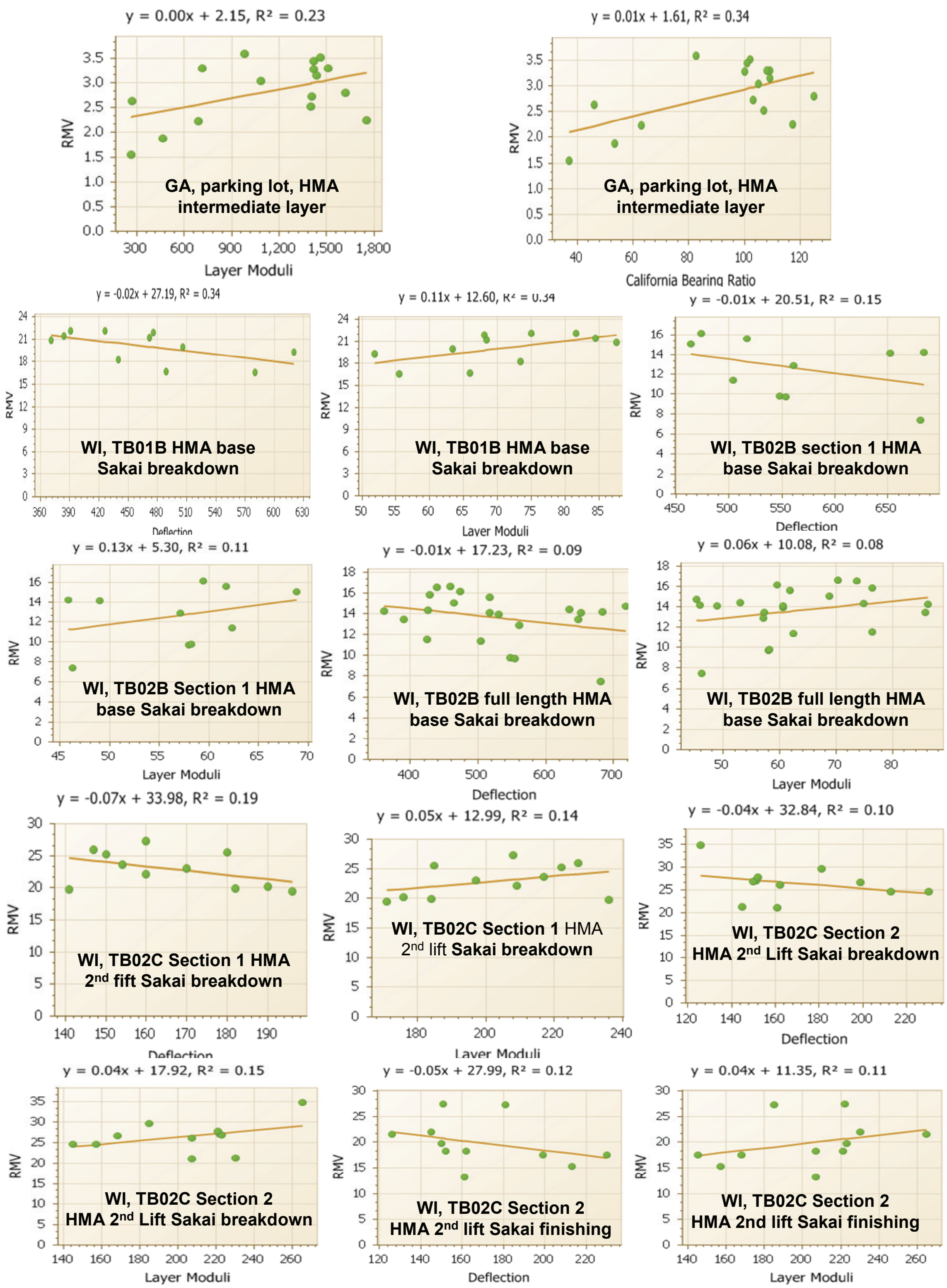


Figure 170. Correlation of ICMV with LWD measurements (layer moduli unit: MPa, deflection unit: x 10-6 m).

Multivariate Correlation

ICMV is potentially influenced by various factors, and therefore a multivariate analysis is warranted to study these effects. Multivariate linear regression study was performed on data from some tests beds of the Minnesota and Wisconsin projects. : The correlation among HMA base ICMV, and in-situ measurements of HMA base, roller vibration frequencies, HMA surface temperatures, subbase ICMV and associated vibration frequencies is studied.

Table 14 and Table 15 summarize the multivariate linear correlation results for the Minnesota and Wisconsin, respectively. Results indicate that correlation indicators (e.g., R^2) have improved with multivariate linear regression compared to those from univariate linear regression. For the Minnesota projects, subbase ICMV and HMA base temperatures are shown to have significant effect on the HMA base ICMV (with lower P values). For the Wisconsin TB01B HMA base study, the FWD deflection and subbase ICMV are shown to have significant relationship with the HMA ICMV (with lowest *P* values). For the Wisconsin TB02B HMA base study, the HMA base temperature and subbase ICMV have shown significant effect (with very low P values) on HMA base ICMV, while the HMA base NG densities have shown less relevant relationship. These results demonstrate that using univariate linear regression may omit the effects of other important factors. Therefore, multivariate analyses are recommended to evaluate the influences of multiple potential factors on the ICMV for future studies.

Table 14. Multivariate Correlation Results of Minnesota Project

a) Sample 1: ICMV of Route 4 HMA base with NG density, Minnesota

Regression Statistics			*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Multiple R	0.9975	Intercept	-276.0905	22.0802	-12.5040	0.0011
R Square	0.9950	HMA Base NG Density	0.3064	0.0340	9.0235	0.0029
Adjusted R Square	0.9866	HMA Base Freq	-0.0013	0.0011	-1.1282	0.3413
Standard Error	0.1623	HMA Base Temp	0.0318	0.0110	2.8950	0.0628
Observations	9	Agg Subbase RMV	0.8823	0.0440	20.0494	0.0003
df	8	Agg Subbase Freq	0.0718	0.0078	9.1625	0.0027

b) Sample 2: ICMV of Route 4 HMA base with core density, Minnesota

Regression Statistics			*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Multiple R	0.9669	Intercept	-238.8587	102.1644	-2.3380	0.1444
R Square	0.9349	HMA Base Core Density	0.0956	0.3005	0.3183	0.7804
Adjusted R Square	0.7720	HMA Base Freq	0.0071	0.0045	1.5994	0.2508
Standard Error	0.6547	HMA Base Temp	0.0550	0.0707	0.7783	0.5179
Observations	8	Agg Subbase RMV	-0.6805	0.3068	-2.2180	0.1568
df	7	Agg Subbase Freq	0.0677	0.0350	1.9350	0.1926

Table 15. Multivariate Correlation Results of Wisconsin Project

a) Sample 1: ICMV of TB01B HMA base, Wisconsin

Regression Statistics			*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Multiple R	0.7575	Intercept	410.5940	409.9901	1.0015	0.3275
R Square	0.5738	HMA base frequency	-0.0946	0.0654	-1.4456	0.1624
Adjusted R Square	0.4769	HMA base temperature	-0.0005	0.0912	-0.0051	0.9960
Standard Error	2.8808	HMA base FWD deflection	0.1100	0.0451	2.4380	0.0233
Observations	28	Subbase RMV	0.4164	0.1612	2.5833	0.0170
		Subbase frequency	-0.0121	0.0870	-0.1387	0.8909

b) Sample 2: ICMV of TB02B HMA base, Wisconsin

Regression Statistics			*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Multiple R	0.9879	Intercept	131.1543	61.2292	2.1420	0.0490
R Square	0.9759	HMA base NG	0.0499	0.0603	0.8274	0.4210
Adjusted R Square	0.9679	HMA base frequency	-0.0755	0.0363	-2.0770	0.0554
Standard Error	0.7279	HMA base temperature	-0.0574	0.0081	-7.0589	3.88E-06
Observations	21	Subbase RMV	0.8173	0.0412	19.8184	3.60E-12
		Subbase frequency	0.0282	0.0249	1.1295	0.2764

Chapter 8 Guidelines for IC Implementation

The recommended guidelines for successful IC implementation consist of: IC Road Map, General IC Plan, IC Data Management, IC Specifications, and IC training/workshops.

IC Road Map

The IC research team has developed an IC Road Map based on lessons-learned and knowledge-gained through various efforts under this project. The IC Road Map is to lay out the shortest path for IC implementation by filling gaps and overcoming barriers through streamlined strategies. This will include applications of IC technologies to various pavement materials including subgrade soils, subbase, and hot asphalt mixture materials.

There are four major tracks with three subtracks under each major track:

Track 1 — Equipment and Technologies

- Subtrack 1.1 : Standardization of IC roller measurement systems
- Subtrack 1.2 : Practical use of GPS in IC
- Subtrack 1.3 : Valid In-situ point tests to correlate with IC measurements

Track 2 — Data Management and Integration

- Subtrack 2.1 : National IC database and data collection guidelines
- Subtrack 2.2 : Standardization of IC data storage and exchange
- Subtrack 2.3 : A software tool for IC data viewing, analysis and reporting

Track 3 — Specifications

- Subtrack 3.1 : National guidelines for IC QC/QA specifications
- Subtrack 3.2 : Expert Task Group (ETG) for AASHTO IC specification development
- Subtrack 3.3 :Technical support for States specifications development and customization

Track 4 — Technology Transfer and Training

- Subtrack 4.1 : IC workshops and certification
- Subtrack 4.2 : IC field demonstration
- Subtrack 4.3 : IC website and knowledge base

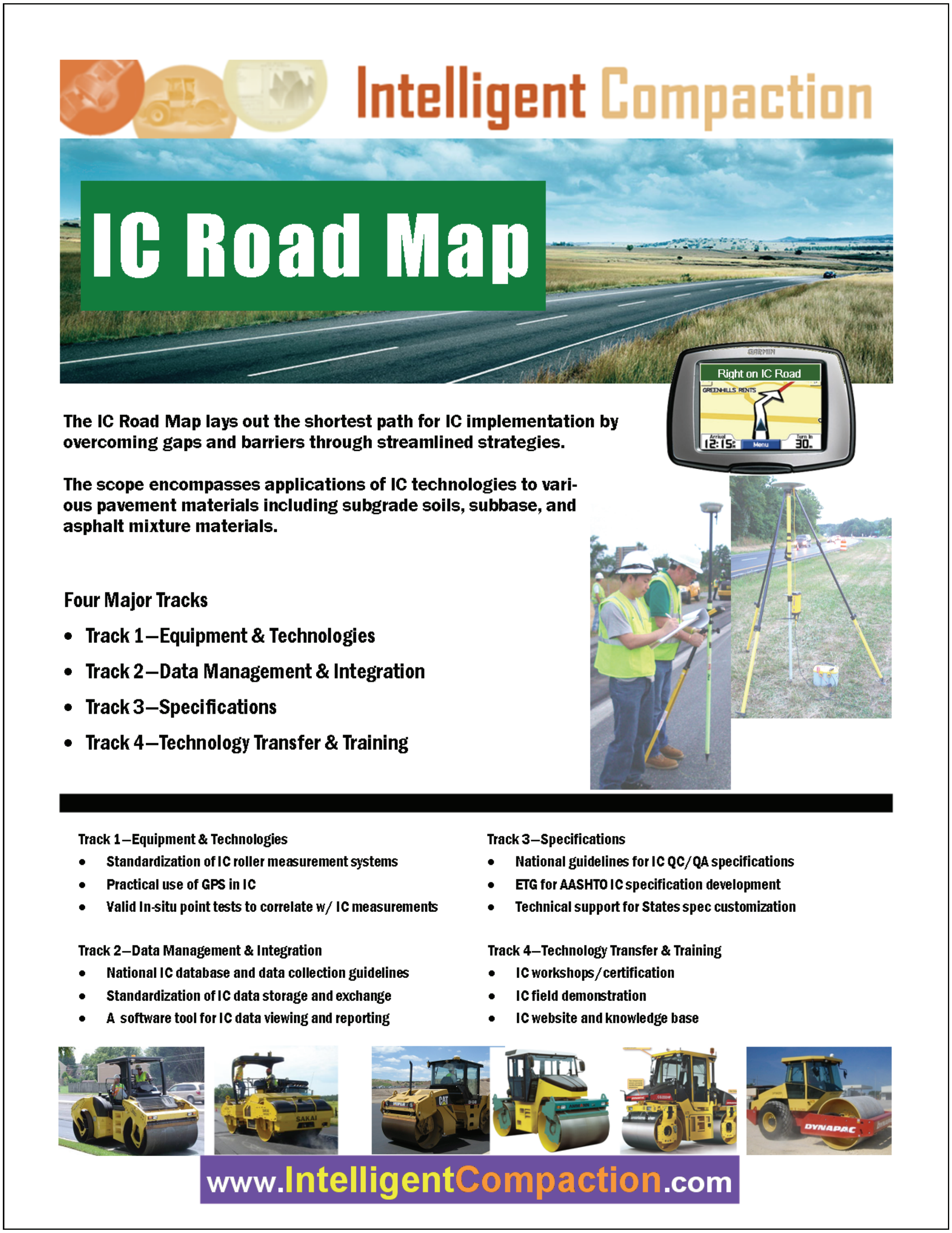


Figure 171. IC Road Map

General IC Plan

The general IC plan can be adapted by State agencies for local implementation. Any successful data collection needs a good plan and communication among all parties. While all the parties will work together and coordinate efforts, each will have primary responsibility for different aspects of the project both in the planning phase and during the actual project, as delineated below.

Project Team Responsibilities

- Coordination among all parties,
- Assisting in the project selection,
- Scheduling and arrangements for IC roller,
- Coordination with IC roller manufacturers and other equipment suppliers,
- Assisting with correlation testing,
- Data collection/management/analysis/reporting,
- Cost of agreed upon fees associated with mobilization of IC roller, and
- Cost of other test parties such as ISU geotechnical mobile lab.

State DOT Responsibilities

- Project selection (with assistance from the project team),
- Project contractual arrangements (if required),
- Coordination with contractors,
- Providing storage locations for IC rollers,
- Providing test equipment and manpower for in-situ testing (using standard equipment and practices for acceptance, but possibly at a higher frequency than normal),
- Providing or coordinating traffic control (when necessary),
- Facilitating the Open House, and
- Project delta costs for contractors.

Roller Manufacturer Responsibilities

- Coordinating with the project team, DOT, and contractor concerning shipping the IC roller in a timely manner,
- Providing the project team a copy of their software to view the information obtained from their IC roller,
- Arranging for necessary GPS base station setup,
- Training the operator, DOT representative, and project team on proper roller operation,
- Participating in the roller demonstrations in a limited capacity, and
- Providing technical support in a timely manner throughout the project (e.g., via phone) including equipment maintenance and repair, if needed.

Paving/Earthwork Contractor Responsibilities:

- Coordination of paving/rolling activities and cooperation with the above parties during the course of field demonstration, and
- Providing conventional roller operation for the control sections.

Special Provision Documents

Often, special provision specifications by the DOT are provided to the contractor as a part of the paving contract. These special provision specifications would clearly define the scope and detailed requirements for the paving contractor's involvement. Costs resulting from field delays, including adverse weather conditions and machine malfunctioning, are normally shared by the project team and DOTs.

Project Website

A project website is essential for effective communication among the above parties. This website normally provides real time, updated information on the current project (see Figure 172 to Figure 175). Information includes:

- Project period
- Site location and real-time weather information
- Material types
- IC rollers
- Objectives
- Meetings, documents, photos, videos
- Host DOT contacts

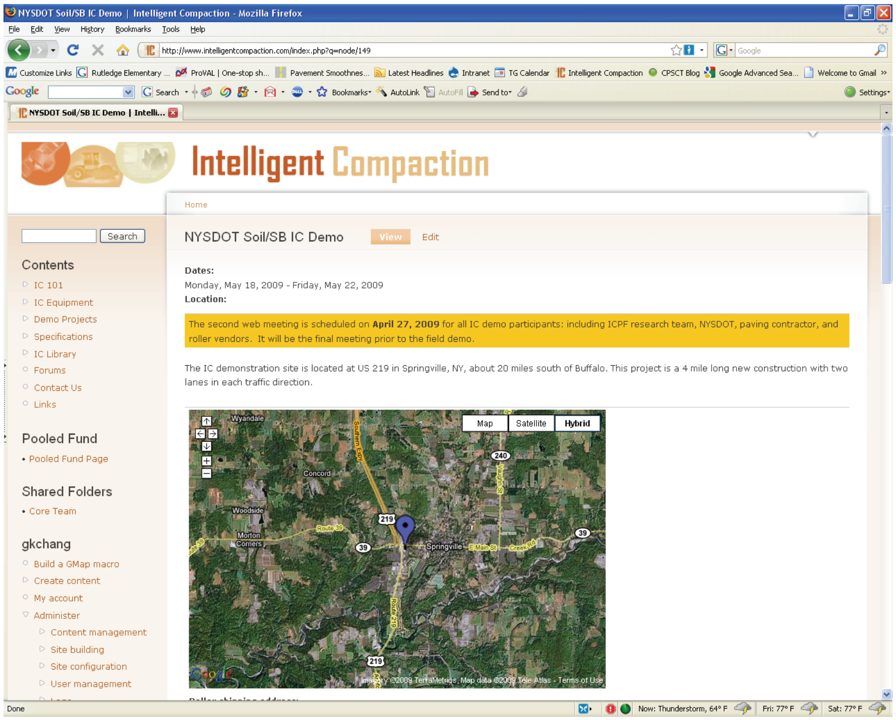


Figure 172. An example of IC project webpage (1 of 4)

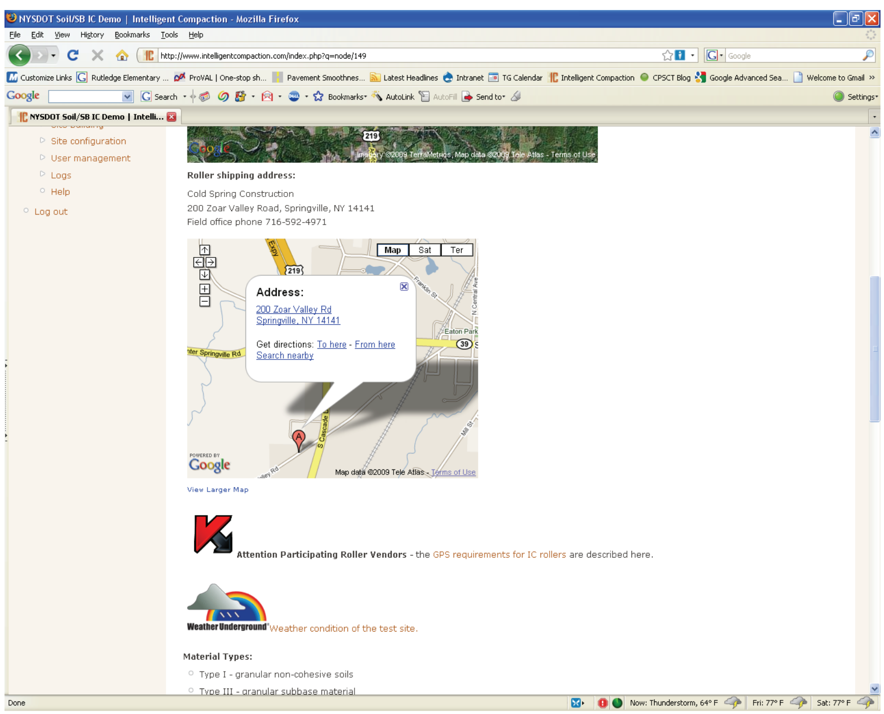


Figure 173. An example of IC project webpage (2 of 4)

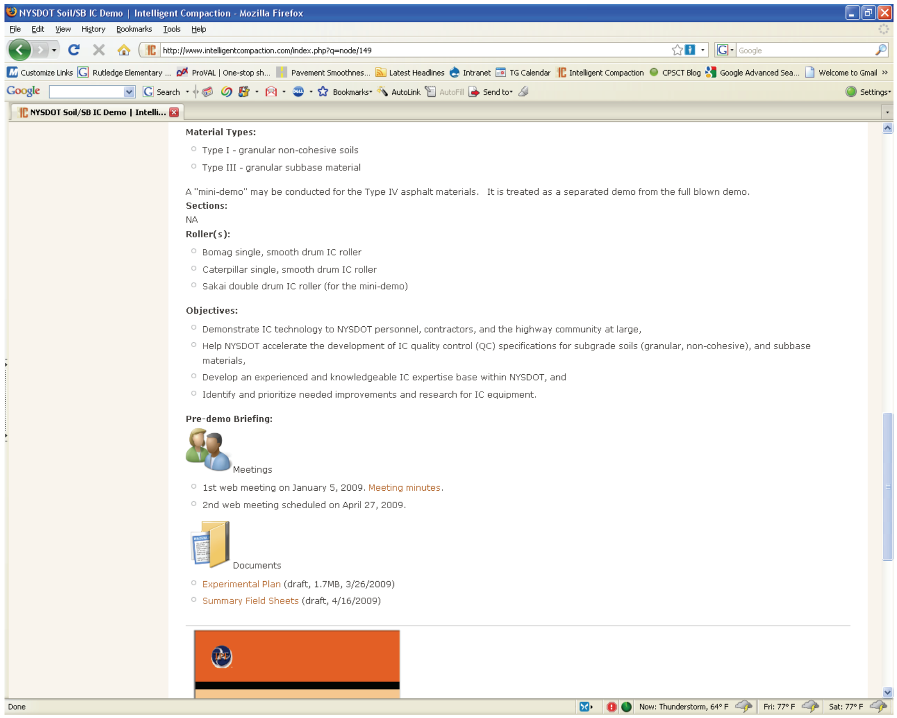


Figure 174. An example of IC project webpage (3 of 4)

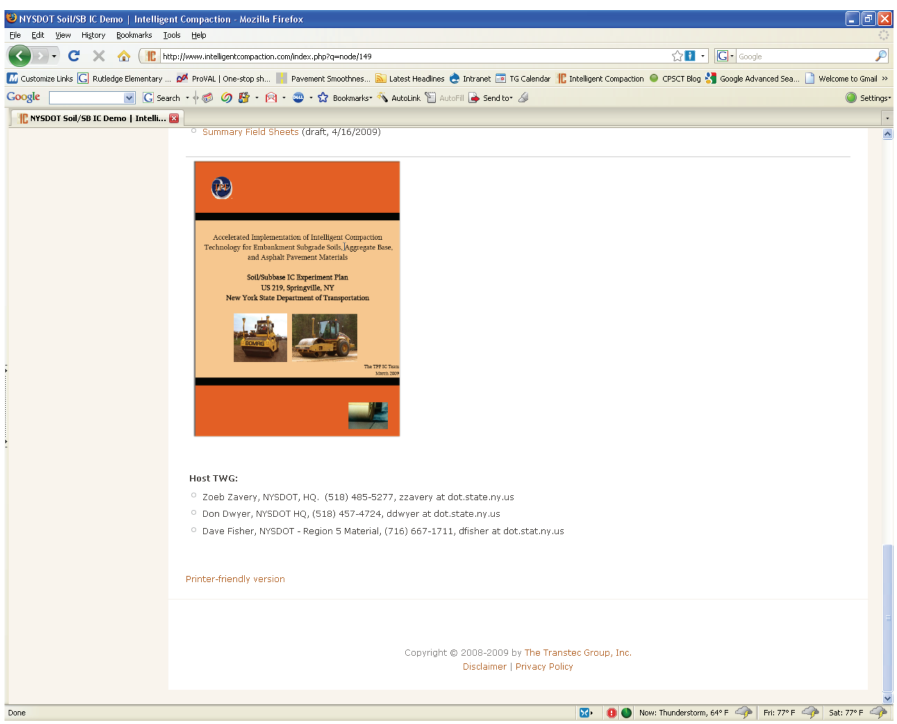


Figure 175. An example of IC project webpage (4 of 4)

On-Site Data Collection Schedule

An example of an on-site daily activity schedule is illustrated in Table 16 and Table 17 as follows:

Table 16. An example of an on-site daily activity schedule (ICPF TxDOT demo)

Date	Tasks	Detailed Activities
Sun., July 20	Set up rollers	**(ISU)** Set up the IC machine(s) and GPS base station system. **(Texana_Ammann)** Conduct trial runs to verify the machine is operating and communicating with the GPS base station. **(All)** Meet at the Sleep Inn at 7:30PM for a field site tour.
Mon., July 21 (Day 1)	Training & Calibration/ Production/ Mapping	**(Research Team)** Initial training of TxDOT and contractor personnel in machine operations, data collection, data management, and in-situ testing strategies. **(Research Team/Dynapac)** Calibration, production and mapping rolling with the pad foot IC roller. **(Research Team/ISU/TxDOT)** A variety of in-situ testing measurements.
Tue. July 22 (Day 2)	Calibration/ Production/ Mapping	**(Research Team/Texana_Ammann)** Calibration, production and mapping rolling with the pad foot IC roller. **(Research Team/ISU/TxDOT)** A variety of in-situ testing measurements.
Wed. July 23 (Day 3)	Calibration/ Production/ Mapping	**(Research Team/Dynapac/Texana_Ammann)** Calibration, production and mapping rolling with the Dynapac smooth drum and Texan pad foot IC rollers and Texana/Ammann smooth drum roller. **(Research Team/ISU/TxDOT)** A variety of in-situ testing measurements.
Thu. July 24 (Day 4)	Calibration/ Production/ Mapping/ Open House	**(Research Team/Texana)** Calibration, production and mapping rolling with the Texana/Ammann smooth drum roller. **(Research Team/ISU/TxDOT)** A variety of in-situ testing measurements. **(Research Team)** Analyze and report the IC and in-situ results, generating a preliminary report and presentation of results. (**TXDOT**) 2-4PM conduct a two-hour Open House to discuss the results and lessons learned followed by a field tour.
Fri. July 25 (Day 5)	Calibration/ Production/ Mapping/	**(Research Team/Texana)** Calibration, production and mapping rolling. **(Research Team/ISU/TxDOT)** A variety of in-situ testing measurements.

An example of an on-site test schedule and machine settings:

Table 17. An example of an on-site test schedule and machine settings

Date	TB	Strip	Layer	Machine	Amp (mm)	Spot Tests	Notes/Comments
07/20	ISU meeet TxDOT at 6:30pm. ISU mobile move from maintenance shop to project site. All parties meet at Sleep Inn at 7:30pm						
07/21	1	Calibration	1	Dynapac	0.7	DCP, LWD, NG, ST	10’ X 150’ test strip (see Note A)
		Production				DCP, LWD, NG, PLT	40’ X 500’ area (see Note A)
		Mapping			Auto	–	Mapping on the production area
07/22	2	Calibration	1	Texana/Ammann (pad)	0.7	DCP, LWD, NG, ST	10’ X 150’ test strip (see Note A)
		Production				DCP, LWD, NG, PLT	40’ X 500’ area (see Note A)
		Mapping			Auto	–	Mapping on the production area
07/23	3	Calibration	2	Dynapac	0.7	DCP, LWD, NG	10’ X 100’ test strip (see Note B)
		Production				DCP, LWD, NG	40’ X 300’ area (see Note B)
		Mapping			Auto	–	Mapping on the production area
	4	Calibration	2	Texana/Ammann (pad)	0.7	DCP, LWD, NG	10’ X 100’ test strip (see Note B)
		Production				DCP, LWD, NG	40’ X 300’ area (see Note B)
		Mapping			Auto	–	Mapping on the production area
	5	Mapping	2	Texana/Ammann (smooth)	0.7	NG, LWD, DSPA, FWD	See Note C
07/24	6	Calibration	3	Texana/Ammann (smooth)	0.7	DCP, LWD, NG, PLT, FWD	See Notes C, D, and E
		Production			0.7	DCP, LWD, NG, PLT, DSPA, FWD	See Notes C and D
07/25		Mapping			Auto, 0.7, 1.8	–	Mapping on the production area
07/24	2-4PM: Open House						

Data Sources

The data source should be identified prior to execution of any IC plan in order to effectively manage the data. This is a crucial step for the success of any IC-related activities.

There are important pre-site visit data needed for the project planning and preparation of experimental plans:

- Project design data – including pavement structural design (layer thicknesses and materials)
- Project alignment data – including geometric design (in AutoCAD or MicroStation formats) or plan files
- Lab material test data – Job Mix Formula for asphalt, soils properties (PL, LL, Proctor data) for embankments, and mixture design for stabilized base

- GPS information of the test site (e.g. control points from the survey data are useful to prepare "plan files" to delineate road edges in the IC data display.)

On-site data include:

- Field notes
- IC data
- In-situ test and GPS data
- Images and videos
- Interview records and other notes (e.g., open house event)

Post site visit data include:

- Lab test data from cores taken from the fields
- Additional on-site tests (e.g. FWD tests on cooled asphalt pavements)

The subsequent IC data analysis and report should follow the guidelines described under Chapter 4.

IC Data Management

One of the key issues during the IC field implementation is the "data management". As mentioned before, different IC rollers produce IC data in different forms (including: data format, data elements, GPS datum, and roller measurement values) and can only be viewed by vendor-specific software tools. In addition, other in-situ test data are either recorded manually or by various vendors' field programs depending on types of devices (such as: nuclear gauges, LWD, FWD, DCP, plate loading test, cores, and their associated GPS measurements, etc.). Data integration for the above poses great challenges. This in turn introduces a steep learning curve for State agencies and paving contractors.

Objectives of Data Management

Therefore, this section is to briefly lay out the blueprint for the solution of IC data management.

The primary objectives of data management are to:

- Establish a data management framework to fill the gap for accelerating the development of IC QC/QA specifications for subgrade soils, aggregate base, and asphalt pavement materials. The focus will be on providing a reliable method to capture the maximum potential value added from current IC technology based on currently used QC/QA field-testing equipment.
- Pave the road for IC data standardization including data requirements, storage formats, processes, and reporting.
- Identify and prioritize needed improvements and/or research for IC data management. Prioritization will be based on the potential for: (1) simplifying IC usage; (2) achieving greater IC cost-benefit, etc.; and (3) improved accuracy.

Data Management Framework

The scope of the IC data management under this study is restricted with a local (e.g., test bed) scale. It does not intend to cover the global scale of such a pavement management system. The IC data management framework consists of data collection guidelines, IC data, in-situ test data, correlation analysis, and geostatistics (spatial statistical) analysis. These elements are illustrated in Figure 176.

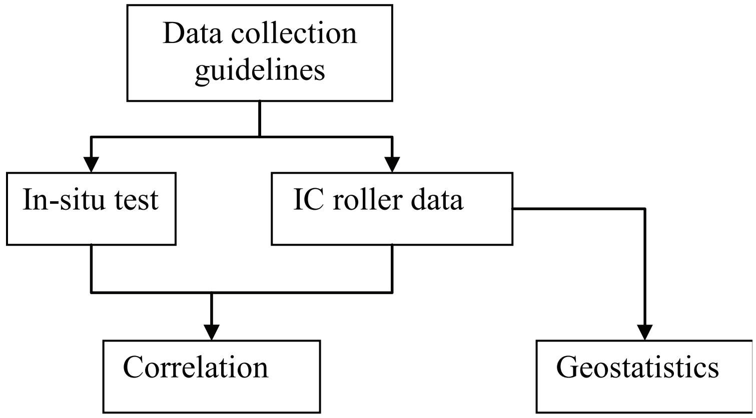


Figure 176. IC data management framework.

The data collection guidelines contain what and how data should be collected. One very important aspect of IC-related data collection is GPS references. All data should be associated with accurate GPS measurements. Normally, survey grade GPS would be required.

IC data should be collected following proper guidelines for GPS referencing (e.g. UTM zone), machine settings (including offsets from the GPS receiver to the bottom center of the roller drums and soil/asphalt system selection for some vendors), electronic filename designation (w.r.t. test beds, operation settings), and ASCII data export.

In-situ test can create further challenges unless the data collection procedure, GPS referencing, and data storage are strictly followed.

The correlation analysis is required to establish confidence of IC roller measurement values (ICMV). It is often performed for IC data and in-situ data from calibration test strips. Until a unified ICMV is reached, the correlation analysis is the only link among various ICMVs and in-situ tests.

Finally, geostatistical analysis of IC data is essential to evaluate spatial uniformity and other statistical characteristics. It is envisioned to be a basis for IC acceptance in future performance-based specifications.

IC Specifications

There are IC specifications developed over the years mostly in European countries and, recently, in the US with the focus mainly on soils and granular materials. The review of the existing IC specifications is described in the followings sections. Alternative approaches to IC specifications are recommended for future development.

IC Specification for Soils and Subbase

Overview of Current Specifications

Some agencies (Swedish Road Administration, Federal Ministry of Transport of the Federal Republic of Germany, The Austrian Federal Road Administration, International Society for Soil Mechanics and Geotechnical Engineering, Mn/DOT, and TXDOT) have developed specifications to facilitate implementation of IC into earthwork construction practices. Table 18 provides a summary of key elements of the current IC specifications. The specifications typically require performing either PLT or LWD on calibration strips to determine average target values (typically based on 3 to 5 measurements) and use the same for quality assurance later in production areas. The German specification suggests performing at least three PLTs in locations of low, medium, and high degree of compaction during calibration process. Further, it is specified that linear regression relationships between roller measurement values and plate load test results should achieve a regression coefficient, $R \geq 0.7$.

White and Vennapusa (2009) documented the following as the key attributes required in soil IC specifications and noted that the largest dissimilarities exist in the current specifications with the final attribute item.

- Descriptions of the rollers and configurations,
- Guidelines for roller operations (speed, vibration frequency, vibration amplitude, and track overlap),
- Records to be reported (time of measurement, roller operations/mode, soil type, moisture content, layer thickness, etc.),
- Repeatability and reproducibility measurements for IC measurement values (ICMVs),
- Ground conditions (smoothness, levelness, isolated soft/wet spots),
- Calibration procedures for rollers and selection of calibration areas,
- Regression analysis between ICMVs and point measurements,
- Number and location of quality control (QC) and quality assurance (QA) tests,
- Operator training, and
- Acceptance procedures/corrective actions based on achievement of minimum ICMV target values (ICMV-TVs) and associated variability.

Table 18. Review of Current IC Specifications

Reference	Equipment	Field Size	Location Specs	Documentation	Compaction Specs	Speed	Freq.
Mn/DOT (2007a, b)	Smooth drum or padfoot vibratory roller (25,000 lbs.)	300 ft x 32 ft (mini-mum at base). Max 4 ft. thick.	One calibration/ control strip per type or source of grading material	Compaction, stiffness, moisture, QC activities, and corrective actions (weekly report)	90% of the stiffness measurements must be at 90% of the compaction target value.	Same during calibration and production compaction	
ISSMGE (2005)	Roller chosen by experience	100 m by the width of the site	Homogenous, even surface. Track overlap ≤ 10% drum width.	Rolling pattern, sequence of compaction and measuring passes; amplitude, speed, dynamic measuring values, frequency, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and mean should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the specified minimum. Standard deviation (of the mean) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)
Austria — RVS 8S.02.6. (1999)	Vibrating roller compactors with rubber wheels and smooth drums suggested	100 m long by the width of the site	No inhomogeneities close to surface (materials or water content). Track overlap ≤ 10% drum width.	Compaction run plan, sequence of compaction and measurement runs, velocity, amplitude, frequency, speed, dynamic measuring values, jump operation, and corresponding locations	Correlation coefficient ≥ 0.7. Minimum value ≥ 95% of Ev1, and median should be ≥ 105% (or ≥ 100% during jump mode). Dynamic measuring values should be lower than the specified minimum for ≤ 10% of the track. Measured minimum should be ≥ 80% of the set minimum. Measured maximum in a run cannot exceed the set maximum (150% of the determined minimum).Standard deviation (of the median) must be ≤ 20% in one pass.	Constant 2–6 km/h (± 0.2 km/h)	Constant (± 2 Hz)

Reference	Equipment	Field Size	Location Specs	Documentation	Compaction Specs	Speed	Freq.
Germany — ZTVE StB/TP BF-StB (1994)	Self-propelled rollers with rubber tire drive are preferred; towed vibratory rollers with towing vehicle are suitable.	Each calibration area must cover at least 3 partial fields ~20 m. long	Level and free of puddles. Similar soil type, water content, layer thickness, and bearing capacity of support layers. Track overlap ≤ 10% machine width.	Dynamic measuring value; frequency; speed; jump operation; amplitude; distance; time of measurement; roller type; soil type; water content; layer thickness; date, time, file name, or registration number; weather conditions; position of test tracks and rolling direction; absolute height or application position; local conditions and embankments in marginal areas; machine parameters; and perceived deviations	The correlation coefficient resulting from a regression analysis must be ≥ 0.7. Individual area units (the width of the roller drum) must have a dynamic measuring value within 10% of adjacent area to be suitable for calibration.	Constant	
Sweden — ROAD 94 (1994)	Vibratory or oscillating single-drum roller. Min. linear load 15–30 kN. Roller-mounted compaction meter optional.	Thickness of largest layer 0.2–0.6 m.	Layer shall be homogenous and non-frozen. Protective layers < 0.5 m may be compacted with sub-base.	—	Bearing capacity or degree of compaction requirements may be met. Mean of compaction values for two inspection points ≥ 89% for sub-base under roadbase and for protective layers over 0.5 m thick; mean should be ≥ 90% for roadbases. Required mean for two bearing capacity ratios varies depending on layer type.	Constant 2.5–4.0 km/h	

Alternative approaches to Soils IC specifications

The following specification options and concepts (Options 1 to 5) were discussed at a national level workshop participated in by representatives from many state and federal agencies, contractors, and manufacturers (see White and Vennapusa 2009). These specification options differ in the required level of upfront calibration work, data analysis, and the level of confidence in the quality of the completed work.

Option 1: Roller based QC with pre-selected ICMV target values

For this specification option, an appropriate ICMV-TV is pre-selected based on documented case histories/literature, a database of information from local projects, laboratory tests, calibration tests on test beds of known engineering properties, mechanical apparatus simulating a range of soil conditions, and/or numerical modeling. The contractor uses the preselected MV-TV primarily for QC. QA is evaluated using a combination of ICMVs and in situ QA point measurements. This option will become more beneficial as experience and data become available through implementation of IC on earthwork projects.

Option 2: ICMV maps to target locations for QA test measurements

ICMV geo-referenced maps are used in this specification option to identify "weak" areas to focus on QA point measurements. Proper QC measures (e.g., controlling moisture content, lift thickness, etc.) should be followed during compaction. The contractor should provide the ICMV map to the field inspector for selection of QA test locations. Judgment is involved with selecting the number of tests and test locations. Acceptance is based on achievement of target QA point measurement values in roller-identified "weak" areas. If in-situ test QA criteria are not met, additional compaction passes should be performed and/or QC operations should be adjusted (e.g. moisture, lift thickness, etc.) and retested for QA.

Option 3: ICMV target values from compaction curves to target locations for QA point measurements

This specification option evaluates the change in ICMVs with successive passes as an indicator of compaction quality. As the number of roller passes increases, the change in MV between passes normally decreases. A production area is monitored by evaluating the percent change in ICMVs between successive passes. Once the percent change of ≤ 5% over 90% (these percentages can be adjusted based on judgment and field experience) of the production area between roller passes is achieved, the production area is considered fully compacted. This option is more effective for controlled field conditions with relatively uniform materials, moisture content, and lift thickness and serves as a QC process control for the roller operator. Judgment is involved with selecting the number of tests and test locations. Acceptance is similar to Option 1, in that QA testing is targeted in areas with relatively low ICMVs.

Option 4: Calibration of ICMV measurements to QA point measurements

This specification option requires calibration of ICMVs to QA point measurements from a representative calibration test strip prior to performing production QA testing. The MV-TV is established from project QA criteria through regression analysis and applying prediction intervals. For modulus/strength measurements simple linear regression analysis is generally suitable, while for correlation to dry unit weight/relative compaction measurements, multiple regression analysis including moisture content as a variable may be needed. If underlying layer support conditions are heterogeneous, relationships are likely improved by performing multiple regression analysis with ICMV or point measurement data from underlying layers. Acceptance of the production area is based on achievement of MV-TV at the selected prediction interval (80% is suggested) and achievement of target QA point measurement values in the areas with MVs < MV-TV.

Option 5: Performance based QA specification with incentive based payment

One of the shortcomings of the existing ICMV specifications might be that the acceptance criteria (specifically the target limits) are dependent on specific IC technology. This specification option, although it requires a more rigorous statistical analysis framework (see White et al. 2009b), could provide a consistent means for specifying acceptance criteria. The acceptance criteria for this option are: (a) the overall level of critical soil engineering properties over an area achieve the MV-TV and (b) the variability of critical soil engineering properties over an area is no more than some specified maximal amount (e.g., COV%). These acceptance criteria are established based on regression analysis from calibration, applying prediction intervals, accounting for the repeatability and reproducibility errors associated with ICMVs and point measurements, and a selected probability or risk level in acceptance decisions. This approach could provide a link to performance-based specifications and a quantitative mechanism to define incentive-based payment.

IC Specification for HMA

Recommendation for Machines and Settings and Compactions

Based on the demonstration projects, the machines and settings for specifications are recommended by the research team, as summarized in Table 19. It includes the specification of IC on HMA pavement for the roller equipment, GPS set, documentation, mapping, and machine setting, as recommended by the research team based on the demonstration results.

Table 19. IC specifications for Equipment, GPS, Documentation, Mapping, and Machine Setting.

Equipment	GPS	Documentation	Mapping	Machine setting
Smooth double-drum vibratory roller. Sakai SW880 and SW990 series, and Bomag tandem IC vibratory roller	A Real-Time Kinematic (RTK); receiver on roller, base station; precision of 5 cm; Verify GPS base station broadcasting verified on the IC rollers and the GPS rover units; verification of spots compared to GPS rover before compaction	Computer system and software is able to present color-contoured CCV, pass count, HMA surface temperature, and machine settings (e.g. frequency, speed, and amplitude) in real time. IC data is exportable in ASCII or binary format, which shall be readable by other software like Microsoft Excel and TextPad, etc. The exported IC data elements for each data record should include, but not limit to: time stamps, GPS (e.g., northing, easting, and elevation), vibration frequency, vibration amplitude, pass counts, speed, directions, ICMV, and HMA temperatures.	Mapping is required prior to HMA paving with single or double-drum vibrated, low amplitude and low frequency setting (e.g. 2000 vpm). One pass at least. Weak spots shall be identified and treatments may be taken before paving HMA materials on weak spots.	Frequency of 2500 vpm or above; Low frequency (e.g. 2500 vpm) corresponds to higher amplitude (e.g. 0.6 mm), higher frequency (e.g. 3500 vpm) corresponds to low amplitude (e.g. 0.3 mm); low speed (e.g. 3 mph)

Alternative approaches to HMA IC specifications

Based on the experiences and knowledge learned from the TPF demonstration projects, the research team recommends the following specification options for the compaction of HMA materials.

Option 1: Roller-based QC with ICMV target values determined from test strip results

For this specification option, an appropriate ICMV target value is selected for a construction project with specific pavement structure and materials. A compaction on a test strip (e.g. 100 ft) is required. For this test strip, in-situ NG tests are following the breakdown roller at discrete locations (e.g. 10 test spots with 20-ft interval between two spots). The linear correlation between NG density and ICMV for all passes can be plotted to determine target ICMV corresponding to the density value from the contract requirement. A multivariate linear regression may be used to better account for multiple influence factors such as machine settings (e.g. frequency, amplitude), environmental conditions (HMA temperatures), and pavement conditions of underlying layers (ICMV of the underlying layers). The subsequent production rolling can then make use of such target ICMV for QC (e.g., 90% of the ICMV should meet the target ICMV).

Option 2: ICMV maps to select locations for QA tests

ICMV geo-referenced maps can be used in this specification option to identify "weak" areas, so that the QA point measurements can be reduced and focused on the weak areas. The contractor should provide the ICMV map to the field inspector for selection of QA test locations (e.g., 2 to 3 tests per weak areas). Acceptance is based on achievement of target QA point measurement values in roller-identified "weak" areas. If in-situ test QA criteria are not met, depending on the quality, treatments may be needed and QC operations should be adjusted (e.g. density, lift thickness, etc.).

Option 3: Selection of the optimal roller pass count and ICMV target value from a compaction curve

This specification option evaluates the optimum roller pass number and the change of ICMV with successive passes as an indicator of compaction quality. As the number of roller passes increases, usually the ICMV increases first and then decreases or increases continuously until it reaches a relatively constant value. From the test strip, the optimum roller pass number achieving the optimum ICMV can be identified, which can be set as the roller pass target for the production compaction. This method may help avoid over-compaction or under-compaction with excess or insufficient compaction passes. A production area can also be monitored by evaluating the percentage change in ICMVs between successive passes. For example, once the percent change is less than 5% or the ICMV reach a plateau, the optimal pass count and target ICMV can be determined. Then, the acceptance of production rolling can be based on the optimal pass count and target ICMV.

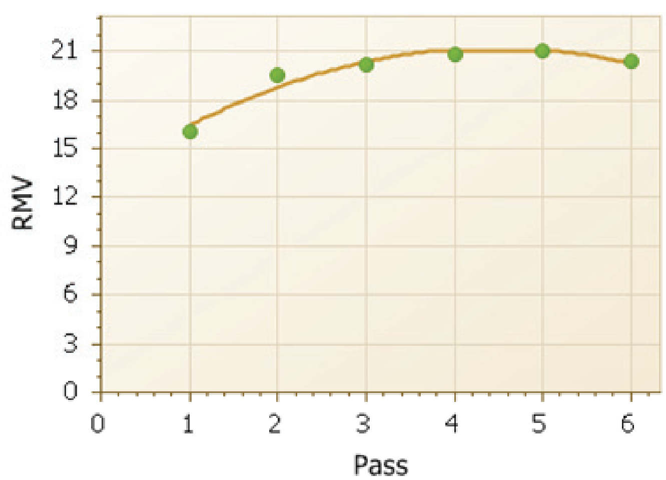


Figure 177. Compaction curve – Breakdown Compaction of HMA Base Course - TPF WisDOT IC demo (TB 01B-Section 2).

Option 4: Compaction Uniformity Evaluation from the geostatistical semivariograms for QA

The geostatistical semivariogram parameters (e.g. sill and range values) can be used to evaluate the compaction uniformity of the compaction area to minimize the variability. The compaction area shall be divided into multiple segments (e.g. 100 ft per segment) for evaluation on each segment. The semivariogram parameters of each segment can be used to evaluate its uniformity. Longer ranges with lower sill values indicate better uniformity. Further research is needed to determine target range and sill value.

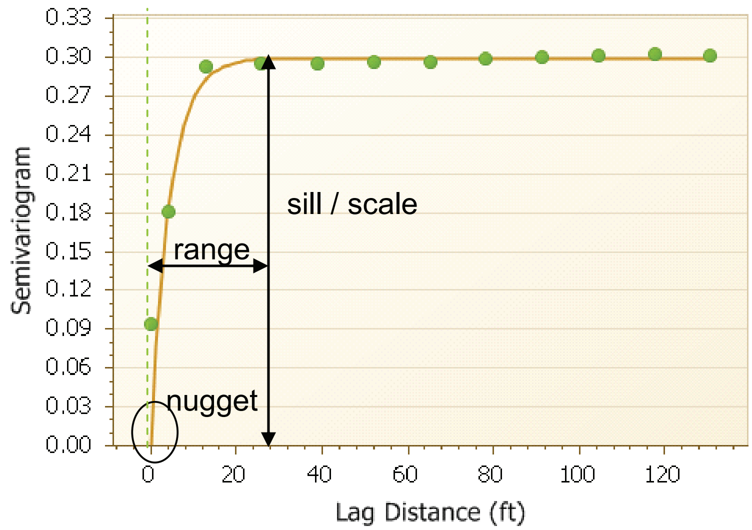


Figure 178. Semivariogram – Breakdown Compaction of HMA Base Course - TPF WisDOT IC demo (TB 01B-Section 2).

Generic IC Specifications for Soils, Subbase HMA

IC Specifications for soils, subbase HMA materials were developed under this project to provide States guidance to implement IC. These specifications are quality control based and can be served as a stepping stone to future quality assurance based specifications. The full contents of the above three IC specifications are included in the appendixes:

- Appendix D - Generic Soils IC Specifications
- Appendix E - Generic HMA IC Specifications
- Appendix F - Generic Subbase IC Specifications

IC Training and Workshops

Open House Activities of IC Demonstrations

Following each field demonstration under this project, an Open House was conducted as part of this field investigation. The people who attended the Open House include the FHWA and DOT engineers/technicians, academics, paving contractors, roller manufacturers/dealer personnel, GPS manufacturers/technical supports, etc. Usually the Open House included a two-hour indoor presentation and question-&-answer session, followed by an outdoor one-hour equipment demonstration.

Usually the indoor presentation included at least the following:

- FHWA/TPF Intelligent Compaction Project - by Dr. George Chang (Transtec Group)
- Asphalt Intelligent Compaction - by Bob Horan (Asphalt Institute)
- IC Roller System – by the IC roller technical supporters
- GPS System - by Trimble or local dealer technical supporters
- DOT IC Demo and Prelim Results - by Dr. George Chang (Transtec Group)

Following the presentations, issues were discussed during the question-&-answer (Q&A) session.

Subsequently, the outdoor equipment demonstration was performed on a parking lot or the construction site. The IC roller manufacturers, GPS dealers, and other in-situ test equipment manufacturers introduced the equipment, their functions, and how to operate the equipment.

Recommended Future IC Training and Workshops

Training and workshops are crucial elements for any successful IC implementation – as described in the IC Road Map. The following plan is recommended for future IC training and workshops.

Purposes of the Workshops:

- Familiarize attendees with fundamentals of intelligent compaction
- Demonstrate the route to successful IC implementation
- Develop attendees as technology champions of IC for their organizations or companies

Target Audiences:

- State DOTs construction and materials QC/QA personnel and specification writers for asphalt and soils/subbase
- Industry paving managers, superintendent, and QC personnel for asphalt (HMA) paving and earthwork-grading contractors
- IC rollers and Global Position Systems (GPS) vendors/dealers
- Estimated number of attendees is 75 for each workshop. Travel expenses up to 15 State DOT personnel may be sponsored by the FHWA for each workshop.

Recommended Workshop Presenters:

- Victor (Lee) Gallivan, P.E., FHWA HIPT, COTR of the FHWA/TPF IC Project

- Dr. George Chang, P.E., Transtec Group, PI of the FHWA/TPF IC research team
- Bob Horan, P.E., Asphalt Institute, Facilitator of the FHWA/TPF IC research team
- Larry Michael, LLM Asphalt Consultant, Co-PI of the FHWA/TPF IC research team
- Rebecca Embacher, Minnesota Department of Transportation, IC DOT representative
- Dr. David White, ISU, Co-PI of the FHWA/TPF IC research team

Products and Processes:

- Three seven-hour national IC workshops in different regions of the country
- Generic IC specifications for HMA (asphalt) and soils/subbase
- Workshop contents that cover the following topics under the IC Road Map:

The recommended workshop agenda would include the following sessions:

1 – Introduction and Overview

2 – Fundamentals of Intelligent Compaction

3 – Global Position Systems for IC

4A – IC for HMA

4B – IC for Soils/Subbase (break-out sessions)

5A – Panel discussion on IC for Asphalt

5B – Panel discussion on IC for Soils/Subbase (break-out sessions)

6 – IC-based QC and QA Specifications

7A – Panel discussion on QC/QA HMA IC

7B – Panel discussion on QC/QA for Soils/Subbase IC

8 – Demonstration of IC Data Management program

9 – Panel Discussion (DOTs) on IC Implementation and Barriers-to-Overcome plus Q&As

10 – Conclusion and Workshop Evaluations

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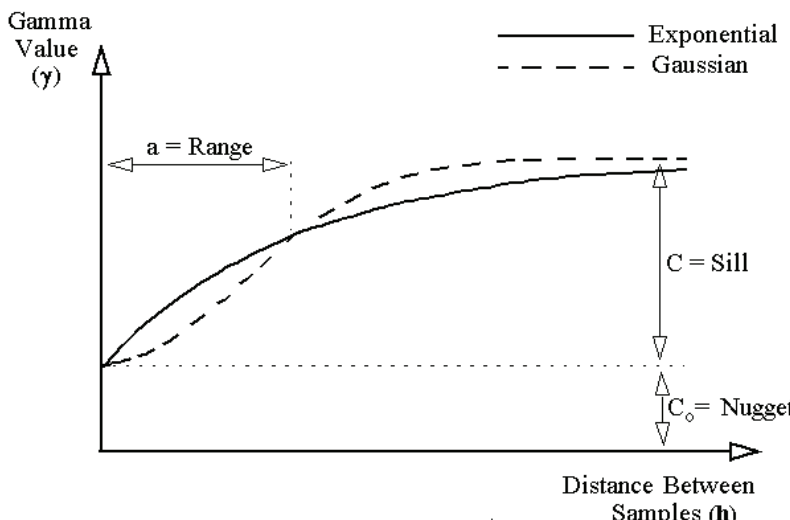
Appendix A Understand Semi-variogram as a Metric for Uniformity

A variogram is a plot of the average squared differences between data values as a function of separation distance, and is a common tool used in geostatistical studies to describe spatial variation. Three important features of a semi-variogram include: sill, range, and nugget (Figure 179, where Gamma Value is the variogram value.). Sill is defined as the plateau that the semi-variogram reaches, range is defined as the distance at which the semi-variogram reaches the sill, and nugget is defined as the vertical height of the discontinuity at the origin which mostly represents sampling error or short scale variations (Srivastava, 1996).



Exponential: $$\gamma(h) = C_o + C(1 - e^{-h/a})$$

Gaussian: $$\gamma(h) = C_o + C(1 - e^{-h^2/a^2})$$

Figure 179. Semi-variogram models with exponential and Gaussian fits (Houlding, 2000).

From a semi-variogram model, a low "sill" and longer "range of influence" can represent best conditions for uniformity, while the opposite represents an increasingly non-uniform condition. Using these semi-variogram parameters, theoretical models can be fit to the experimental semi-variogram data. Exponential model (the solid line in Figure 179) generally fits well with the roller-integrated and in-situ compaction measurements (see White et al. 2007a, White et al. 2007b, Vennapusa and White 2008). Detailed descriptions of theoretical models can be found elsewhere in the literature (e.g., Clark and Harper 2002).

Data conversion

Spatial variability/continuity depends on the detailed distribution of the petrophysical attribute. Attributes, such as permeability with highly skewed data distribution present problems in variogram calculation, and the extreme values have significant impact on varigoram. Therefore, before analyzing the semivariogram raw IC data is transformed to the logarithmical scale first:

$$Z = \log_{10}(z) \qquad (16)$$

Location and lag vector definition

The location vector and lag vector is shown in Figure 180 for a 2-dimentional (2-D) space.

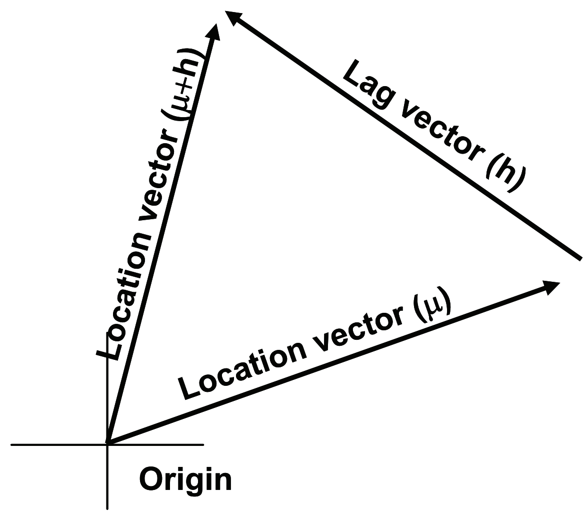
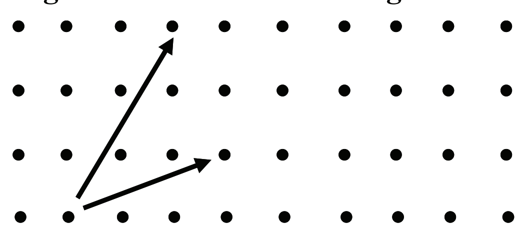


Figure 180. location and lag vectors.



Direction and model parameter definition

The direction specification (irregular) is defined by users, as shown in Figure 181. The direction (angle), lag number, interval for lag distance, bandwidth, and total length (distance) are defined by user.

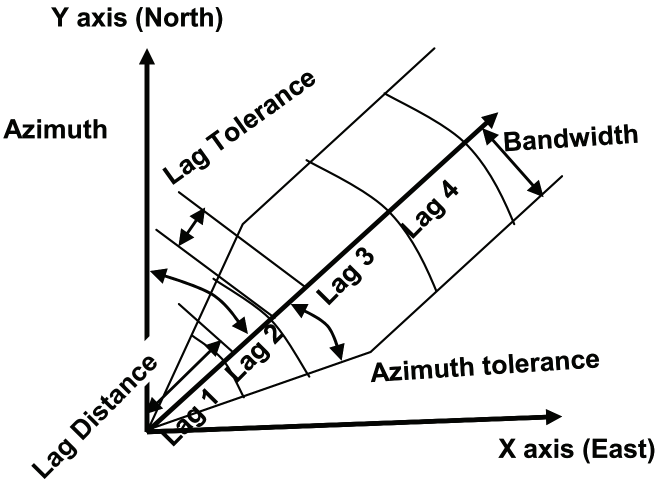


Figure 181. semnivariogram direction.

Calculation of semi-variogram:

The variogram for lag distance h is defined as the average squared difference of values separated approximately by h, for all possible location μ:

$$2\gamma(h) = E\left\{\left[Z(u) - Z(u+h)\right]^2\right\} \tag{17}$$

Where,

μ is the location;

h is the lag distance (h could be constant for the same lag area).

The variogram can be re-expressed as follows:

$$2\gamma(h) = \frac{1}{N(h)} \sum_{N(h)} \left[Z(u) - Z(u+h)\right]^2 \tag{18}$$

Where,

$N(h)$ the number of pairs for lag distance h of a specific lag area

The semi-variogram is then defined as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{N(h)} \left[Z(u) - Z(u+h)\right]^2 \tag{19}$$

Figure 182 shows that one moves from one node to the next to determine the $Z(u) - Z(u+h)$ value for the calculation of variogram.

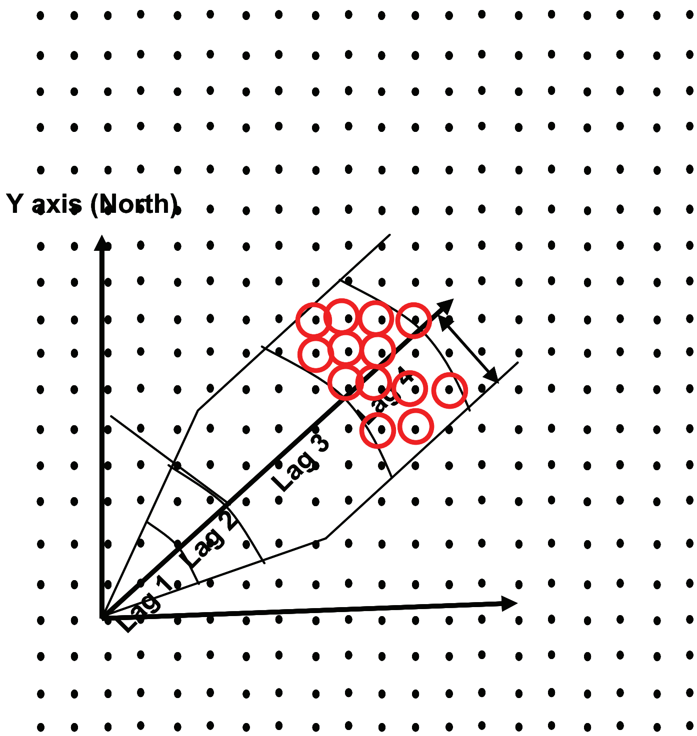


Figure 182. semnivariogram direction.

Model fit

The determined semivariograms for each lag area is plotted with lag distance as shown in Figure 183, which is the experimental semivariogram.

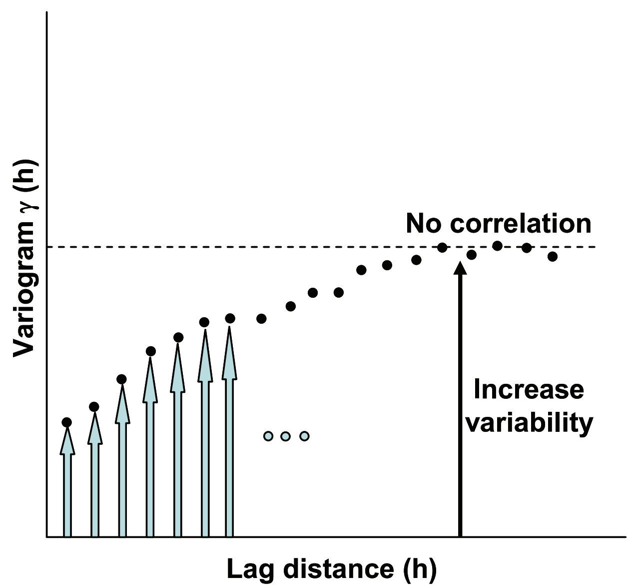


Figure 183. Experimental semnivariogram.

In this project the Surfer@ software is used to produce the semivariogram of RMV values for the final pass of the base and binder course. Based on the data analyzed, it appears that the exponential model or the Gaussian model (see **Error! Reference source not found.**) can fit the data better than other models (e.g. linear model).

Different mathematical models can be used to fit the experimental semivarigrams, including the power model, exponential model, and the Gaussian model, etc.

Power model:

$$r(h) = a.\left(\frac{h}{a}\right)^{c} \tag{20}$$

Exponential model:

$$r(h) = c\left[1 - \exp\left(-\frac{3h}{a}\right)\right] \tag{21}$$

Gaussian model:

$$r(h) = c\left[1 - \exp\left(-\frac{9h^2}{a^2}\right)\right] \tag{22}$$

Figure 184 shows the experimental semivariogram of the IC demonstration project and fitted curves with the exponential, Gaussian, and power model, respectively.

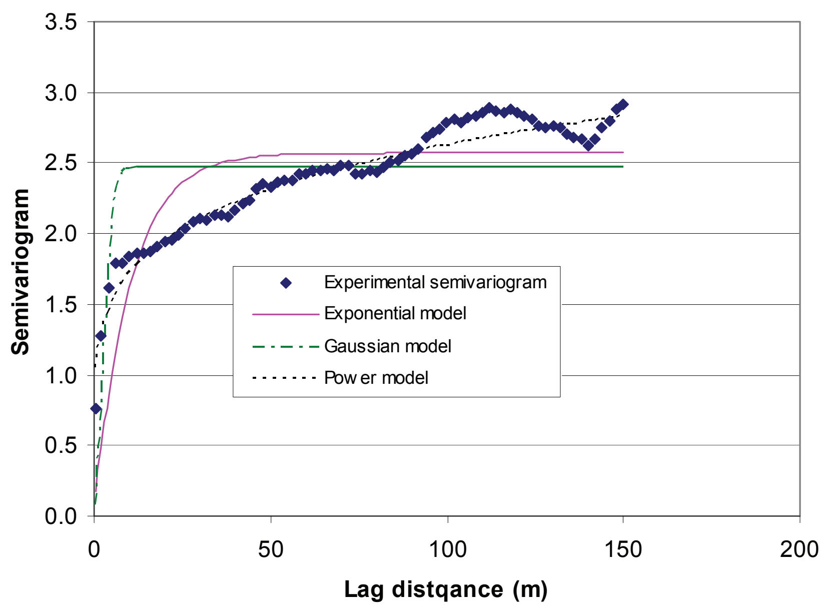


Figure 184. Semivariogram model fit.

The field demonstration projects have shown that an exponential model generally fits well for IC measurement data, thus it is used in the Veda - IC Viewer software.

The semivariogram reports in Veda include:

- Plot: semi-variogram vs. lag distance – with data points and fitted curve.
- Parameters: determined from the fitted curve based on a exponential model
- Range (horizontal range)

- Variance (known as sill which the sum of vertical scale and nugget effect)
- Vertical scale (vertical scale for the structured component of the variogram)
- Sampling error (known as nugget effects that quantifies the sampling and assaying erros and the short scale variability)

Low variance (sill) and longer range (of influence) represent better uniformity.

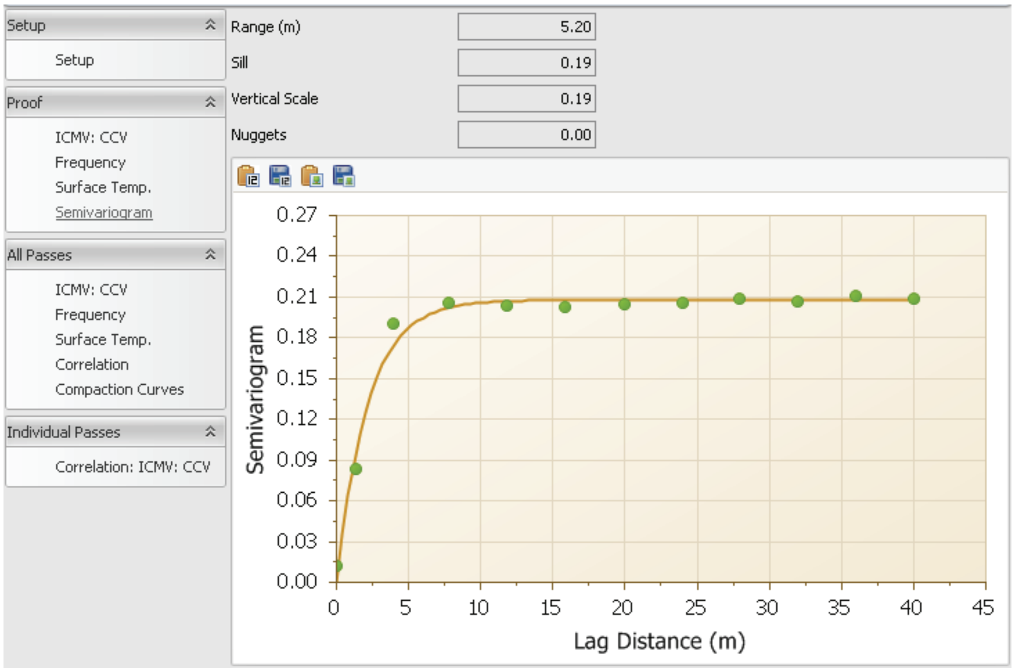


Figure 185. Semi-variogram report of IC data.

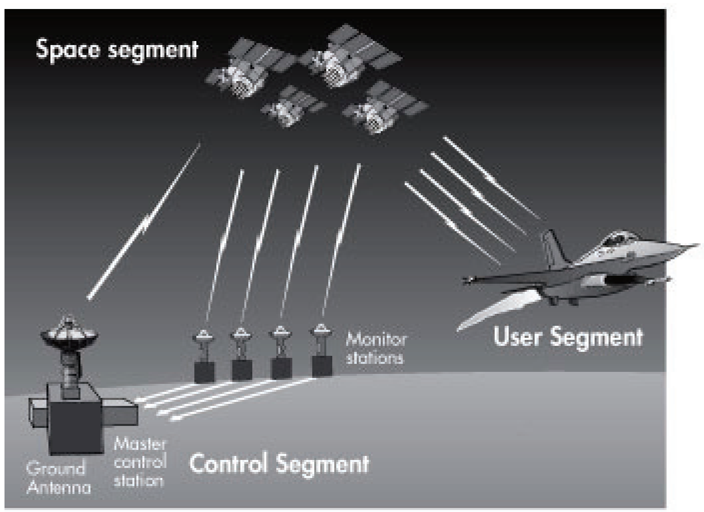
Appendix B. Understand GPS and Datum

How GPS Works

The Global Positioning System (GPS) is a location system based on satellite signals and their ground stations. GPS was developed by the United States Department of Defense (DOD), for its application as a locating utility, but GPS has proven to be a useful tool in non-military mapping applications.

The GPS, also known as Navstar GPS, consists of three segments as shown in Figure 186:

- Space Segment: a constellation of satellites orbiting about 20,000 km above the earth's surface which transmit ranging signals on two frequencies in the microwave part of the radio spectrum.
- Control Segment: a control segment which maintains GPS through a system of ground monitor stations and satellite upload facilities.
- User Segment: the receivers – both civil and military.



(Courtesy of Aerospace)

Figure 186. Three segments of GPS.

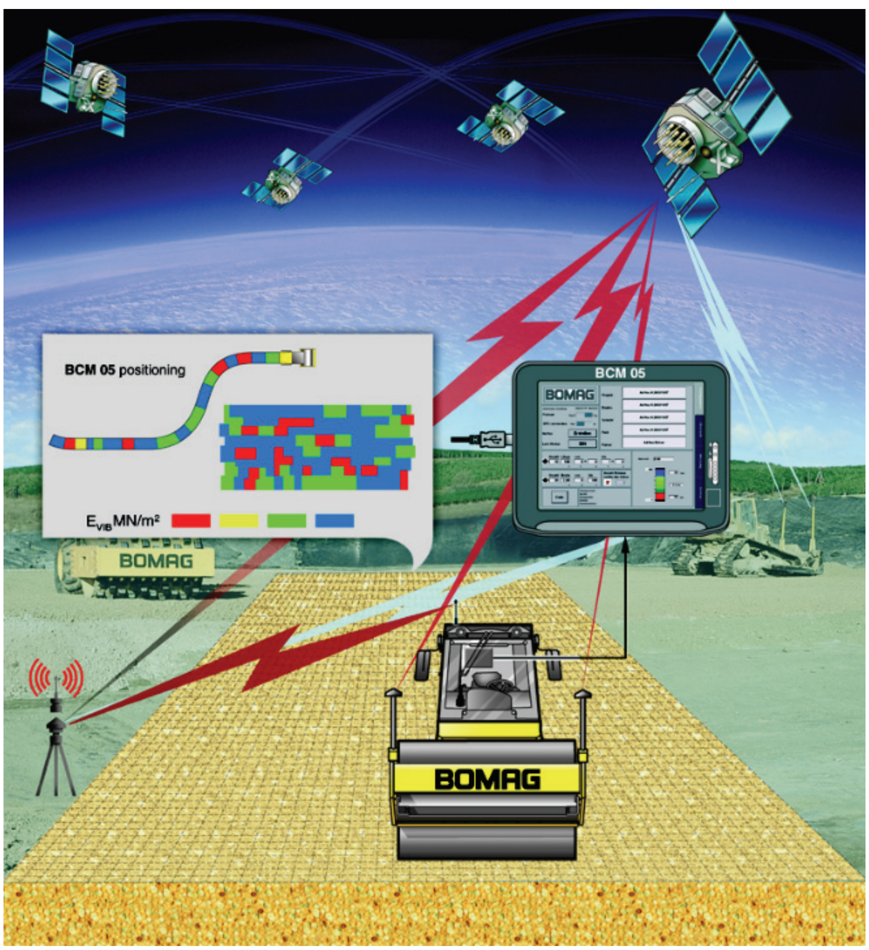
The receiver can use the trilateration technique to compute distances to four or more satellites simultaneously and knowing the exact locations of the satellites. Then, the receiver can determine its latitude, longitude, and height while at the same time synchronizing its clock with the GPS time standard.

Most civil GPS receivers access the C/A-code (coarse/acquisition code) transmitted on the L1 frequency (1575.42 MHz). Military receivers, in addition, use the encrypted P-code (precise or precision code) which is transmitted on both L1 and the L2 frequency (1227.60 MHz). Some military receivers can access the P-code directly rather than acquiring the C/A-code first and then transferring to the P-code. Since 2005, the newest satellites transmit a civil signal, L2C, on the L2 frequency that makes GPS, a.k.a. carrier phase tracking or surveying, more precise.

Depending on the quality of the receiver, the environment, the type of measurements made, and how the measurements are processed, the positioning accuracy of GPS can vary from a few meters to below 1 centimeter, permitting a wide range of positioning applications from vehicle navigation to studies of the motion of the Earth's tectonic plates.

Use of Differential GPS in IC Systems

GPS is used in the IC system to record the coordinates of rollers at each pass (see Figure 187). However, there are several external sources that may introduce errors into a GPS position including: atmospheric conditions, ephemeris errors/clock drift/measurement noise, selective availability, multipath, and etc. The IC systems normally use differential correction GPS to improve accuracies. Differential correction requires a second GPS receiver, a base station, collecting data at a stationary position on a precisely known point (e.g., a surveyed benchmark). With the known physical location of the base station, a correction factor can be computed by comparing the known location with the GPS location determined by using the satellites. Then, the correction factor can be applied to the GPS data collected by a GPS receiver in the field.



(Courtesy of Bomag)

Figure 187. Use GPS in an IC system.

Various IC systems are normally equipped with Real Time Kinematic (RTK) GPS receiver but have slightly different requirements for GPS connection from the receiver to the IC control panels.

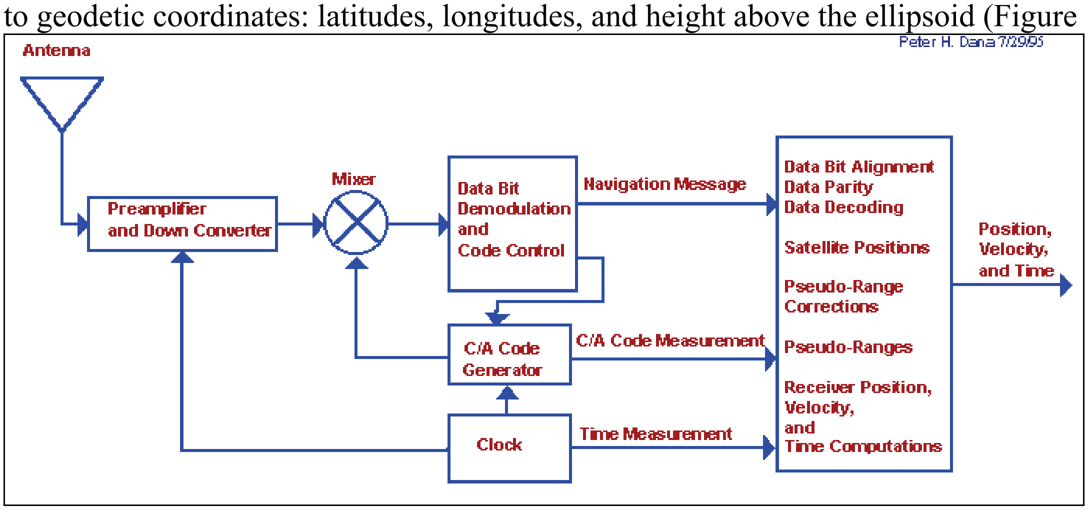
Table 20: GPS connection requirements for IC rollers

Vendor	Case/Ammann	Bomag	Caterpillar	Dynapac	Sakai
Software System	ACEPlus	BCM05	AccuGrade	NA	Aithon MT
Interface	Serial	Serial (sub-D 9 pin)	NA	NA	NA
Baud rate	38400	38400	NA	NA	NA
Data bits	8		NA	NA	NA
Parity	None	None	NA	NA	NA
Stop bits	1	1	NA	NA	NA
Flow control	None/hardware		NA	NA	NA
GPS mode	RTK	RTK?	RTK	NA	RTK
Sampling rates	1 Hz	10 Hz	NA	NA	NA
Type of message	NMEA	NMEA	NA	NA	NA
Subtype	GGA	GGA	NA	NA	NA

NMEA: The National Marine Electronics Association (NMEA) has developed a specification that defines the interface between various pieces of marine electronic equipment. GPS receiver communication is defined within this specification. NMEA consists of sentences, the first word of which, called a data type, defines the interpretation of the rest of the sentence. Each Data type would have its own unique interpretation and is defined in the NMEA standard.
GGA: The GGA sentences are essential fix data which provide 3D location and accuracy data.

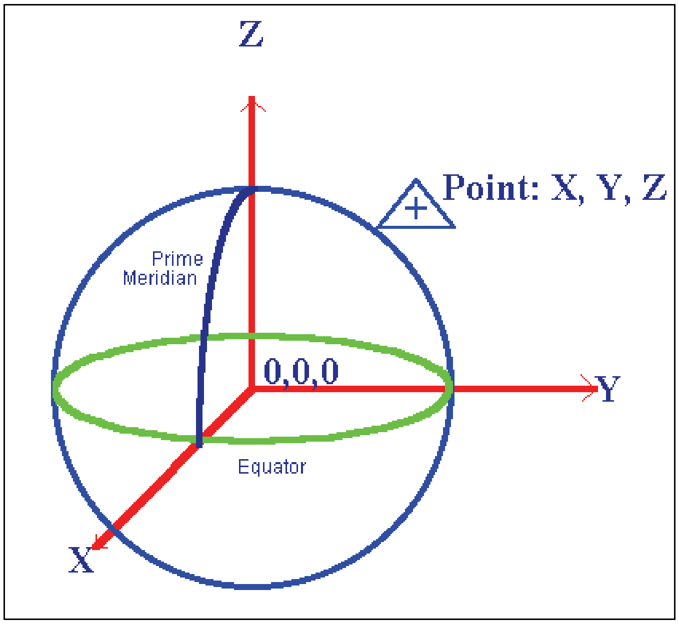
Position and Time from GPS

The GPS signals received by the receivers including position, velocity and time, etc. (Figure 188) can be processed to compute earth-centered, earth-fix (ECEF) x-y-z position and time of the receiver (Figure 189). The earth centered position x-y-z is then converted to geodetic coordinates: latitudes, longitudes, and height above the ellipsoid (Figure 190).



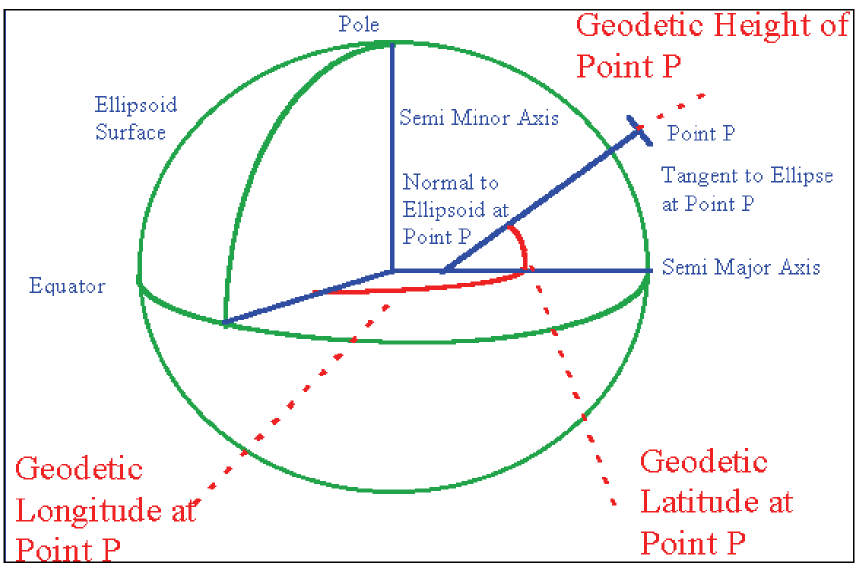
(Courtesy of Dana)

Figure 188. Position, velocity and time from GPS.



(Courtesy of Dana)

Figure 189. Earth-centered, earth-fix x-y-z GPS position.



(Courtesy of Dana)

Figure 190. Geodetic coordinates – latitudes, longitudes, and height above the ellipsoid.

Use of UTM in IC Data Process

The Universal Transverse Mercator Coordinate (UTM) system provides coordinates, northings and eastings, on a world wide flat grid for easy computation. Therefore, UTM is normally used in the IC data processing. The Universal Transverse Mercator Coordinate system divides the Earth into 60 zones, each being 6 degrees longitude wide, and extending from 80 degrees south latitude to 84 degrees north latitude. The polar regions are excluded. The first zone starts at the International Date Line (longitude 180 degrees) proceeding eastward. Cautions should be taken when the area of interest extends from one zone to another. Under this study, the UTM zones are restricted in the US from zone No. 10 to zone No. 19 as shown in Figure 191.

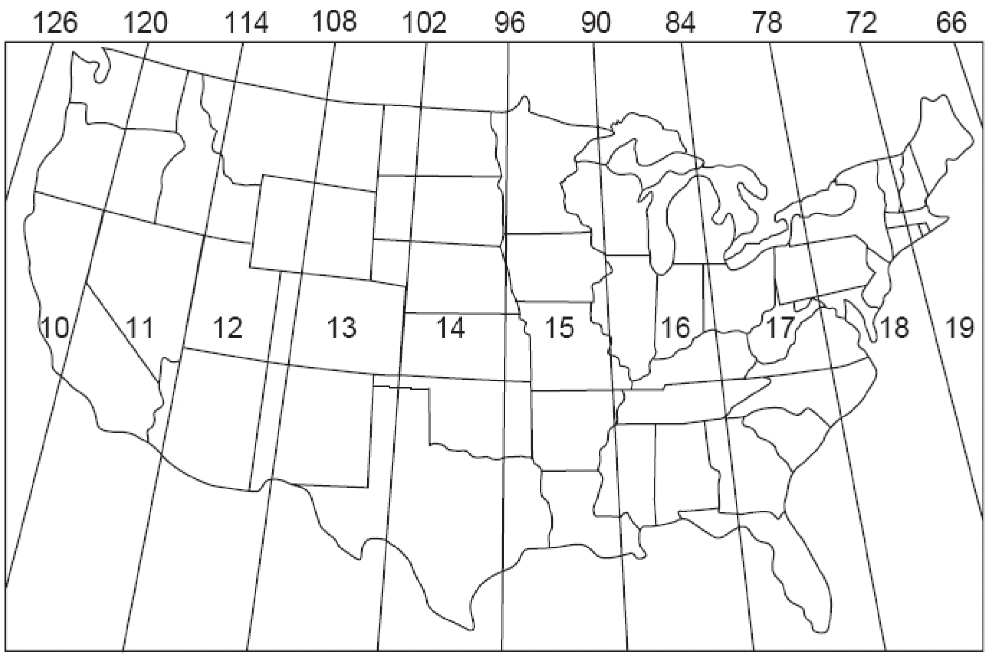


Figure 191. UTM Zones in the US.

Datum Conversion between Geodetic Longitude/latitude and UTM

Conversion from geodetic coordinates (longitude/latitude) to UTM is recommended to be based on the World Geodetic System 84 (WGS84) and North American Datum of 1983 (NAD83). The conversion algorithm is based on the US Army (revised from http://www.uwgb.edu/dutchs/UsefulData/UTMFormulas.htm).

Appendix C. How to Setup GPS for IC

GPS setup is currently one of the most challenging steps for IC implementation. There are many pitfalls for losing or degrading IC data due to incorrect GPS setup. The followings are the specific procedures to do it properly. (Courtesy of TopCon)

Step 1 – Select a desired coordinate system or datum

- Select the datum to be used for this project. The order of preferred coordinate systems is: UTM, state plane, and local coordinate system.

Step 2 – Setup a GPS base station

- Select a known position with established NEZ (northing-easting-elevation) coordinates w.r.t. the selected coordinate system.
- Use a network rover and dialed up a specific State reference station network.
- Launch GPS software and apply the desired datum (e.g., UTM) for a projection.
- Set up a tripod, and install the receiver on top of the tripod.

- Measured the point using a 2-minute occupation time and save it as the base station location.

Figure 192. A Trimble GPS base station (left) and a TopCon GPS base station (ICPF WisDOT demo).

Step 3 – Setup hand-held GPS receiver (rover)

- Set up the handheld GPS geodetic receiver (rover) on the tripod. Start the base station using the measured coordinates to broadcast the NEZ coordinates of the selected datum (e.g., UTM) for that location.
- If the NEZ values are not being broadcasted from the base, the GPS data can have a horizontal error up to 12 to 15 feet. This is called an autonomous start, which only broadcasts the Latitude and Longitude of the base station and does not apply the datum correction.
- Caution: If one base station is started autonomously and then restarted with the UTM correction applied, the measurement of the same point will have different NEZ values depending on the UTM grid factor that is applied by the software.
- While the use of an autonomous start provides relative reference points, the use of a state plane or UTM base station start is strongly recommended to ensure GPS measurements at any time (e.g., after the project is complete) can be at the exact locations.

Figure 193. A Trimble GPS rover (left) and a TopCon GPS rover (ICPF WisDOT demo).

Step 3 – Setup GPS receiver on IC rollers

- Launch the onboard display software on the IC roller. Check the status of the GPS signals. Read out the GPS measurements from the GPS receiver on the IC roller.
- Remove the rover receiver unit from the rover and stack it on top of the receiver unit on the IC roller. Read out the GPS measurements from the rover and compare it with that from the previous measurements from the roller unit. The tolerance should be within ½".

Figure 194. Validation of roller mounted GPS with a hand-held rover (ICPF VADOT demo).

Appendix D. Generic Soils IC Specification

The following is a generic soils IC specification that can be served as a national guideline for States to implement IC.

Intelligent Compaction Technology for Soils Applications

DESCRIPTION

This work shall consist of the construction of the roadway fill embankment utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records various critical compaction parameters correlated to agency standard testing protocols in real time during the compaction process.   IC uses roller vibration measurements to assess the mechanistic soils properties and to ensure optimum compaction is achieved through continuous monitoring of the operations. Additional information on the IC technology may be found on the website www.intelligentcompaction.com and from the Transportation Research Board - NCHRP Report 676 on Intelligent Soil Compaction Systems.

The Contractor shall supply sufficient numbers of rollers and other associated equipment necessary to complete the compaction requirements for the specific materials. The Contractor will determine the number of IC rollers to use depending on the scope of the project. The IC roller(s) may be utilized during production with other standard compaction equipment and shall be used for the evaluation of the compaction operations.

EQUIPMENT

The IC rollers shall meet the following specific requirements:

1. IC rollers shall be self propelled single-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compaction effort. Rollers may be smooth or pad footed drums.

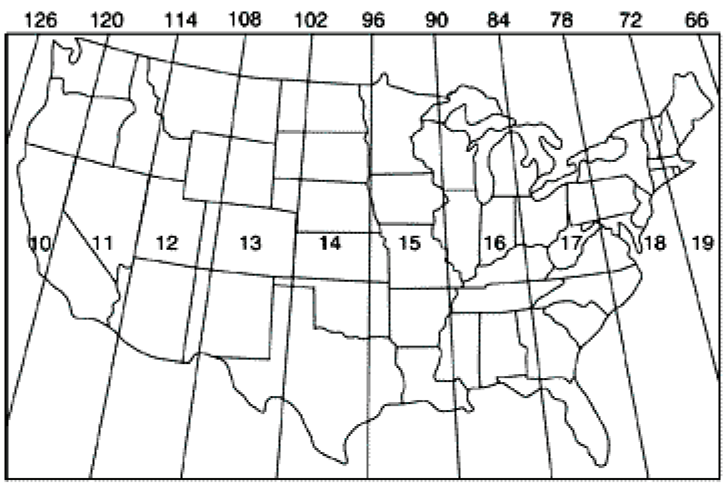
2. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.

3. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, machine settings, together with the speed, frequency and amplitude of roller drums. The display unit shall be capable of transferring the data by means of a USB port.

4. Roller mounted GPS radio and receiver units shall be mounted on each IC roller. RTK-GPS radio and receivers are required to monitor the location and track the number of passes of the rollers.

Real Time Kinematic Global Positioning System (RTK-GPS)

The Universal Transverse Mercator (UTM) Coordinates system divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. Zones outside of the Continental United States can be acquired on the web at www.dmap.co.uk/utmworld.htm. The UTM for this project is Zone (xx) N. (*DOT to fill in the zone number*)



Base Station - Ground mounted or virtual GPS base units that record values in northing, easting, and the elevation data in meters using the UTM coordinate system along with the longitude/latitude of the measurement values shall be provided. The GPS base station shall broadcast updated correction data to the GPS receivers on the IC rollers and the hand-held rovers during operations with a survey tolerance of not greater than 1.6 in. (40 mm) in both the horizontal (x and y) directions.

Rover - A portable hand-held GPS radio/receiver for in-situ point measurements shall be provided.

Data Analysis Software - Standardized data analysis software (Veda Alfa Vr.8.0 or later) is available on the website www.intelligentcompaction.com or will be provided by *xxDOT.* The software program will utilize the IC-MV data from the IC roller for analysis of coverage, uniformity, and stiffness values during construction operations. As a minimum, the following Essential IC Data Information and IC Data Elements shall be available in either ASCII or text format for post processing.

- Essential IC Data Information:

Item No.	Description
1	Section Title
2	Machine Manufacture
3	Machine Type
4	Machine Model
5	Drum Width (m)
6	Drum Diameter (m)
7	Machine Weight (metric ton)
8	Name index of intelligent compaction measurement values (IC-MV)
9	Unit index for IC-MV
10	Reporting resolution for independent IC-MVs – 90 degrees to the roller moving direction (mm)
11	Reporting resolution for independent IC-MVs – in the roller moving direction (mm)
12	UTM Zone
13	Offset to UTC (hrs)
14	Number of IC data points

- Essential IC Data Elements:

Item No.	Date Field Name	Example of Data
1	Date Stamp (YYYYMMDD)	e.g. 20080701
2	Time Stamp (HHMMSS.S -military format)	e.g. 090504.0 (9 hr 5 min. 4.0 s.)
3	Longitude (decimal degrees)	e.g. 94.85920403
4	Latitude (decimal degrees)	e.g. 45.22777335
5	Easting (m)	e.g. 354048.3
6	Northing (m)	e.g. 5009934.9
7	Height (m)	e.g. 339.9450
8	Roller pass number	e.g. 2
9	Direction index	e.g., 1 forward, 2 reverse
10	Roller speed (kph)	e.g. 4.0
11	Vibration on	e.g., 1 for yes, 2 for no
12	Frequency (vpm)	e.g. 3500.0
13	Amplitude (mm)	e.g. 0.6
14	Surface temperature (^{o}C) - HMA	e.g. 120
15	Intelligent compaction measurement values	e.g. 20.0

QUALITY CONTROL PLAN

The Contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. As a minimum, the QCP shall contain the following information:

General Requirements.

1. QCP shall be contract specific, stating how the contractor proposes to control the materials, equipment, and construction operations including subcontractors and suppliers as well as production facilities and transportation modes to the project for the embankment operations.

2. The QCP shall include an organizational chart showing all quality control personnel and how these personnel integrate with other management/production and construction functions and personnel.

3. The QCP shall be signed and dated by the Contractor's representative at the time the QCP is submitted to the Engineer. The QCP shall be submitted no later than 15 days prior to commencing the embankment operations.

4. The *xxDOT* will review, sign, and date the QCP if the contents of the QCP are in compliance with the requirements as stated herein.

5. The QCP shall be maintained to reflect the current status of the operations, and revisions shall be provided in writing prior to initiating the change. The QCP revision shall not be implemented until the revision has been accepted.

6. The QCP shall contain the name, telephone number, duties, and employer of all quality control personnel necessary to implement the QCP. The minimum qualifications of quality control personnel shall be as follows:

    a. QCP Field Manager or Plan Administrator. The person responsible for the execution of the QCP and liaison with the Engineer. Additionally the QCP Field Manager requirements include:

        1. Full-time employee of the Contractor or an independent consultant not involved with the Quality Assurance (acceptance) activities on the project.

        2. Minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations

        3. Full authority to institute actions necessary for successful implementation of the QCP.

b. Quality Control Technician (QCT). The person(s) responsible for conducting quality control and inspection activities to implement the QCP. There may be more than one QCT on a project.

   1. Full-time employee of the Contractor or an independent consultant with a minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations.

   2. Completed the *xxDOT* requirements for the applicable testing.

   3. Full authority to institute actions necessary for successful implementation of the QCP.

c. IC Roller Operator. The person responsible for operating the IC roller and attached IC equipment. Sufficient training for the roller operator shall be supplied by a representative of the manufacturer of the equipment.

7. IC Equipment. The Roller supplier, make, roller model, number of IC rollers to be provided, and the GPS system supplier to be utilized.

8. Embankment operations shall not begin before the QCP has been accepted.

9. The Engineer may require the replacement of ineffective or unqualified equipment or Quality Control personnel. Construction operations may be required to stop until Quality Control corrective actions are taken.

References. ***(****to be modified/expanded as applicable by the DOT****)***

1. **AASHTO Standards**.

AASHTO T 99	Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop
AASHTO T 272	Family of Curves – One-Point Method

2. **ASTM Standards**.

ASTM D 2583	Measuring Deflections with a Light Weight Deflectometer (LWD)

ASTM D 6951	Dynamic Cone Penetrometer in Shallow Pavement Applications (17.6-lb (8-kg) hammer)

3. ***xxDOT* Standards**.

xxx	Field Determination of Moisture Content of Soils
xxx	Field Determination of Deflection Using Light Weight Deflectometer

Quality Control Technician. The QCT shall be responsible for the following minimum functions:

1. GPS check testing for the IC roller(s) and rover(s).

2. Test section construction and establishing target values for the maximum dry density, optimum moisture content, production moisture content, strength of the materials using the dynamic cone penetrometer (DCP), light weight deflectometer (LWD), nuclear gauge, and the IC-roller(s).

3. Monitoring of the construction operations and the IC roller(s) during production and final proofing operations.

4. Quality control testing for the maximum dry density and moisture content.

5. Downloading and analysis of the IC-data from the roller(s).

6. Daily set-up, take down and secure storage of GPS and IC roller components

Testing Facility. The location of the testing facility and a list of test equipment shall be included. The testing facility shall be sufficient size to conduct the Quality Control tests, and a satisfactory base on which compaction of the soil can be achieved in accordance with AASHTO T 99 Method A (*or as otherwise defined by the DOT*) shall be provided. A statement of accessibility of the testing facility shall be included that allows *xxDOT* personnel to witness Quality Control activities and to review Quality Control tests.

A list of the testing equipment proposed for Quality Control testing and the test methods and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility. The minimum frequency and procedures shall be as follows:

Equipment	Requirement	Minimum	Procedure*

		Frequency	
Balances	Verification	12 months	xxx
Sieves	Check Physical Condition	12 months	xxx
Etc.*	*	*	

**to be filled in by the DOT*

Materials Sampling and Testing. The procedures for sampling and testing of the soil embankment and the frequency of tests shall be identified and include as a minimum the following: ***(****details to be modified/expanded as applicable by the DOT****)***

1. Moisture. The procedure for measuring the moisture content of the soil during production compaction. The minimum frequency of tests per lift of material shall be one test for each construction area.

2. Strength. The procedure for measuring the in-place strength of the soil. The minimum frequency of tests shall be a minimum of one test for each construction area.

3. Maximum Dry Density and Optimum Moisture Content. The procedure for measuring the maximum dry density and optimum moisture content of the soil for the test sections and when there is a change in the soil type.

4. IC Roller Data. The procedure for obtaining the IC roller data. The frequency of obtaining the data shall be a minimum of two times each day of soil compaction. The data is date/time stamped which permits for external evaluation at a later time.

GPS Check Testing. Prior to the start of production, the Contractor, GPS representative and IC roller manufacturer shall conduct the following to check the proper setup of the GPS, IC roller(s) and the rover(s) using the same datum:

1. On a location nearby or within the project limits, the GPS base station shall be established and the IC roller and the GPS rover tied into the base station.

2. Verification that the roller and rover are working properly and that there is a connection with the base station.

3. The coordinates of the roller from the on-board, color-coded display shall be recorded.

4. The receiver from the rover shall be removed and placed on top of the roller receiver and the coordinates shown on the rover display recorded.

5. The roller and rover coordinates shall be compared. If the coordinates calculate as being within 1.6 in. (40 mm), the comparison is acceptable. If the coordinates are not within 1.6 in. (40 mm), corrections shall be made as needed and the above steps repeated until verification is acceptable. Work shall not begin until proper verification has been obtained.

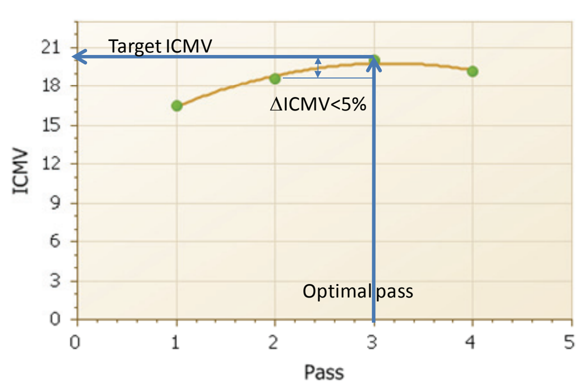
6. The project plan file provided by *xxDOT* shall be uploaded into the IC Data analysis software and depending on the roller manufacture, the on-board IC computer.

7. GPS check testing shall be conducted daily during production operations.

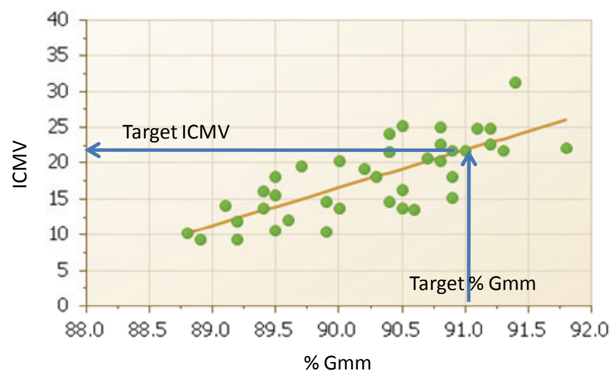
Test Sections. Test section evaluations are intended to determine the number of passes it takes to achieve compaction at the optimum moisture content for the materials. Test sections shall be approximately 225 ft (75 m) long and 24 ft (8 m) wide. The IC roller shall be utilized on the test sections to establish the target IC-MV as correlated to the *xxDOT* standard testing devices. GPS measurements for all testing devices will be obtained with the rover for correlation to the IC-MV. ***(test section details to be modified/expanded as applicable by the DOT)***

The evaluations shall be conducted for the various material types, on every lift where there is a change of materials. The rollers shall use the same settings (speed, frequency) throughout the section while minimizing overlapping of the roller. After each roller pass, a nondestructive density device shall be used to estimate the density or stiffness of the material at 10 locations uniformly spaced throughout the test section within the width of a single roller pass. The readings and the number of roller passes will be recorded. The estimated target density will be the peak of the average of the nondestructive readings. Linear regression relationships between the in-place density data and the number of passes will be used to determine if process meets the *xxDOT* in-place compaction requirements.

The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Once the target IC-MV is determined, compact an adjoining section using same roller settings and the estimated roller passes to verify the compaction with the same nondestructive devices after the final roller pass. Straight line best fit linear regression relationships between the density testing and IC-MV data will be used to establish the production target IC-MV that meets the *xxDOT* in-place compaction requirements. A linear regression curve example is as follows.



Mapping. Pre-construction mapping/proofing of the initial layer of the fill is recommended to identify weak areas that may need to be addressed in advance of the production fill operations. Subsequent mapping may be conducted at anytime to recognize the changes in the fill that affects the target IC-MV or the density verification testing. At a minimum, production mapping is recommended at the final surface of the fill and the elevation levels at 1.0 ft., 2.0 ft, 4.0 ft, and 8.0 ft below the final surface as applicable. The stiffness of the underlying materials should increase with subsequent lifts of soils. The Contractors procedures for mapping shall be included.

Soil Management. The procedures for management of the borrow pit and soil cut sections to assure uniform soil material shall be included. The procedures for the necessary adjustments in compaction because of a change in soil type shall be stated.

Response to Test Results. The response to quality control tests for the test sections and during production compaction shall include as a minimum the following:

1. Moisture. The procedure for corrective action when the QC moisture tests are not within -3 and +2 percentage points of the optimum moisture content.

2. Strength. The procedure for corrective action when tests do not meet the *xxDOT* requirements for each soil type.

3. Maximum Dry Density and Optimum Moisture Content. The procedure for corrective action when the maximum dry density and optimum moisture content test results indicate that there is a change in the soil type.

4. IC Coverage Area and Uniformity Criteria. The procedures for re-working the construction area when IC criteria for coverage area or the minimum IC-MV are not met.

Documentation. The documentation shall include the following:

1. Quality Control Tests. The results from the moisture, strength, and maximum dry density and optimum moisture content tests. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 h of testing.

2. Equipment. Documentation of the manufacture, model, and type of rollers used each day of soil compaction and the IC roller used for mapping the compaction of the soil. The positioning of the IC roller(s) in the paving operations shall be noted.

3. IC-MV Analysis. The Contractors will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.

   IC data will be saved as Time History Data and Post-Processed Data. Post-Processed Data will be imported using the all-passes and proofing-data formats. All passes data includes the data from all of the passes and proofing data is the data from just the last pass within a given area.

IC CONSTRUCTION

Technical Assistance. The Contractor shall coordinate for on-site technical assistance from the IC roller representative during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

Construction Areas. IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The magnitude of the evaluation areas may vary with production but they need to be at least 25,000 ft^2 for evaluation. Partial construction areas of 5000 ft^2 or less will be included in the previous area evaluation. Partial construction areas of greater than 5000 ft^2 will constitute a full area to close out the mixture. Construction areas may extend over multiple days depending on the operations.

IC Construction Operations Criteria. A minimum coverage of 90% of the individual construction area shall meet the optimal number of roller passes and 70% of the target IC-MV determined from the test sections. Construction areas not meeting the IC criteria shall be reworked and re-evaluated prior to continuing with the operations in that area. The IC Construction Operations Criteria does not affect the standard *xxDOT* acceptance processes for the materials or construction operations.

METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for Soils on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for Soils**.**

Payment will be made under:

Pay Item	**Unit**
Intelligent Compaction for Soils	LS

This item includes all costs related to providing the IC roller including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support and testing facility shall be included in the contract lump sum price.

Appendix E. Generic HMA IC Specification

The following is a generic HMA IC specification that can be served as a national guideline for States to implement IC.

Intelligent Compaction Technology for HMA Applications

DESCRIPTION

This work shall consist of the construction of the Hot Mix Asphalt (HMA) utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records various critical compaction parameters correlated to agency standard testing protocols in real time during the compaction process.   IC uses roller vibration measurements to assess the mechanistic properties to ensure optimum compaction is achieved through continuous monitoring of the operations. Additional information on the IC technology may be found on the website www.intelligentcompaction.com and from the Transportation Research Board - NCHRP Report 676 on Intelligent Soil Compaction Systems.

The Contractor shall supply sufficient numbers of rollers and other associated equipment necessary to complete the compaction requirements for the specific materials. The Contractor will determine the number of IC rollers to use depending on the scope of the project. The best location in the paving operations for the IC roller is in the breakdown position and can be used with non-IC rollers.

EQUIPMENT

The IC rollers shall meet the following specific requirements:

5. IC rollers shall be self propelled double-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compaction effort. IC rollers shall also be equipped with non-contact temperature sensors for measuring pavement surface temperatures.

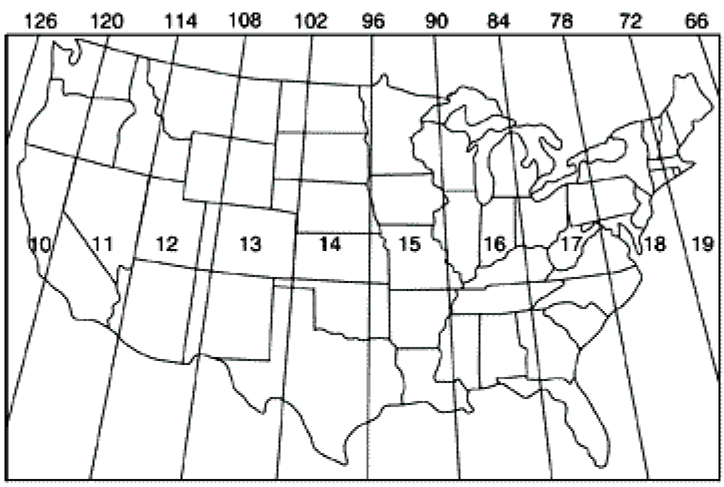
6. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.

7. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, machine settings, together with the temperature, speed and the frequency and amplitude of roller drums. The display unit shall be capable of transferring the data by means of a USB port.

8. Roller mounted GPS radio and receiver units shall be mounted on each IC roller. RTK-GPS radio and receivers are required to monitor the location and track the number of passes of the rollers.

Real Time Kinematic Global Positioning System (RTK-GPS)

The Universal Transverse Mercator (UTM) Coordinates system divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. Zones outside of the Continental United States can be acquired on the web at www.dmap.co.uk/utmworld.htm. The UTM for this project is Zone (xx) N. (*DOT to fill in the zone number*)



Base Station - Ground mounted or virtual GPS base units that record values in northing, easting, and the elevation data in meters using the UTM coordinate system along with the longitude/latitude of the measurement values shall be provided. The GPS base station shall broadcast updated correction data to the GPS receivers on the IC rollers and the hand-held rovers during operations with a survey tolerance of not greater than 1.6 in. (40 mm) in both the horizontal (x and y) directions.

Rover - A portable hand-held GPS radio/receiver for in-situ point measurements shall be provided.

Data Analysis Software - Standardized data analysis software (Veda Alfa Vr.8.0 or later) is available on the website www.intelligentcompaction.com or will be provided by *xxDOT*. The software program will utilize the IC-MV data from the IC roller for analysis of coverage, uniformity, and stiffness values during construction operations. As a minimum, the following Essential IC Data Information and IC Data Elements shall be available in either ASCII or text format for post processing.

- Essential IC Data Information:

Item No.	Description
1	Section Title
2	Machine Manufacture
3	Machine Type
4	Machine Model
5	Drum Width (m)
6	Drum Diameter (m)
7	Machine Weight (metric ton)
8	Name index of intelligent compaction measurement values (IC-MV)
9	Unit index for IC-MV
10	Reporting resolution for independent IC-MVs – 90 degrees to the roller moving direction (mm)
11	Reporting resolution for independent IC-MVs – in the roller moving direction (mm)
12	UTM Zone
13	Offset to UTC (hrs)
14	Number of IC data points

- Essential IC Data Elements:

Item No.	Date Field Name	Example of Data
1	Date Stamp (YYYYMMDD)	e.g. 20080701
2	Time Stamp (HHMMSS.S -military format)	e.g. 090504.0 (9 hr 5 min. 4.0 s.)
3	Longitude (decimal degrees)	e.g. 94.85920403
4	Latitude (decimal degrees)	e.g. 45.22777335
5	Easting (m)	e.g. 354048.3
6	Northing (m)	e.g. 5009934.9
7	Height (m)	e.g. 339.9450
8	Roller pass number	e.g. 2
9	Direction index	e.g., 1 forward, 2 reverse
10	Roller speed (kph)	e.g. 4.0
11	Vibration on	e.g., 1 for yes, 2 for no
12	Frequency (vpm)	e.g. 3500.0
13	Amplitude (mm)	e.g. 0.6

14	Surface temperature (^{o}C) - HMA	e.g. 120
15	Intelligent compaction measurement values	e.g. 20.0

QUALITY CONTROL PLAN

The Contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. As a minimum, the QCP shall contain the following information:

General Requirements.

10. QCP shall be contract specific, stating how the contractor proposes to control the materials, equipment, and construction operations including subcontractors and suppliers as well as production facilities and transportation modes to the project for the HMA pavement operations.

11. The QCP shall include an organizational chart showing all quality control personnel and how these personnel integrate with other management/production and construction functions and personnel.

12. The QCP shall be signed and dated by the Contractor's representative at the time the QCP is submitted to the Engineer. The QCP shall be submitted no later than 15 days prior to commencing the paving operations.

13. The *xxDOT* will review, sign, and date the QCP if the contents of the QCP are in compliance with the requirements as stated herein.

14. The QCP shall be maintained to reflect the current status of the operations, and revisions shall be provided in writing prior to initiating the change. The QCP revision shall not be implemented until the revision has been accepted.

15. The QCP shall contain the name, telephone number, duties, and employer of all quality control personnel necessary to implement the QCP. The minimum qualifications of quality control personnel shall be as follows:

    d. QCP Field Manager or Plan Administrator. The person responsible for the execution of the QCP and liaison with the Engineer. Additionally the QCP Field Manager requirements include:

4. Full-time employee of the Contractor or an independent consultant not involved with the Quality Assurance (acceptance) activities on the project.

5. Minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations

6. Full authority to institute actions necessary for successful implementation of the QCP.

e. Quality Control Technician (QCT). The person(s) responsible for conducting quality control and inspection activities to implement the QCP. There may be more than one QCT on a project.

1. Full-time employee of the Contractor or an independent consultant with a minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations.

2. Completed the *xxDOT* requirements for the applicable testing.

3. Full authority to institute actions necessary for successful implementation of the QCP.

f. IC Roller Operator. The person responsible for operating the IC roller and attached IC equipment. Sufficient training for the roller operator shall be supplied by a representative of the manufacturer of the equipment.

16. IC Equipment. The Roller supplier, make, roller model, number of IC rollers to be provided, and the GPS system supplier to be utilized.

17. HMA pavement operations shall not begin before the QCP has been accepted.

18. The Engineer may require the replacement of ineffective or unqualified equipment or Quality Control personnel. Construction operations may be required to stop until Quality Control corrective actions are taken.

References. ***(****to be modified/expanded as applicable by the DOT****)***

4. **AASHTO Standards**.

AASHTO R 42	Standard Practice for Developing a Quality Assurance Plan for Hot Mix Asphalt (HMA)

5. **ASTM Standards**.

xxx xxx

6. ***xxDOT* Standards**.

xxx xxx

Quality Control Technician. The QCT shall be responsible for the following minimum functions:

1. GPS check testing for the IC roller(s) and rover(s).

2. Test section construction to establish target compaction pass counts and target values for the strength of the materials using the standard testing devices, e.g. Nondestructive density gauges, pavement cores, and IC roller(s).

3. Monitoring of the construction operations and the IC roller(s) during production and final evaluation operations.

4. Quality control testing to monitor the pavement temperature and the required level of compaction.

5. Downloading and analysis of the IC data from the roller(s).

6. Daily set-up, take down and secure storage of GPS and IC roller components

Testing Facility. The location of the testing facility and a list of test equipment shall be included. The testing facility shall be sufficient size to conduct the Quality Control tests shall be provided. A statement of accessibility of the testing facility shall be included that allows *xxDOT* personnel to witness Quality Control activities and to review Quality Control tests.

A list of the testing equipment proposed for Quality Control testing and the test methods and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility. The minimum frequency and procedures shall be as follows:

Equipment	Requirement	Minimum Frequency	Procedure
*	*	*	*

**to be filled in by the DOT*

Materials Sampling and Testing. The procedures for sampling and testing of the pavement shall be identified and include as a minimum the following: ***(****details to be modified/expanded as applicable by the DOT****)***

5. Temperature. The procedure for monitoring the temperature of the materials during production, transportation, laydown and compaction operations. A minimum frequency shall be one test for two hours of placement and shall include all steps in the process.

6. Density/Compaction. Identification of the standard testing device(s) and frequency for measuring the in-place density of the HMA. The minimum frequency of tests shall be one test for each 250 tons of HMA placed.

7. IC Roller Data. The procedure for obtaining the IC roller data. The frequency of obtaining the data from the roller shall be at a minimum of two times per day of HMA compaction operations. The data is date/time stamped which permits for external evaluation at a later time.

GPS Check Testing. Prior to the start of production, the Contractor, GPS representative and IC roller manufacturer shall conduct the following to check the proper setup of the GPS, IC roller(s) and the rover(s) using the same datum:

8. On a location nearby or within the project limits, the GPS base station shall be established and the IC roller and the GPS rover tied into the base station.

9. Verification that the roller and rover are working properly and that there is a connection with the base station.

10. The coordinates of the roller from the on-board, color-coded display shall be recorded.

11. The receiver from the rover shall be removed and placed on top of the roller receiver and the coordinates shown on the rover display recorded.

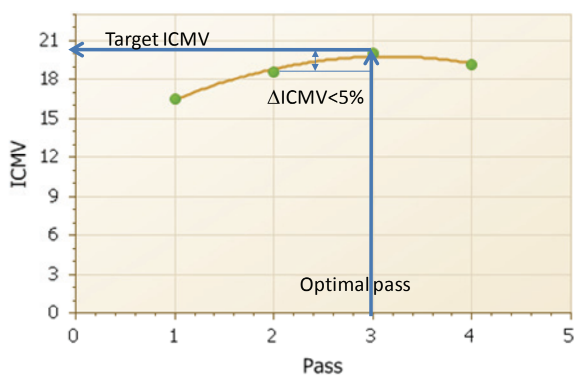
12. The roller and rover coordinates shall be compared. If the coordinates calculate as being within 1.6 in. (40 mm), the comparison is acceptable. If the coordinates are not within 1.6 in. (40 mm), corrections shall be made as needed and the above steps repeated until verification is acceptable. Work shall not begin until proper verification has been obtained.

13. The project plan file provided by *xxDOT* shall be uploaded into the IC Data analysis software and depending on the roller manufacture, the on-board IC computer.

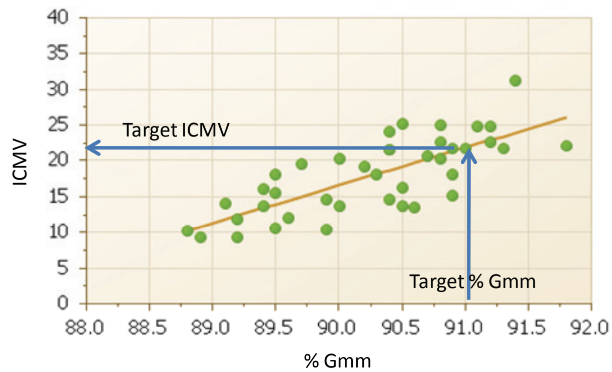
14. GPS check testing shall be conducted daily during production operations.

Test Sections. Test section evaluations are intended to verify the mixture volumetric of mixtures and determine a compaction curve of the HMA mixtures in relationship to number of roller passes and to the stiffness of mixture while meeting the *xxDOT* in-place compaction requirements. ***(****test section details to be modified/expanded as applicable by the DOT****)***

The evaluations shall be conducted every lift and be approximately 300 tons of mainline mixtures. The IC rollers shall use low amplitude and the same settings (speed, frequency) throughout the section while minimizing overlapping of the roller. After each roller pass, a nondestructive density device shall be used to estimate the density of the HMA at 10 locations uniformly spaced throughout the test section within the width of a single roller pass. The density readings and the number of roller passes that takes to achieve the desired compaction will be recorded. The estimated target density will be the peak of the average of the nondestructive readings within the desired compaction temperature range for the mixture. The IC roller data in conjunction with the IC data analysis software will create an IC compaction curve for the mixture. The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Once the target IC-MV is determined, compact an adjoining 300 tons using same roller settings and the number of estimated roller passes and verify the compaction with the same nondestructive devices after the final roller pass. At 10 locations, cores should be taken uniformly spaced throughout the test section within the width of the single roller. GPS measurement of the core locations will be obtained with a GPS rover. Straight line best fit linear regression relationships between the core data and IC-MV will be used to establish the production target IC-MV as the target density (% G_{mm}) meets the *xxDOT* in-place compaction requirements. A linear regression curve example is as follows.



Mapping. Pre-paving mapping with an IC roller of the underlying materials is recommended to be completed prior to tacking operations is recommended to identify weak areas and may be part of the test section evaluations on the project or independently run. Pre-construction mapping should be approximately 500 ft in length and conducted on mainline paving sections. Underlying materials includes treated or non-treated subgrades, treated or non-treated aggregate bases, or on milled or non-milled asphalt pavements. Mapping operations are intended to provide the Contractor and understanding of the stiffness of the existing roadway being paved. Subsequent mapping may be conducted at anytime to understand the changes in the roadway that affects the target IC-MV or the density verification testing. The stiffness of the underlying materials should increase with subsequent lifts of HMA. The Contractors procedures for mapping shall be included.

Response to Test Results. The response to quality control tests for the test sections and during production compaction shall include as a minimum the following:

5. Temperature. The procedure for corrective action when the QC or IC temperature readings are not within the recommended laydown values for the mixtures.

6. Density/Compaction. The procedure for corrective action when the maximum specific density (G_{mm}) results fall below the *xxDOT* specification limits or 92.0% whichever is greater.

7. IC Coverage Area and Uniformity Criteria. The procedures to be taken when the coverage area for pass counts requirements or IC-MV targets are not being met.

Documentation. The documentation shall include the following:

4. Quality Control Tests. The results from the temperature and density testing. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 h of testing.

5. Equipment. Documentation of the manufacture, model, type of paver, and rollers used each day of HMA operations. The positioning of the IC roller(s) in the paving operations shall be noted.

6. IC Roller Data. At a minimum, the electronic data from IC roller(s) shall be provided to the Engineer upon the completion of the Test Section, Mapping and individual IC Construction Area operations.

7. IC-MV Analysis. The Contractors will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.

   IC data will be saved as Time History Data and Post-Processed Data. Post-Processed Data will be imported using the all-passes and proofing-data formats. All passes data includes the data from all of the passes and proofing data is the data from just the last pass within a given area.

IC CONSTRUCTION

Technical Assistance. The Contractor shall coordinate for on-site technical assistance from the IC roller representative during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

IC Construction Area. IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The magnitude of the evaluation areas may vary with production but they need to be at least 1000 tons per mixture for evaluation. Partial construction areas of 500 tons or less will be included in the previous area evaluation. Partial construction areas of greater than 500 tons will constitute a full area to close out the mixture. Construction areas may extend over multiple days depending on the operations.

IC Construction Operations Criteria. A minimum coverage of 90% of the individual construction area shall meet the optimal number of roller passes and 70% of the target IC-MV values determined from the test sections. Construction areas not meeting the IC criteria shall be investigated by the *xxDOT* prior to continuing with the paving operations. The IC Construction Operations Criteria does not affect the standard *xxDOT* acceptance processes for the materials or construction operations.

METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for HMA on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for HMA**.**

Payment will be made under:

Pay Item	**Unit**
Intelligent Compaction for HMA	LS

This item includes all costs related to providing the IC roller including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support and testing facility shall be included in the contract lump sum price.

Appendix E. Generic Subbase IC Specification

The following is a generic subbase IC specification that can be served as a national guideline for States to implement IC.

Intelligent Compaction Technology for Aggregate Base Applications

DESCRIPTION

This work shall consist of the construction of the aggregate base materials utilizing Intelligent Compaction (IC) rollers within the limits of the work as described in the plans. IC is defined as a process that uses vibratory rollers equipped with a measurement/documentation system that automatically records various critical compaction parameters correlated to agency standard testing protocols in real time during the compaction process. IC uses roller vibration measurements to assess the mechanistic properties and to ensure optimum compaction is achieved through continuous monitoring of the operations. Additional information on the IC technology may be found on the website www.intelligentcompaction.com and from the Transportation Research Board - NCHRP Report 676 on Intelligent Soil Compaction Systems.

The Contractor shall supply sufficient numbers of rollers and other associated equipment necessary to complete the spreading and compaction requirements for the aggregate materials. The Contractor will determine the number of IC rollers to use depending on the scope of the project. The IC roller(s) may be utilized during production with other standard compaction equipment and shall be used for the evaluation of the compaction operations.

EQUIPMENT

The IC rollers shall meet the following specific requirements:

9. IC rollers shall be self propelled single-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compaction effort. Rollers shall have smooth drums.

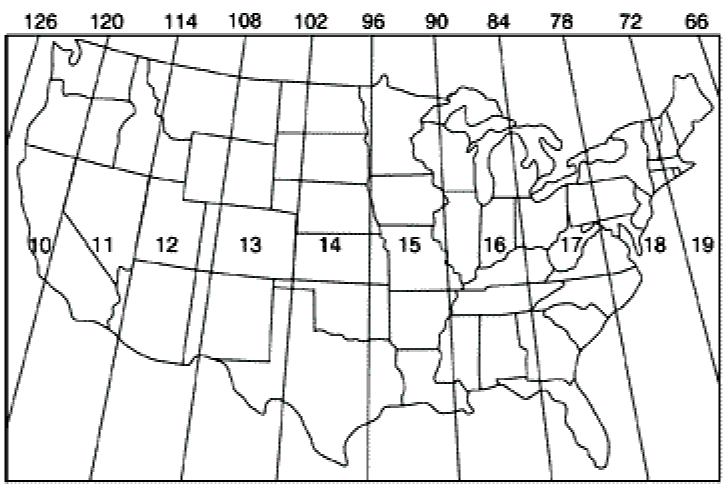
10. The output from the roller is designated as the Intelligent Compaction Measurement Value (IC-MV) which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.

11. The IC rollers shall include an integrated on-board documentation system that is capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, machine settings, together with the speed, frequency and amplitude of roller drums. The display unit shall be capable of transferring the data by means of a USB port.

12. Roller mounted GPS radio and receiver units shall be mounted on each IC roller. RTK-GPS radio and receivers are required to monitor the location and track the number of passes of the rollers.

Real Time Kinematic Global Positioning System (RTK-GPS)

The Universal Transverse Mercator (UTM) Coordinates system divides the surface of Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width and centered over a meridian of longitude. Zone 1 is bounded by longitude 180° to 174° W and is centered on the 177th West meridian. Zones outside of the Continental United States can be acquired on the web at www.dmap.co.uk/utmworld.htm. The UTM for this project is Zone (xx) N. (*DOT to fill in the zone number*)



Base Station - Ground mounted or virtual GPS base units that record values in northing, easting, and the elevation data in meters using the UTM coordinate system along with the longitude/latitude of the measurement values shall be provided. The GPS base station shall broadcast updated correction data to the GPS receivers on the IC rollers and the hand-held rovers during operations with a survey tolerance of not greater than 1.6 in. (40 mm) in both the horizontal (x and y) directions.

Rover - A portable hand-held GPS radio/receiver for in-situ point measurements shall be provided.

Data Analysis Software - Standardized data analysis software (Veda Alfa Vr.8.0 or later) is available on the website www.intelligentcompaction.com or will be provided by *xxDOT.* The software program will utilize the IC-MV data from the IC roller for analysis of coverage, uniformity, and stiffness values during construction operations. As a minimum, the following Essential IC Data Information and IC Data Elements shall be available in either ASCII or text format for post processing.

- Essential IC Data Information:

Item No.	Description
1	Section Title
2	Machine Manufacture
3	Machine Type
4	Machine Model
5	Drum Width (m)
6	Drum Diameter (m)
7	Machine Weight (metric ton)
8	Name index of intelligent compaction measurement values (IC-MV)
9	Unit index for IC-MV
10	Reporting resolution for independent IC-MVs – 90 degrees to the roller moving direction (mm)
11	Reporting resolution for independent IC-MVs – in the roller moving direction (mm)
12	UTM Zone
13	Offset to UTC (hrs)
14	Number of IC data points

- Essential IC Data Elements:

Item No.	Date Field Name	Example of Data
1	Date Stamp (YYYYMMDD)	e.g. 20080701
2	Time Stamp (HHMMSS.S -military format)	e.g. 090504.0 (9 hr 5 min. 4.0 s.)
3	Longitude (decimal degrees)	e.g. 94.85920403
4	Latitude (decimal degrees)	e.g. 45.22777335
5	Easting (m)	e.g. 354048.3
6	Northing (m)	e.g. 5009934.9
7	Height (m)	e.g. 339.9450
8	Roller pass number	e.g. 2
9	Direction index	e.g., 1 forward, 2 reverse
10	Roller speed (kph)	e.g. 4.0
11	Vibration on	e.g., 1 for yes, 2 for no
12	Frequency (vpm)	e.g. 3500.0
13	Amplitude (mm)	e.g. 0.6
14	Surface temperature (^oC) - HMA	e.g. 120
15	Intelligent compaction measurement	e.g. 20.0

	values	

QUALITY CONTROL PLAN

The Contractor shall prepare and submit a written Quality Control Plan (QCP) for the project. As a minimum, the QCP shall contain the following information:

General Requirements.

19. QCP shall be contract specific, stating how the contractor proposes to control the materials, equipment, and construction operations including subcontractors and suppliers as well as production facilities and transportation modes to the project for the embankment operations.

20. The QCP shall include an organizational chart showing all quality control personnel and how these personnel integrate with other management/production and construction functions and personnel.

21. The QCP shall be signed and dated by the Contractor's representative at the time the QCP is submitted to the Engineer. The QCP shall be submitted no later than 15 days prior to commencing the embankment operations.

22. The *xxDOT* will review, sign, and date the QCP if the contents of the QCP are in compliance with the requirements as stated herein.

23. The QCP shall be maintained to reflect the current status of the operations, and revisions shall be provided in writing prior to initiating the change. The QCP revision shall not be implemented until the revision has been accepted.

24. The QCP shall contain the name, telephone number, duties, and employer of all quality control personnel necessary to implement the QCP. The minimum qualifications of quality control personnel shall be as follows:

    g. QCP Field Manager or Plan Administrator. The person responsible for the execution of the QCP and liaison with the Engineer. Additionally the QCP Field Manager requirements include:

        7. Full-time employee of the Contractor or an independent consultant not involved with the Quality Assurance (acceptance) activities on the project.

8. Minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations

9. Full authority to institute actions necessary for successful implementation of the QCP.

h. Quality Control Technician (QCT). The person(s) responsible for conducting quality control and inspection activities to implement the QCP. There may be more than one QCT on a project.

4. Full-time employee of the Contractor or an independent consultant with a minimum (x) years experience (*as determined by the DOT*) in quality control activities in construction operations.

5. Completed the *xxDOT* requirements for the applicable testing.

6. Full authority to institute actions necessary for successful implementation of the QCP.

i. IC Roller Operator. The person responsible for operating the IC roller and attached IC equipment. Sufficient training for the roller operator shall be supplied by a representative of the manufacturer of the equipment.

25. IC Equipment. The Roller supplier, make, roller model, number of IC rollers to be provided, and the GPS system supplier to be utilized.

26. Material placement and compaction operations shall not begin before the QCP has been accepted.

27. The Engineer may require the replacement of ineffective or unqualified equipment or Quality Control personnel. Construction operations may be required to stop until Quality Control corrective actions are taken.

References. ***(****to be modified/expanded as applicable by the DOT****)***

7. **AASHTO Standards**.

AASHTO T 99	Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop
AASHTO T 272	Family of Curves – One-Point Method

8. **ASTM Standards**.

9. ***xxDOT* Standards**.

Quality Control Technician. The QCT shall be responsible for the following minimum functions:

7. GPS check testing for the IC roller(s) and rover(s).

8. Test section construction and establishing target values for the maximum dry density, optimum moisture content, production moisture content, strength of the materials using the light weight deflectometer (LWD), nuclear gauge, and the IC-roller(s).

9. Monitoring of the construction operations and the IC roller(s) during production and final proofing operations.

10. Quality control testing for the maximum dry density and moisture content.

11. Downloading and analysis of the IC-data from the roller(s).

12. Daily set-up, take down and secure storage of GPS and IC roller components

Testing Facility. The location of the testing facility and a list of test equipment shall be included. The testing facility shall be sufficient size to conduct the Quality Control tests, and a satisfactory base on which compaction of the aggregates can be achieved in accordance with AASHTO T 99 Method A (*or as otherwise defined by the DOT*) shall be provided. A statement of accessibility of the testing facility shall be included that allows *xxDOT* personnel to witness Quality Control activities and to review Quality Control tests.

A list of the testing equipment proposed for Quality Control testing and the test methods and frequency of calibration or verification of the equipment shall be included. The Contractor shall maintain a record of all equipment calibration or verification results at the testing facility. The minimum frequency and procedures shall be as follows:

Equipment	Requirement	Minimum Frequency	Procedure*
Balances	Verification	12 months	xxx
Sieves	Check Physical Condition	12 months	xxx
Etc.*	*	*	

**to be filled in by the DOT*

Materials Sampling and Testing. The procedures for sampling and testing of the aggregates and the frequency of tests shall be identified and include as a minimum the following: ***(details to be modified/expanded as applicable by the DOT)***

8. Moisture. The procedure for measuring the moisture content of the aggregates during production compaction. The minimum frequency of tests per lift of material shall be one test for each construction area.

9. Strength. The procedure for measuring the in-place strength of the aggregates. The minimum frequency of tests shall be a minimum of one test for each construction area.

10. Maximum Dry Density and Optimum Moisture Content. The procedure for measuring the maximum dry density and optimum moisture content of the aggregates in the test sections.

11. IC Roller Data. The procedure for obtaining the IC roller data. The frequency of obtaining the data shall be a minimum of two times each day of aggregate base production. The data is date/time stamped which permits for external evaluation at a later time.

GPS Check Testing. Prior to the start of production, the Contractor, GPS representative and IC roller manufacturer shall conduct the following to check the proper setup of the GPS, IC roller(s) and the rover(s) using the same datum:

15. On a location nearby or within the project limits, the GPS base station shall be established and the IC roller and the GPS rover tied into the base station.

16. Verification that the roller and rover are working properly and that there is a connection with the base station.

17. The coordinates of the roller from the on-board, color-coded display shall be recorded.

18. The receiver from the rover shall be removed and placed on top of the roller receiver and the coordinates shown on the rover display recorded.

19. The roller and rover coordinates shall be compared. If the coordinates calculate as being within 1.6 in. (40 mm), the comparison is acceptable. If the coordinates are not within 1.6 in. (40 mm), corrections shall be made as needed and the above steps repeated until verification is acceptable. Work shall not begin until proper verification has been obtained.

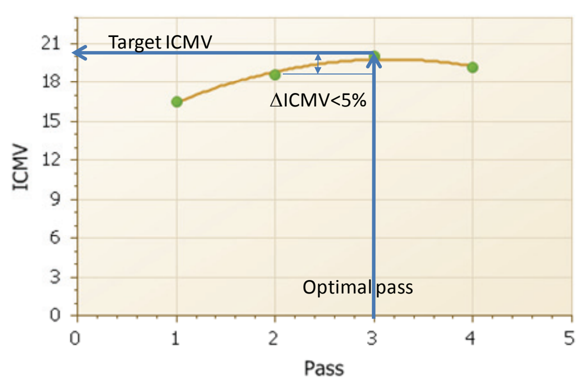
20. The project plan file provided by *xxDOT* shall be uploaded into the IC Data analysis software and depending on the roller manufacture, the on-board IC computer.

21. GPS check testing shall be conducted daily during production operations.

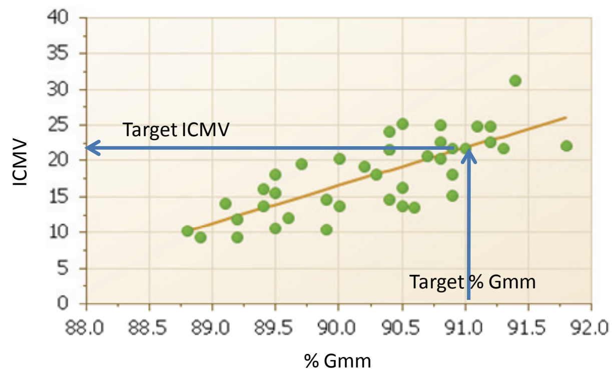
Test Sections. Test section evaluations are intended to determine the number of passes it takes to achieve compaction at the optimum moisture content for the materials. Test sections shall be approximately 225 ft (75 m) long and 24 ft (8 m) wide. The IC roller shall be utilized on the test sections to establish the target IC-MV as correlated to the *xxDOT* standard testing devices. GPS measurements for all testing devices will be obtained with the rover for correlation to the IC-MV. ***(****test section details to be modified/expanded as applicable by the DOT****)***

The rollers shall use the same settings (speed, frequency) throughout the section while minimizing overlapping of the roller. After each roller pass, a nondestructive density device shall be used to estimate the density or stiffness of the material at 10 locations uniformly spaced throughout the test section within the width of a single roller pass. The readings and the number of roller passes will be recorded. The estimated target density will be the peak of the average of the nondestructive readings. Linear regression relationships between the in-place density data and the number of passes will be used to determine if process meets the *xxDOT* in-place compaction requirements.

The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Once the target IC-MV is determined, compact an adjoining section using same roller settings and the estimated roller passes to verify the compaction with the same nondestructive devices after the final roller pass. Straight line best fit linear regression relationships between the density testing and IC-MV data will be used to establish the production target IC-MV that meets the *xxDOT* in-place compaction requirements. A linear regression curve example is as follows.



Mapping. Mapping/proofing of the final layer of the subgrade is recommended to identify weak areas that may need to be addressed in advance of the aggregate placement and compaction operations. The stiffness of the underlying materials should increase with subsequent lifts of aggregate materials. The Contractors procedures for mapping shall be included.

Response to Test Results. The response to quality control tests for the test sections and during production compaction shall include as a minimum the following:

8. Moisture. The procedure for corrective action when the QC moisture tests are not within -3 and +2 percentage points of the optimum moisture content.

9. Strength. The procedure for corrective action when tests do not meet the *xxDOT* requirements for aggregate bases.

10. Maximum Dry Density and Optimum Moisture Content. The procedure for corrective action when the maximum dry density and optimum moisture content test results indicate that there is a change in the aggregate source.

11. IC Coverage Area and Uniformity Criteria. The procedures for re-working the construction area when IC criteria for coverage area or the minimum IC-MV are not met.

Documentation. The documentation shall include the following:

8. Quality Control Tests. The results from the moisture, strength, and maximum dry density and optimum moisture content tests. All quality control test results shall be signed by the QCT and submitted to the Engineer within 24 h of testing.

9. Equipment. Documentation of the manufacture, model, and type of rollers used each day of aggregate compaction and the IC roller used for mapping

the compaction of the aggregate. The positioning of the IC roller(s) in the operations shall be noted.

10. IC-MV Analysis. The Contractors will analyze the IC-MV data for conformance to the requirements for coverage area and uniformity and will submit the results to the Engineer at the completion of the individual IC Construction Area operations.

    IC data will be saved as Time History Data and Post-Processed Data. Post-Processed Data will be imported using the all-passes and proofing-data formats. All passes data includes the data from all of the passes and proofing data is the data from just the last pass within a given area.

IC CONSTRUCTION

Technical Assistance. The Contractor shall coordinate for on-site technical assistance from the IC roller representative during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

Construction Areas. IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The magnitude of the evaluation areas may vary with production but they need to be at least 25,000 ft^2 for evaluation. Partial construction areas of 5000 ft^2 or less will be included in the previous area evaluation. Partial construction areas of greater than 5000 ft^2 will constitute a full area to close out the material. Construction areas may extend over multiple days depending on the operations.

IC Construction Operations Criteria. A minimum coverage of 90% of the individual construction area shall meet the optimal number of roller passes and 70% of the target IC-MV determined from the test sections. Construction areas not meeting the IC criteria shall be reworked and re-evaluated prior to continuing with the operations in that area. The IC Construction Operations Criteria does not affect the standard *xxDOT* acceptance processes for the materials or construction operations.

METHOD OF MEASUREMENT

This item will not be measured as it will be paid as a lump sum for providing for the Intelligent Compaction for Aggregates on the project.

BASIS OF PAYMENT

The incorporating of the Intelligent Compaction process will be paid at the contract lump sum price for Intelligent Compaction for Aggregates**.**

Payment will be made under:

Pay Item	Unit
Intelligent Compaction for Aggregates	LS

This item includes all costs related to providing the IC roller including the fuel, roller operator, GPS system, or any other equipment required for the IC process. All quality control procedures including IC rollers and GPS systems representatives support and testing facility shall be included in the contract lump sum price.

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