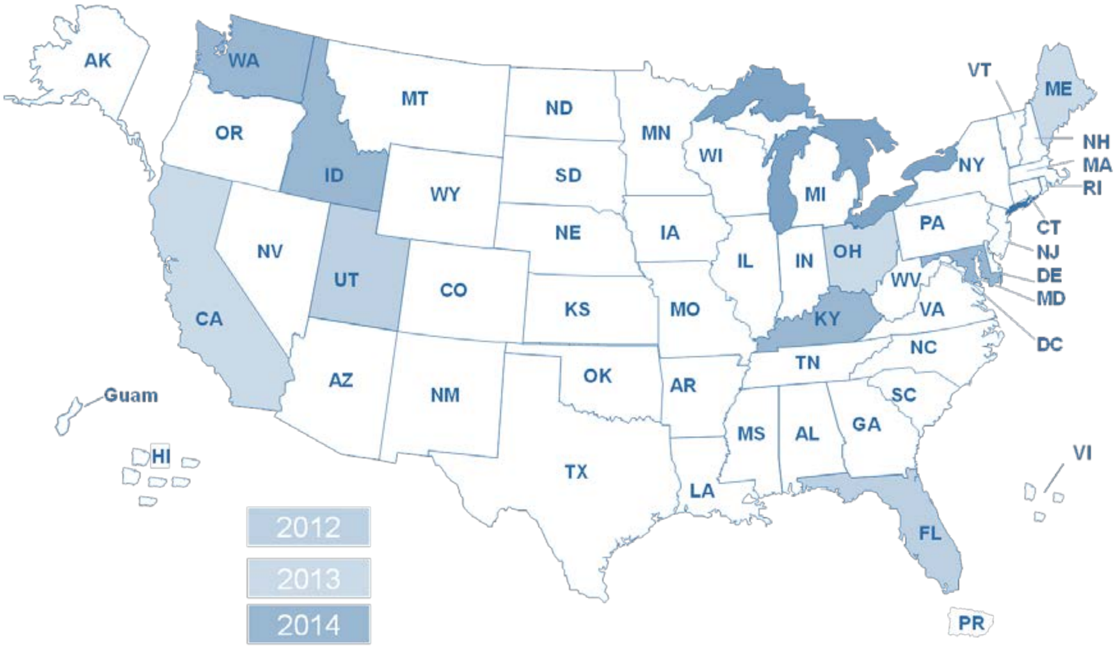

A STUDY ON INTELLIGENT COMPACTION AND IN-PLACE ASPHALT DENSITY

Publication No. FHWA-HIF-14-017

1. Report No. FHWA-HIF-14-017	2. Government Accession No. N/A	3 Recipient Catalog No. N/A
4. Title and Subtitle A Study on Intelligent Compaction and In-Place Asphalt Density Final Report		5. Report Date December 2014 6. Performing Organization Code N/A
7. Author(s) George Chang, Qinwu Xu, Jennifer Rutledge, and Sabrina Garber, Transtec Group		8. Performing Organization Report No. N/A
9. Performing Organization Name and Address The Transtec Group, Inc. 6111 Balcones Drive Austin TX 78731		10. Work Unit No. (TRAIS) N/A 11. Contract or Grant No. DTFH61-07-C-0032
12. Sponsoring Agency Name and Address Federal Highway Administration Office of Pavement Technology, HIPT-10 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final report 14. Sponsoring Agency Code N/A
15. Supplementary Notes Contracting Officer's Representatives: Victor (Lee) Gallivan and Richard Duval		

16. Abstract

Intelligent Compaction (IC) technology is an innovation of roller technology that can be used to improve quality control (QC) of the asphalt pavement compaction process. It is increasingly used by the asphalt paving industry in the US. Currently, IC is being adopted by many federal and state highway agencies. Asphalt IC technology uses accelerometer-based methods to collect IC measurement values (ICMV) that relate to the stiffness of the compacted materials. Across the US, in-place asphalt density measurement is still the de facto method for acceptance as the in-place densities relate to long-term performance of asphalt pavements. Past limited research has not been successful in finding a strong correlation between ICMV and measured in-place density. To accelerate the implementation of IC technology, it is essential to further study the relationship between IC measured data and core density to assess the use of IC measurements beyond QC. This project includes extensive field studies and data analysis and modeling in order to investigate the relationship between ICMV and other IC measurements (such as pass counts, temperatures, vibration frequencies/amplitudes, direction, speed, etc.) and asphalt in-place densities. The pass-by-pass ICMV correlate well with nuclear density gauge measurements during breakdown compaction. As the final ICMV does not correlate well with core densities, the final ICMV data is not recommended to replace cores for acceptance. An IC-based nonlinear panel data model was also developed to reasonably predict asphalt in-place density as an enhanced QC tool. Recommendation are also provided regarding future research and implementation to maximize the potential benefits of IC.

17. Key words Compaction, intelligent compaction, roller, asphalt, in-place density, quality control, acceptance.		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized (art. 5/94)

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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Acknowledgement

This project would not be possible if not for the funding from FHWA and support from the State departments of transportation, IC roller vendors, GPS vendors, and paving contractors of the nine (9) field 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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Disclaimer

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The authors and the FHWA do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to this report.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AFC	Auto-Feedback Control
ATDB	Asphalt Treated Dense Base
BCM	BOMAG Compaction Manager IC system
BEM	Boundary Element Method
CCV	Compaction Control Value from Sakai
CMV	Compaction Meter Value used by Caterpillar, Dynapac, and Trimble IC retrofit
COV	Coefficient of Variation
DGA	Dense Graded Aggregate
EDC	FHWA Everyday Counts initiative
Evib	Vibration modulus from BOMAG
FEM	Finite Element Method
FWD	Falling Weight Deflectometer
GPR	Ground Penetration RADAR
GPS	Global Positioning System
HCQ	Hamm Compaction Quality IC system
HMA	Hot Mix Asphalt
HMV	Hamm Measurement Value from Hamm
IACA	Intelligent Asphalt Compaction Analyzer
IC	Intelligent Compaction
ICMV	Intelligent Compaction Measurement Value
IRI	International Roughness Index

Kb	IC-integrated soil stiffness from Ammann
LWD-a	Light Weight Deflectometer for Asphalt
MDP	Machine Drive Power from Caterpillar
NDG	Nuclear density Gauge
NMAS	Nominal Maximum Aggregate Size
NNDG	Non-Nuclear density Gauge
OLS	Ordinary Least Square Method
PCC	Portland Cement Concrete
RAP	Recycled Asphalt Pavement
RMV	Resonance Meter Value from Geodynamics
RTK	Real-Time Kinematic
SBAS	Satellite-Based Augmentation Systems
SMA	Stone Matrix Asphalt
TCC	Trimble Connected Community from Trimble
TFHRC	Turner Fairbanks Highway Research Center
TPF	Transportation Pooled Fund
UTM	Universal Transverse Mercator

Symbols

$A_{0.5\Omega}$	magnitude of frequency strength at a sub-harmonic frequency caused by drum jumping movement (i.e., the drum skips every other cycle)
A_{Ω}	magnitude of frequency strength at fundamental frequency
$A_{1.5\Omega}$	magnitude of frequency strength at sub-harmonic frequencies
$A_{2.5\Omega}$	magnitude of frequency strength at sub-harmonic frequencies
$A_{2\Omega}$	magnitude of frequency strength at the second order harmonic frequency
$A_{3\Omega}$	magnitude of frequency strength at the third order harmonic frequency
$\rho(i,j)$	material density at the location i and time index or pass count j
ρ_{max}	maximum density of the specific material
$\hat{\varepsilon}_{\rho}(u)$	the observed error at location u from the experimental data
γ_k	fitted model parameters
T_r	reference temperature
V_R	roller speed
$\bar{X}(i)$	the mean value of observations of independent variables at the i^{th} index across all time indexes of j
$X_k(u)$	the observed variable (IC information) at the location vector u for $k = 1,2 \ldots N$
β_i	slopes
ε_{ρ}	idiosyncratic error of density prediction and its mean value
λ_a	kriging weight assigned to the datum $z(u_a)$
$\hat{\rho}(i,j)$	the observation or measured density at location i and time index j
$\bar{\rho}(i)$	the mean value of observed density, at the i^{th} location across all time indexes of j
ρ_0	the fixed effect at the initial conditions, i.e. the initial density right behind paver
Amp	amplitudes of roller vibration
DenDiff	differences between measured densities and predicted densities
DenDiff^2	squares of differences between measured densities and predicted densities

Dens core density and NDG density

Dfwd FWD deflection at Sensor 0 under the load platen and normalized to 9,000 lb. reference load

Efwd asphalt layer moduli backcalculated from the FWD deflections

Elwd20 asphalt layer moduli backcalculated from LWD-a data and normalized to 20°C reference temperature.

Freq frequency of roller vibration

F_s roller-soil interaction force

Gmm theoretical maximum specific gravity

ICMV specific ICMV from a specific vendor, mostly from the breakdown compaction

ID location ID for coring or NDG measurements

L length of the roller drum

Passes roller pass counts, i.e., number of times a roller drum passes a given location

PredDen predicted densities by the IC-based model

PredDen1 predicted densities by the IC-based model in Form I

PredDen2 predicted densities by the IC-based model in Form II

R' radius of the drum

Speed roller speed

Temp asphalt surface temperatures

W_d contact width of the drum

X(i,j) the observed independent variable at the i-th index and j-th index

β_k(i) the slope of the k-th independent variable at the i^th location for k=1,2,3…N as the number of independent variables

$\bar{\varepsilon}$ mean value of observed ε

ε(i,j) idiosyncratic errors or idiosyncratic disturbances at the i-th index and j-th index due to uncertainty

η Poisson's ratio of the material;

ρ_0(i,j) individual heterogeneity as an intercept at the i-th location

σ^2 (ε) variance of error observations

A	vibration amplitude
T	temperature;
f	vibration frequency
$m(u_a)$	mean value of $z(u_a)$
$m(u)$	mean value of $z(u)$
$m(\varepsilon_\rho)$	idiosyncratic error of density prediction and its mean value
$n(u)$	number of data points in the neighbor
u	location vector for estimation
$u(a)$	location vector of the neighboring data points, and a is number of a data point
ε	fixed-effect error across location
$\rho\ (i,j)$	predicted density

Executive Summary

Background

Adequate compaction is required to obtain specified asphalt densities in the field. Density is the criteria most state agencies measure for asphalt pavement acceptance. Cores are extracted from the pavement and standard laboratory tests are conducted to determine the density of the cores, which are considered representative of the entire pavement. There are many factors affecting in-place asphalt densities including materials and structure properties (Nominal Maximum Aggregate Size or NMAS to layer thickness ratio), use of paving and compaction equipment (material transfer vehicle, paver, screed in vibration/static, rollers sizes/amplitude/frequency/speed/rolling patterns), environmental conditions (ambient/support surface temperature), etc. Therefore, achieving desired density is always challenging.

Intelligent Compaction (IC) is an innovative technology that captures the "complete compaction history" – when, where, and how compaction is performed. It is revolutionary to the industry allowing the contractor and owner agencies, for the first time, to measure real-time material properties during compaction, track progress visually, record measured data and machine settings digitally, and report everything from the field all while using a technically advanced roller. Intelligent Compaction is defined as vibratory rollers equipped with the following: accelerometers mounted on the axle of drums, survey-grade global positioning systems (GPS), infrared temperature sensors, and on-board computers that can display IC measurements as color-coded maps in real time. IC measurements include IC measurement values (ICMV), roller passes, asphalt surface temperatures, and roller settings including roller vibration frequencies, amplitudes, and speeds. This kind of tool is ideal for quality control (QC). *The purpose of this study, however, is to answer the question: Can IC measurements be substituted for core data as a basis for acceptance?*

The Federal Highway Administration (FHWA) has been leading a national effort to advance the IC technology through several research projects including the Transportation Pooled Fund (TPF) IC project TPF-5(128) *Accelerated Implementation of Intelligent Compaction Technology for*

Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material . This TPF research effort was a partnership with twelve (12) participating states and achieved three primary objectives: to develop IC specifications, to develop a knowledgebase that includes experience for participating states, and to identify and prioritize needed improvements of IC technologies. One of the major findings of the TPF study was that more extensive research on the relationship and possible correlation of ICMV and density was needed. If an adequate correlation could be established, it would then be feasible to use IC as an acceptance tool.

As a continuing effort of the above FHWA IC project, an extensive study was conducted between 2011 and 2014 to assess the correlation between IC measurements and asphalt core densities. The goal was to evaluate whether IC can be both a quality control and acceptance tool for compaction. The challenge with achieving this goal was to determine and characterize any correlation between IC measurements and asphalt density. The scope of work included IC implementation and extensive field testing at nine (9) different field sites across the country. These field sites were real construction jobs, owned by state agencies. The selection of field sites was based on the diversity of climate, traffic, and type of construction (overlay and new construction), as well as availability of project windows.

Summary of the Sites

In 2012, implementation and testing was conducted at sites along an urban section of US-89 in Lehi, Utah and on a rural section of I-95 in Brevard, Florida. The US-89 project was the construction of a hot mix asphalt (HMA) overlay. IC implementation and testing was conducted on the base course, which consisted of a 2.5-inch 19-mm Superpave HMA mix with recycled asphalt particles (RAP) and a PG 58-34 binder. The I-95 project was also the construction of an HMA overlay. IC implementation and testing was conducted on the base course. This time, the base course was constructed to be 1.5 inches thick. Mix design details were not made available to the research team. A Hamm IC roller and a Sakai IC roller were used for compaction of the base courses in both projects.

In 2013, IC implementation and testing was conducted at sites in Ohio, Maine, and California. The Ohio site was the construction of an overlay along a rural stretch of I-71 in Morrow County, Ohio. IC implementation and testing was conducted on the base course. The base course is 1.75 inches of a 19-mm Type A Superpave mix with RAP and a PG 64-28 binder. A Hamm IC roller and a Sakai IC roller were used for compaction of this layer. The site in Maine was a new construction on a rural stretch of I-95 in Island Falls. IC implementation and testing was done on the intermediate course. The intermediate course was constructed with a 12.5-mm coarse-graded Superpave mix incorporating 20% RAP and a PG 64-28 binder. A Caterpillar IC roller and a Hamm IC roller were used to compact this layer. An overlay was constructed in California along an urban stretch of I-80 in Solano. IC implementation and testing was conducted on the intermediate course. The intermediate course was constructed to be 3.0 inches of a ¾-inch Type A Superpave mix with 15% RAP and a PG 64-16 binder. A BOMAG IC roller, a Caterpillar IC roller, and a Hamm IC roller were used to compact this layer.

In 2014, IC implementation and testing was conducted at sites in Idaho, Maryland, Kentucky, and Washington. The site in Idaho was a new construction on a rural stretch of US-95 in Garwood. IC implementation and testing was conducted on the 2.0-inch base course. Mix design details were not made available to the research team. A Hamm IC roller and a Sakai IC roller were used to compact this layer. An overlay constructed along an urban stretch of MD 170 near the Baltimore Washington International Airport (BWI) was the site chosen in Maryland. IC implementation and testing was conducted on the base course constructed with a 19-mm Superpave mix incorporating a PG 64-22 binder. A Caterpillar IC roller and a Hamm IC rollers were used to compact this layer. New construction along a rural section of I-65 in Hart County was the location of the Kentucky site. IC implementation and testing was conducted on the base course, which is a 4.0-inch 1.5D CL4 mix with a PG 64-22 binder. Caterpillar and Hamm IC rollers were used to compact this layer. In Washington, the site was new construction along a rural stretch of SR-539 in Lynden-Aldergrove. IC implementation and testing was conducted on the base course, which was constructed to be 4.5 inches thick. Mix design details were not made available to the research team. Caterpillar and Hamm IC rollers were used to compact this layer.

Summary of the IC Rollers

The IC systems used in this study include double drum IC rollers by BOMAG, Caterpillar, Hamm, and Sakai. As explained by the definition of IC, IC rollers are really a system of components that work together to evaluate material properties during compaction. It is important to understand that each manufacturer's system is different from the next. While all must have the same basic IC components mentioned in the IC definition, there are specific differences between them that sets them apart. In particular, the ICMV is different for each system.

The BOMAG double drum IC rollers are generally equipped with Trimble GPS and BOMAG AsphaltManager hardware and software. The ICMV of the BOMAG IC system is called vibration modulus or Evib. Evib is back-calculated from the accelerometer signals using a mechanical lumped parameter model. Evib is correlated to layer stiffness calculated from plate load tests.

The Caterpillar double drum IC rollers are factory-equipped with Caterpillar Compaction Control hardware and software and standard Satellite-based augmentation systems (SBAS) GPS accuracy that can be upgraded to Real-Time Kinematic(RTK) GPS accuracy with the purchase of additional software option keys. VisionLink software purchased through SITECH is required to view and analyze IC data. The ICMV of the Caterpillar IC system is Compaction Meter Value or CMV. CMV is calculated using a frequency analysis technique. CMV is correlated with layer stiffness.

The Hamm double drum IC rollers are generally equipped with Trimble OmniSTAR GPS and Hamm Compaction Quality (HCQ) hardware and software. The OmniSTAR GPS makes use of a virtual reference station via subscription without the need of an on-ground GPS base station. The ICMV of the Hamm IC system is Hamm Measurement Value or HMV. HMV is similar to CMV in that it is calculated with a frequency analysis technique. HMV is also correlated to layer stiffness.

The Sakai double drum IC rollers are generally equipped with TopCon GPS and TopCon SiteLink3D hardware and web software. The ICMV of the Sakai IC system is Compaction Control Value or CCV. CCV is similar to CMV and HMV in that it is calculated with a frequency analysis technique. CCV is also correlated to layer stiffness.

It should be noted that ICMV is influenced by the roller type, weight, vibration frequencies/amplitudes, direction, and roller speeds. If the roller operation settings change, the ICMV values will change. Therefore, the operating settings should be kept constant during IC compaction on a test strip in order to determine a rolling pattern to optimize the compaction. Settings should also remain constant during construction of the actual pavement to ensure consistency. Any comparison between ICMV for a single roller is only valid when the roller settings are the same. Because different manufacturers have different systems and different measurement values, it is not valid to compare the results of one system to another in a side-by-side comparison of the ICMV. For all systems, the ICMV correlates to layer stiffness and not density. Therefore, extensive field testing and analysis of all data had to be conducted to determine any kind of correlation with caution.

Summary of the Field Procedure

In order to determine the relationship between in-place asphalt densities and IC measurements (including ICMV, roller passes, asphalt surface temperatures, roller vibration frequencies/amplitudes, direction, and roller speed) IC implementation and testing for a given test site took place over four consecutive days. On the fifth day, an open house was organized by the hosting state agency providing them a better forum to learn more from the experts on hand (i.e., the FHWA research team and the vendors) and ask questions about IC in general. Implementation and testing activities followed a strict, intense schedule.

Prior to each field study, GPS measurements were validated a day before paving began to ensure all roller GPS measurements and hand-held GPS rover devices provided consistent measurements with reference to the same coordinate system. GPS data must be collected accurately for any implementation to be successful. In addition to validating GPS, pre-mapping of the granular subbase, if applicable, using IC rollers was performed at some sites (based on availability of time and test areas) in order to assess the existing condition of supporting layers. The roller settings for pre-mapping were at low frequency and low amplitude to avoid disturbing the existing support condition. However, it is not recommended to preamp solid surfaces such as milled asphalt.

On the morning of paving at each site, vendors trained the roller operators on their proprietary IC components and software. They then guided them through viewing IC results on the computer monitors in real time. Once paving began, at least two IC rollers were used to collect IC measurements. One IC roller was positioned as the breakdown roller and the other as the intermediate roller. The selection of IC rollers for use at the breakdown or intermediate position was made jointly by the paving contractors and the IC research team in order to optimize the compaction efforts. Contractors normally made the decision based on their past experiences on similar projects.

After paving was underway for a short while, a minimum of two spot locations were identified. At these locations a nuclear density gauge (NDG) was used to collect asphalt in-place density measurements. These measurements were obtained just after the paver passed over the spot, and then immediately after each pass of the breakdown and intermediate rollers. Surface temperature measurements were taken with each density measurement. GPS for each spot location was obtained using a hand-held rover. This activity is commonly referred to as collection of pass-by-pass test data.

A 1,500-ft section of pavement was identified after pass-by-pass test data was collected. When the finish roller completed the final pass of this section, a total of 60 spot locations were marked along this section for testing. This includes Nuclear density gauge measurements (NDG), coring (four inches in diameter), GPS measurements, and other in situ tests with light weight deflectometer (LWD-a) and/or falling weight deflectometer (FWD) testing. The cores were tested in state-agency asphalt laboratories to obtain bulk density values. A total of 515 asphalt cores were taken, tested, and analyzed. For some selected sites, ground penetrating radar (GPR) was conducted either by the state agency or consultants.

At the end of each day's paving, IC data was downloaded from the computers on the IC rollers in Veda compatible formats. These data were then viewed and analyzed using the Veda software. Each IC roller manufacturer has their own, proprietary software for storing, viewing, analyzing, and reporting raw data. Veda, however, is a more powerful, standardized, geospatial software tool for IC data management funded by the Minnesota Department of Transportation (MNDOT) and FHWA that can be downloaded from the IC website (www.IntelligentCompaction.com).

Summary of the Analyses

Data Collection and Pre-Processing

Before IC data can be viewed or analyzed, it is pre-processed by each manufacturer's proprietary software. This pre-processing is generally similar for all manufacturers. Temperature, ICMV, GPS, roller speed, vibration frequency and amplitude data are collected for a single point along the drum. This point is at the center of the front drum. Vendor software then takes the data for this one point and duplicates it across the entire width of the one drum in finer meshes. This duplication results in approximately six to seven one-foot-by-one foot squares or meshes that represent areas of contact between the a full size roller drum and compacted materials. Processing the data as described produces a more refined, gridded data set that can be used for further analysis. Gridded IC data is then exported using the vendor-specific IC software to a Veda-compatible format. The exported format includes two files: all-passes data and final coverage data. The all-passes data includes all IC data through the entire compaction history while the final coverage is the last pass data (i.e., subset of the all-passes) indicating the final surface results.

Data from in situ spot tests gathered in either raw or reduced formats also had to be processed for further analysis in Excel and Veda. GPS data were obtained by exporting the measurements from GPS devices to text formats. Nuclear density gauge (NDG) data were recorded manually during the measurements onsite. Asphalt core data were provided by state agency laboratories in either PDF or Excel format. If available, LWD-a data and back-calculation results were provided by Kessler in either PDF or Excel format. If available, FWD data were provided by state agencies in raw data formats. The FWD data were analyzed to obtain normalized reflections underneath the load platen with respect to 9,000 lb. load and back-calculated using a multi-layer analysis program to obtain layer moduli.

Analyses of the Data and Discussion of Results

Once all data was collected and formatted, analyses began and focused on the following:

- Statistical Analyses of IC Data: The IC data were analyzed with Veda to produce basic statistics and histogram reports for ICMV, roller passes, roller speed, vibration frequency, amplitude, and asphalt surface temperatures.
- Density Compaction Curves and Pass-by-Pass IC Data Analyses: Based on detailed observation of density growth curves based on NDG measurements, the influencing factors on in-place density can be better understood.
- Correlation Analysis between core density, pass-by-pass, final coverage IC data, and in situ test data including NDG, LWD-a, and FWD Data: This is a one-to-one linear correlation analysis to investigate the relationship between core densities and ICMV.

Statistical Analyses of IC Data and Correlation Analysis

IC data were imported to Veda for viewing and statistical analyses. The Viewer feature in Veda allows IC data to be plotted on a geographical map (currently OpenStreetMap) for detailed inspections of ICMV, roller passes, surface temperature, roller speeds, roller vibration frequency, and amplitude measurements. Veda's display of IC data is color coded with an option to customize the color palette. Veda's Viewer also allows viewing of selected individual passes or final coverage with powerful filtering options. The viewing and statistical analyses with Veda allow better understanding the IC operation, rolling patterns, and compaction results.

Density Compaction Curve Analyses

Pass-by-pass NDG and temperature data was entered into an Excel spreadsheet and charts were created to evaluate density growth. The charts showed that density growth curves or patterns could vary from one spot to another in a given project even when the equipment, personnel, and materials remained the same. These results suggest that the relationship between compaction and density is very complex. It was hypothesized that other factors may have caused this variability including the starting densities (or "zero-pass") right behind the paver, roller settings (amplitude/frequency/speed), timing and environmental conditions during roller passes, and the sequence of rolling train and rolling patterns.

Correlation Analyses

The in situ test data obtained from all spot test locations were added to the Point Test feature in Veda for correlation analysis from Excel spreadsheets by copy-and-paste functions. The Veda analyses produce basic statistics and histogram charts for overall analysis or fixed segment analysis. Veda extracts IC data within a radius of a given spot test location, normally about three feet in cover the width a roller drum, for the correlation analysis. The correlation analyses provide linear regression results with fitted linear equations and associated goodness-of-fit, R^2, values. The Veda results were extracted for further processing with Excel.

Analyses were conducted to determine and evaluate any correlation between core densities, LWD-a, FWD, IC measurements, and NDG measurements taken at the 60 spot locations within the 1,500-foot test section. Excel spreadsheets and linear regression were used for these analyses.

NDG measurements correlate well with ICMV from breakdown rollers, but not intermediate rollers. The mean R^2 of linear correlation between the breakdown ICMV and NDG measurements is 0.6. On the other hand, the mean R^2 of linear correlation between the intermediate ICMV and NDG measurements is only 0.3. Based on these observations, it appears that ICMV correlates better to in situ density measurements when asphalt temperatures are high, which is when the breakdown roller is compacting the asphalt. At the point when the intermediate roller passes over a section, the ICMV value obtained may be affected by the stiffening of the cooling HMA and is likely the reason why there is not as good of a correlation. It is also postulated that the ICMV influence depth is shallow during the first several passes of the breakdown roller when asphalt temperatures are much higher.

It was determined that asphalt core density data does not correlate well to LWD-a data. The linear regression between core density and layer moduli (normalized to 20°C) back-calculated from LWD-a data exhibits no linear trend or occasionally reverse trend. The lack of linear relationship is expected due to the different nature of density and moduli.

Asphalt core density data does not correlate well to FWD data, either. Similar to the core density and LWD moduli correlation, the linear regression between core density and layer moduli back-calculated from FWD data exhibits no linear trend or occasionally reverse trend. Similar observations were obtained between core density and FWD deflections beneath the load platen that were normalized to 9,000 lb. Again, it is not a surprise results either due to the difference of density and moduli.

It was determined that the correlation between asphalt core density data and NDG measurements was fair. The R^2 values range from 0.5 to 0.8 for all test sites; however, significant bias was observed for 50% of the field data sets. NDG calibration against cores are highly recommended and stringent rules of operation (e.g., free of moisture and asphalt residue on the gauge contact surface) should be observed.

The correlation between final coverage ICMV and the asphalt layer moduli back-calculated from LWD-a data is poor. These results reflect the limitations regarding differences in measurement depths and foot prints.

Asphalt core density data does not correlate well to final coverage ICMV. Recall that the final coverage data is the last pass data. The probable cause of the lack of correlation include the following:

- The asphalt mat temperatures corresponding to the final coverage (last pass) ICMV are generally in the lower temperature range where the asphalt binder viscosity is increasing, which will influence the rebound behavior of the roller drum;
- The influence depths of ICMV may vary after each roller pass due to the complex vehicle-surface interactions while the mix is compacted;
- ICMV influence depth at the final coverage may be deeper than the asphalt layer as materials density and stiffness increase in turn changing the rebound behavior of the roller drum;
- The ICMV were only measured during the breakdown and intermediate compaction while the gains/losses of in-place densities by the finish rollers, even though changes in density are likely small, may affect the correlation between final coverage ICMV and core densities;
- The uncertainties of IC data gridding and GPS precision may affect the accuracy of data extraction. Therefore, ICMV alone cannot be used for asphalt density-related acceptance.

IC-Based Density Model

Although no direct correlation between core densities and ICMV was identified, it does not mean there is no correlation at all between IC data as a whole and asphalt core densities. IC measurements include more than just the ICMV, after all. Therefore, a density model was developed to predict in situ density based on all IC-related measurements. Two types of density models were investigated during the development process for reliable density prediction: a Multivariate Linear Panel Density Model and a Multivariate Nonlinear Panel Density Model. Different forms of the latter were also developed: Model I and Model II. The models were implemented for analysis in an Excel spreadsheet using the Solver function to determine best-fit parameters based on IC-related measurements from the field. It was determined that the Multivariate Linear Panel Density Model provided improved correlation results and required only limited data for validation. Of the two models, Model I performed better with a vast majority of predictions falling within confidence levels. Linear regression was used to correlate the model-predicted density to asphalt core density data. The validation test results of the IC-based density model indicate good correlation between model-predicted densities and actual measured values. The level of correlation is similar to that between NDG and core densities. Therefore, the IC-based density model can used to predict density with similar accuracy as using NDG measurements.

Summary of Conclusions and Recommendations

The goal of this study was to determine if IC measurements can be used as a substitute for density measurements obtained from cores for acceptance testing. The IC technology was implemented at nine (9) sites. Additional in situ tests were conducted. All data were analyzed to determine whether any relationship or correlation between data collected exists.

The followings conclusions and recommendations are for implementing a successful IC field project:

- GPS validation prior to construction is critical to data quality assurance by ensuring all positioning system referencing and measurements are consistent. However, it is recommended to simply the current FHWA procedure to make it more practical.
- Usage of ground-based GPS stations or virtual GPS base stations can successfully provide high precision positioning only when set up and checked correctly. Lack of cellular coverage would not be suitable for a virtual GPS base station or internet-based GPS correction services. Being too close to a tree line or tree/foliage coverage would create GPS shadow and GPS will not work properly for both of the above solutions. The MD site is the most challenging one for GPS signals due to one of the construction lanes is being adjacent to a tree line with foliage coverage. In this case, other laser-based technique (TotalStation) can supplement the positioning measurements. Please note that lase-based equipment would add significant cost. Consistently obtaining good GPS satellite coverage and correction signals are critical to maintain the real-time kinematic (RTK) GPS mode or equivalent in order to measure positioning at a precision of within 0.5 inch.

- Universal Transverse Mercator (UTM) is recommended to be the choice of GPS coordinate system. Caution should be taken when using State Plane System with surface adjustment factors. All GPS devices for a given jobsite should be using the same coordinate system and referencing to the same GPS base station. Other coordinates are not recommended.
- Pre-mapping the existing granular bases for new construction projects with IC rollers at low frequency and low amplitude is recommended to better understand the existing support condition and identify possible soft spots. The soft spots may potentially affect compaction of upper asphalt layers.
- IC data transfer should be performed on a daily basis, either with a physical USB flash drive or downloaded from the Cloud. Buffering data on local devices are recommended to create redundancy and maintain data security to prevent data loss.
- Daily IC data quality checks are essential to produce reliable and quality data. The data QA process would include exporting all-passes and final coverage IC data with vendors' software to Veda-compatible forms. Then, those data shall be imported to Veda for map-based viewing and statistical analysis/histogram. It is then easy to identify any issues with the positioning from GPS signals, signal issues from all sensors, gridding process with vendors' software, incorrect roller settings, etc.
- All IC systems performed well during the field studies due to the following procedure:
    - Full IC system checkup/ trial runs and GPS validation tests were conducted a day prior to the construction.
    - The connection for temperature sensors was checked on a daily basis.
    - The computer docking station and similar within roller cabinet were checked daily to ensure full connection with the tablet PC or other IC display.
    - IC data QA were also performed on a daily basis.

The followings conclusions and recommendations are drawn from the analysis results of this study:

- Pass-by-pass NDG data and temperature data from various compaction curves and temperature drop curves for a given site can vary significantly even when the same materials, the same pavement equipment and the same work force were used. This indicates the complexity that exists to achieve desired in-place asphalt density on a daily basis.

- Based on the pass-by-pass NDG, temperature, and ICMV data, compaction is most effective at high temperature range and large gains in density are seen during the breakdown rolling. However, the specific high temperature range is dependent on the mixture type/thickness and asphalt binder grades. There were much lower gains in density during the intermediate and finish rolling phases. Therefore, these findings reaffirm the best practice is to focus on breakdown compaction within the higher temperature range to obtain optimum in-place asphalt density.

- Since the pass-by-pass ICMV data correlate well with NDG measurements during breakdown compaction, IC can be used as an enhanced tool for QC by monitoring the ICMV in real time during construction in order to maximize the window of opportunity for compaction.

- Since the final ICMV does not correlate well with core densities, the final ICMV data is not recommended to replace cores for acceptance. There are many likely causes of this, including differences in measurement depths and foot prints as well as the changes in drum rebound when asphalt temperatures drop below a certain threshold (e.g., glassy temperature) at which point the depth of ICMV measures beyond the compacted layer. There is also possible minor gain or loss of density due to finish compaction which would affect the above correlation.

- The IC-based density model predictions do correlate reasonably well with core densities by considering the ICMV, roller passes, roller vibration frequency/amplitude, and roller speeds. It makes use of panel model to capture family of compaction curves in spatial and temporal domains. It also includes a term to consider the gap between breakdown IC measurements and eventual core densities. With this IC-based density model calibrated with pass-by-pass NDG measurements and core density data from a test strip of a specific project, this model can produce predicted density values along with other existing IC measurements for enhanced QC during production compaction.

- The current IC technology can be readily used for method-based acceptance such as roller pass counts and coverage. It is recommended to require at least 70% of compacted areas with target passes or more. Cautions need to be taken when considering transition areas of adjacent rolling zones.

Recommended Future Efforts on IC Research and Implementation

The following are recommended future efforts to continually enhance IC technologies and push for broader implementation.

- The IC Road Map described in the TPF IC final report needs to be updated in order to provide industry guidance for future IC research and implementation:
  - *Track 1 – Equipment and Technologies (Standardization of IC roller measurement systems, Practical use of GPS in IC, Valid In-situ point tests to correlate with IC measurements).*
  - *Track 2 – Data Management and Integration (National IC database and data collection guidelines, Standardization of IC data storage and exchange, A software tool for IC data viewing and reporting).*
  - *Track 3 – Specification (National guidelines for IC QC/QA specifications, Expert Task Group - ETG for AASHTO IC specification development, Technical support for States spec customization).*
  - *Track 4 – Technology Transfer and Training (IC workshops/certification, IC field demonstration, IC website and knowledge base).*
- Since IC data management with Veda is one of the critical paths for IC implementation, the following are recommended to overcome data management-related issues:
  - *Upgrades and Improvements*: It is anticipated that a TPF IC data management project will be established from the *Solicitation No. 1381 "Enhancement to the Intelligent Construction Data Management System (Veda) and Implementation*" in order to fund and guide future improvements on Veda software. With FHWA as the liaison for this TPF project, it is recommended for the State DOTs which are implementing IC or will be implementing in the near future to join this pooled fund project in order to pool resources, share experiences, and prioritize upgrades and improvements on Veda to facilitate IC data management.
  - *Training and Implementation*: It is recommended that FHWA continue the IC data management training program and technical support center to meet the training needs around the country.
  - *Training the Trainers*: In order to reach out to all State DOT IC projects and provide timely support, it is recommended to conduct a "training the trainers"

    program at a yearly basis in order to produce DOT in-house IC experts for meeting the above needs. It is also recommended for this program to cover all IC manufacturers' systems.
  - *Industry Partnership with FHWA and DOTs*: It is also recommended for the industry to form partnership with FHWA and DOTs in order to develop IC data standards and improve IC data security, data sharing, and Veda-compatibility.
- Research on the influence depths of ICMV during asphalt compaction is recommended. This work can be accomplished by instrumenting geophones in the subgrade, subbase, and asphalt layers and monitoring vibration signals at these locations during each roller pass. The signals from geophones can then be compared with the accelerometer signals on the IC roller that produce ICMV by mapping each construction layers from the ground up. The intent is to understand better the rebound behavior of the roller drums when asphalt mix is being compacted and mix temperatures are dropping.
- Simplification and strengthening of the GPS setup and validation process is needed to ensure consistency of GPS records among different devices.
- Standardization of the color palette for IC data maps are recommended to facilitate consistent data interpretation. This would include color palettes for roller passes and temperatures. Simplified color palettes can also be standardized to provide roller operators simple color zones signifying under the desired level, at the desired level, and over the desired level, e.g., red, green, and blue for under, proper, and over compaction.
- Standardization of the IC data recording and gridding process is needed to ensure consistency of IC data among different IC vendors. A standard for binary IC data format is also recommended. This would help with integrating IC data collected with different IC systems during different stages of construction, e.g., from grading, subbase compaction, and asphalt compaction.
- Since FHWA will not dictate any new standardized ICMV, the current ICMVs from all manufacturers are expected to evolve to meet the industry demands.
- Since standards for IC component/system checks are needed to ensure IC systems meet the IC requirements and function properly, the following are recommended:
  - Individual accelerometer component needs to be checked with off-the-shelf "standard-traceable" test devices;

    - System check is needed once accelerometer is connected to an IC system by following a standard field procedure with independent "standard-traceable" devices and the range of measurements needs to be assigned correctly in the IC settings;
    - Individual temperature sensor needs to be checked with off-the-shelf "standard-traceable" test devices within a set tolerance;
    - System check is needed once temperature sensor is connected to an IC system by following a standard field procedure with independent "standard-traceable" devices, and the range of measurements needs to be assigned correctly in the IC settings to avoid incidents such as timing-out;
    - Suggested certification for the above with programs at a given time interval similar to those for certifying inertial profilers. A type-test may be employed to qualify new models of OEM to cover all machines of the same models. Therefore, OEM machines may be exempt for the above tests on accelerometers and temperature sensors.
- National guide specifications (e.g., FHWA or AASHTO): It is recommended to split national guide specifications into separate standards in order to provide standards that are practical and implementable by agencies and industry:
    - A Specification on IC Equipment (including IC and GPS system),
    - A Specification on IC Operation and Checks (including practical GPS validation, data transmission, data QA, standard color palettes for ICMV, roller passes, and temperature),
    - A Specification on Data Management (including standard data format, gridding algorithm, IC data maps, data analysis, and reporting).
- De-coupling ICMV are important to separate an ICMV to values that correspond to layer properties which will satisfy the interest of specific work such as grading, subbase, and asphalt paving. Therefore, such research is warranted to develop such de-coupling methods and analysis by utilizing multi-sensors, multi-layer pavement analysis, and real time back-calculation techniques.
- There are IC data related issues need to be resolved in order to provide agencies and industry reliable data for future forensic analysis and acceptance:

- IC data integration and security is important to prevent data loss and altering.
    - IC data standard should be in raw, ungridded, secured, binary form when submitted to agencies. Therefore, the data storage and transmission by contractors can be reduced and simplified. Also, it is recommended that the gridding process is performed by Veda to provide a consistent process and results and avoid any issues such as contract disputes.
    - IC data are recommended to allow redundancy for storage on local display devices and the cloud. Both wireless and local (USB) methods are allowed.
    - Simplification of data management and standard IC data format are recommended to speed up IC storage, transmission, and inspection.
- To maximize the potential benefits of the IC-based density models, the following efforts are recommended:
    - Improving the IC-based density models by considering multi-machine data of the entire rolling train is recommended to improve the correlation with core density.
    - Implementing IC-based density models as a re-usable computing component is recommended so that it can be used as a plug-in of vendors' real time IC monitoring systems to improve quality control. It is expected IC data and spot measurements with core and nuclear density gauge measurements (such as pass-by-pass density/temperature measurements) from a test strip can be used to calibrate the density model for a given project condition. Then, the calibrated density model can be used to produce density prediction as another map on an IC onboard display during production compaction.
- Based on the experiences of utilizing original engineering manufacturers' (OEM) IC systems for this study, it should be emphasized that IC system setup and checks are critical for IC systems to function as expected, especially regarding correct installation of accelerometers, temperature sensors, and GPS components by certified technicians. Therefore, cautions should be taken when using non-OEM systems or IC retrofits. Certification of technicians to perform IC retrofit installation is recommended. Field certification tests are recommended for both OEM and retrofitted IC rollers if IC is allowed to be used as an acceptance tool in the future either on method-based or end-results-based specifications.

- To leverage benefits of geospatial IC data, the following are recommended:
    - Quantification of uniformity is recommended with the combination of coefficient of variation (COV) and semivariogram.
    - Study on the relationship between uniformity indictors and long-term pavement performance are recommended by using a combination of numerical modeling and accelerated loading tests.

As of the writing of this report, IC technologies are still evolving. It is anticipated that further IC research as well as many enhanced IC-related products and services from the IC vendors will occur in the near future. With such momentum, the asphalt paving industry is anticipated to continue using the IC technologies to improve quality of road construction. The public will then benefit from longer lasting roads.

Chapter 1 Introduction

Background

Intelligent Compaction (IC) is defined as vibratory rollers equipped with accelerometers mounted on the axle of drums, survey-grade global positioning systems (GPS), infrared temperature sensors, and on-board computers that can display IC measurements as color-coded maps in real time (Figure 1). IC measurements include IC measurement values (ICMV), roller passes, asphalt surface temperatures, roller vibration frequencies/amplitudes, and speeds. More comprehensive resource on IC can be found on the IC website (www.IntelligentCompaction.com).

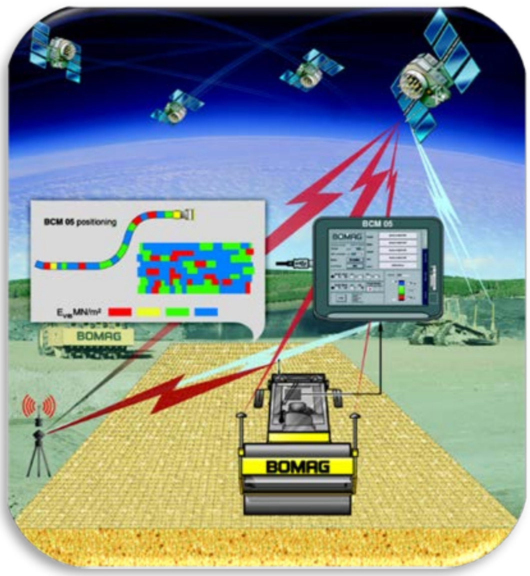


Figure 1. An illustration of intelligent compaction technology.

Asphalt in-place density, a common measurement for mix durability and performance, is influenced by many factors including material properties, the environment, paving, and compaction. Based on the compaction history captured by IC, a stochastic method was developed to correlate the IC measurements to asphalt in-place density, either measured with nuclear density gauges or from cores.

The Federal Highway Administration (FHWA) has been leading a national effort to advance the IC technology through Transportation Pooled Funded (TPF) IC project TPF-5(128) Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material. This TPF study, partnership with twelve (12) participating states, had achieved three primary objectives: develop IC specifications, develop a knowledgebase that includes experience for participating states, and identify and prioritize needed improvements.

The scope of this FHWA IC project is to conduct field demonstrations of the IC technology in the twelve (12) participating states on various material types including non-cohesive soils, cohesive soils, granular subbase, stabilized base, and asphalt materials in order to establish a knowledge base for further advancement and implementation of IC. Between 2007 and 2011, the FHWA IC research team had conducted sixteen (16) field projects around the US to validate and enhance the statistical correlation between IC measurements and asphalt in-place density. The validation data show that the critical period of initial breakdown compaction is the most dominating factor to achieve a desired density.

Current IC technology includes various real-time recording including the IC measurement values (ICMV). ICMV is a generic term for accelerometer-based measurements related to the stiffness of the computed materials as well as underlying materials where the influence depth depends on the roller types/weights, drum widths, operation settings (e.g., vibration amplitudes/frequencies and speeds), as well as the stiffness of various pavement layers. Density measurement is still commonly used for quality acceptance by most agencies because in-place densities often relate to long-term performance of asphalt or hot mix asphalt pavements. The field data collected under the study from 2007 and 2011 show unsatisfactory correlation between ICMV and asphalt core density. This is due to many factors such as the differences in nature of measurements between ICMV and in-place densities, limited core samples for being statistically significant, etc. In response to these results it was deemed essential to further study the correlation between ICMV and asphalt in-place densities. Therefore, a new FHWA IC project was initiated, funded solely by FHWA.

Under this new FHWA IC project (2011 to 2014), an extensive study was conducted to assess the correlation between the IC measurements and asphalt in-place densities. This work investigates the relationship between in-place asphalt densities and all IC-related measurements.

In this report, the results from the new FHWA IC project are reported. Field data collection and analysis were performed to study the correlation between IC measurements and asphalt in-place density. An IC-based density model was developed and validated to predict in-place asphalt density with the model consideration including ICMV, asphalt surface temperatures, roller pass counts, roller vibration frequencies/amplitudes, and speeds. Conclusions and recommendations were then drawn from the above analysis results.

Report Structure

This report is structured as follows:

- Executive Summary – It provides a concise summary and key points of this report.
- Chapter 1 – Introduction: It provides an overview of this report.
- Chapter 2 – Literature Review: It contains a detailed description of past IC research that relates to in-place asphalt density.
- Chapter 3 – Experimental Work: It describes the experiment designs of field experiment and data collection for this study.
- Chapter 4 – Data Analysis: It consists of GPS data verification, IC data analysis, correlation study between core density and nuclear density gauge measurements, correlation study between core density and ICMV, etc.
- Chapter 5 – Density Model Development and Validation: It describes the details of IC-based density prediction model development and validation with field data.
- Chapter 6 – Conclusions and Recommendations: It contains key conclusions from this IC study and recommendations for future IC improvements and research.
- References: It lists all literature referenced in this report.
- Appendix A – IC Data Analysis: It consists of the detailed IC data analysis for the key Day 2 tests of all field sites.
- Appendix B – Core Density and In Situ Test Data: It consists of the tabulated core density data and other in situ tests (including nuclear density gauge, LWD-a, and FWD test data) of all field sites.
- Appendix C – Validation of IC-Based Density Model: It consists of tabulated IC measurements, core density data, NDG density data for IC-based density model calibration and validation for all field sites.

Chapter 2 Literature Review

Past IC-Density Research

There are various efforts to evaluate the potential benefits of intelligent compaction and relate ICMVs and other measurements to in-place field density. Past researches have shown poor or inconsistent correlations between ICMVs and asphalt core density, which could be due to factors such as the influences of the IC systems (e.g., vibration frequency and amplitudes) and pavement conditions (e.g., underlying layer stiffness). In summary, these factors include the following:

- Stiffness indexes derived from ICMVs of existing IC rollers represent an integral pavement structure with influence depths normally deeper than those by point test devices such as the nuclear density gauge. That is, ICMV includes influences from deeper layers such as subbase and subgrade in additional top bound layers. Therefore, the industry has the needs to separate ICMV values to individual pavement structure layers in order to better utilize the ICMV. Though there were past research on this topic, these ICMVs are currently not yet decoupled successfully to characterize individual layer stiffness. See the discussion under the *NCHRP IDEA Project 145* for further details.
- The current ICMVs for asphalt are tied to temperatures at test conditions instead of being normalized to a reference temperature. On the other hand, core density is independent of in-situ temperatures. Therefore, it would result in unsatisfactory correlation between ICMVs and core densities.
- Asphalt cores are taken after finish rolling, while ICMVs are normally measured at breakdown or intermediate compaction. Therefore, there would be a gap of correlation created by the effects of intermediate and finish rolling.

FHWA/TPF IC Study (2007 to 2011)

The FHWA/TPF IC study was conducted between 2007 and 2011. Field demonstration projects are the major work under the FHWA-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. Sixteen (16) IC field demonstration projects were performed for non-cohesive soils, cohesive soils, granular subbase, stabilized base, and asphalt materials. There were twelve (12) asphalt IC projects on various types of bases, overlay, and new construction under this study. HMA IC rollers from BOMAG America, Inc. and Sakai America, Inc. were used during the above field demonstration.

The analysis results from FHWA-IC study have shown inconsistent correlations between ICMVs and nuclear density gauge (NDG) densities. From the FHWA-IC study, ICMV generally increases with increasing density measurements by NDG indicating that a higher stiffness corresponds with a greater material density. However, the correlation is often where the R^2 values ranges from 0.04 to 0.97. For the cases with more satisfactory correlation, it is often associated with larger number of in-place measurements on denser asphalt mixtures. On the other hand, cases associated with coarser mixtures such as the Stone Matrix Asphalt (SMA) in the Maryland demonstration often result in poor correlation. Therefore, consistent and repeatable NDG measurements are the keys for improved correlation with ICMV. The analysis results from FHWA-IC study have also shown inconsistent correlations between ICMVs and asphalt core densities. The correlation reverses for some cases such as the SMA overlay project in Maryland and new asphalt paving on the saturated base in Georgia.

As ICMV is potentially influenced by a number of factors, a multivariate analysis was conducted to include those factors as an attempt to improve the correlation under the FHWA-IC project (Xu et al. 2010; Chang et al. 2011). The factors included: ICMV from mapping the baseline structure, ICMVs during compaction of asphalt base courses, roller vibration frequencies, and asphalt surface temperatures during different stages of mapping and construction. The coefficients of determination, R^2, were improved for the multivariate linear regression compared to those from simple linear regression. For the Minnesota asphalt IC demonstration project, ICMVs from mapping the subbase as well as asphalt surface temperatures have shown significant effects on ICMVs during asphalt base course compaction. For the Wisconsin asphalt IC demonstration project, the most significant factors to the ICMVs during HMA compaction are: FWD deflections on the baseline structure, asphalt surface temperatures, and ICMVs from mapping the rubblized Portland cement concrete (PCC) subbase (Chang et al. 2011). Nonetheless, IC has been proven a practical tool for improving the quality control process through harmonization and standardization efforts in the US (Gallivan et al. 2011; Gallivan and Chang 2012). The FHWA IC team have also published numerous papers on various aspect of the IC technologies (Chang et al., 2014; Xu et al., 2010, 2011, 2012, and 2014).

Highways for LIFE IACA Project (2008 to 2010)

The intelligent asphalt compaction analyzer (IACA) is a device based on neural network technology to report the density of an asphalt pavement continuously in real time during its construction. The IACA uses a neural network to compare the vibrations of the vibratory compactor with known patterns of the vibrations and estimate the density/stiffness of the pavement. The IACA technology was developed and adapted for field study under the Highways for LIFE Technology Partnerships Program and Volvo Construction Engineering (Commuri 2009 and 2010). From this research, relatively high correlation was observed between IACA estimated density and NNDG measurements. Also, similar observation was found between IACA estimated densities and core and concluded that the IACA was a good tool for contractors' quality control operations. However, the IACA system is not ready for commercial production, and further independent verification study for acceptance is recommended.

Iowa DOT IC Study (2010)

The Iowa Department of Transportation (Iowa DOT) Intelligent Compaction Research and Implementation was initiated in summer 2009. There was one asphalt IC field demonstration project conducted at the IA 218 asphalt overlay project under the Iowa Phase I IC research to evaluate continuous compaction value (CCV) technology on the Sakai SW880 dual drum vibratory asphalt roller (White et al. 2010). The asphalt demonstration project under this study was performed to demonstrate mainly IC tracking capability for the asphalt surface temperatures and roller passes. Only qualitative analysis was performed to investigate the correlation between ICMV and core density by using approximate geospatial references of test locations. Correlation between ICMV and core density showed a moderate correlation with linear regression R^2 equaling 0.4.

Wisconsin DOT HMA IC Study (2010)

The Wisconsin Department of Transportation (WisDOT) conducted an asphalt overlay IC demonstration on US 45, during 2008-2009 (Von Quintus and Rao 2010). The goals of this project were to help WisDOT evaluate the advantages and limitations of IC for achieving density, and to determine the material types and conditions that might cause inaccuracies in IC roller output concerning layer stiffness and other properties. Caterpillar, BOMAG, and Sakai IC rollers were used for this study. However, the Caterpillar IC roller was not equipped with an accelerometer-based measurement system and the BOMAG IC roller was not equipped with a GPS. The main findings identified the IC benefits including:

1) the IC roller's on-board display unit shows color-coded image to ensure adequate number of passes;
2) mapping stiffness of the underlying layer; and
3) IC response corresponds to laboratory measured resilient modulus, etc.

For the asphalt IC, this research pointed out some issues including:

1) IC cannot prevent the intermediate or finish rollers from being operated in the temperature sensitive zone and reducing the density;
2) ICMV is heavily influenced by supporting layers; and
3) IC could not detect cold spots by stiffness measurements, etc.

The major issue for this research is that only printed strip charts from the BOMAG machines were used and no geospatial referenced data (i.e., GPS) were available for a more precise geostatistical analysis. Therefore, results and conclusions from this study may not be supported with sufficient evidence.

Minnesota DOT HMA IC Studies (2001 to 2011)

In 2001, a Minnesota Department of Transportation (MNDOT) showed that the thermal segregation affects the density. For example, profiles with the temperature difference below 25^{o} F (-3.8^{o} C) had 93% passing the density target, while those with the temperature difference higher than 25^{o}F (-3.8^{o} C) only had 50% passing the density target. In 2010, IC projects were conducted on TH 169 and TH 13. Results confirmed immediate IC benefits including:

1) map existing layers;
2) improve roller patterns;
3) improve roller operators' accountability;
4) improve density;
5) improve efficiency; and
6) increase information for QC/QA, etc.

It pointed out that the influence depth varies dependent on the technology and site conditions. This study encouraged IC's use as a construction aid to reduce thermal segregation, and suggested to install retrofit systems on an entire roller train (Johnson 2010). In 2011, MNDOT conducted an asphalt IC study on an I-35 project with several IC retrofit systems on a break-down roller, an intermediate roller, and a finish roller. The main goal was to track temperatures and roller passes, but there is no attempt to correlate ICMVs with in-place asphalt density.

NCHRP IDEA Project 145 (2013)

An improved ICMV model was developed to decouple stiffness for each pavement layer to improve the correlation of ICMV and in-situ spot measurements under the National Cooperative Highway Research Program (NCHRP) Innovations Deserving Exploratory Analysis (IDEA) project 145 "Extraction of Layer Properties from Intelligent Compaction Data." This study used numerical Finite Element Method and Boundary Element Method (FEM/BEM) as a forward model for the roller-soils systems and trained a neural network based on the FEM/BEM results to produce a stochastic method for real-time back-calculation to decouple the layer properties. The back-calculation model was demonstrated for a two-layer soils system but not asphalt pavement systems. This back-calculation model is influenced by IC measurement uncertainties and sensitivities of back-calculation parameters (e.g., E1/E2, and d1/d2 or ratios of layer stiffness and thicknesses).

Normalizing ICMV to a Referenced Temperature

For asphalt compaction, an improved ICMV model is recommended to normalize ICMV to a referenced temperature. ICMV represents a relative stiffness of pavement materials during compaction at elevated temperatures. The asphalt stiffness is dependent on temperature, while the asphalt density is independent of temperature. During compaction, the ICMVs are associated with the asphalt surface temperature measurements. If the master curve of the asphalt mixture is known, the ICMV can be shifted along the curve to represent a value at a desired reference temperature.

Geospatial Analysis for ICMV

The geostatistical analysis of the ICMV is recommended to account for the influence of geospatial dependency in order to improve the correlation study. The commonly adopted linear regression analysis is based on the generalized regression without considering the effects of geographical dependency such as autocorrelation.

IC Measurement Values (ICMV)

The IC Measurement Values (ICMV) used in the US include Compaction Meter Value (CMV), Hamm Measurement Value (HMV), Compaction Control Value (CCV), vibration modulus (E_{VIB}), soil stiffness value (K_b), and Machine Drive Power (MDP). The Hamm Measurement Value (HMV) is identical to CMV. The K_b and MDP are not included in the continuing FHWA IC study due to the machine availability for asphalt IC.

Compaction Meter Value (CMV)

CMV is a dimensionless compaction parameter developed by Geodynamik based on the phenomenon that different harmonic components of drum rebounds occur when compacting materials of different stiffness, displayed in Figure 2. CMV is influenced by roller dimensions, (i.e., drum diameter and weight) and roller operation parameters (e.g., frequency, amplitude, speed) (Thurner and Sandström 1994).

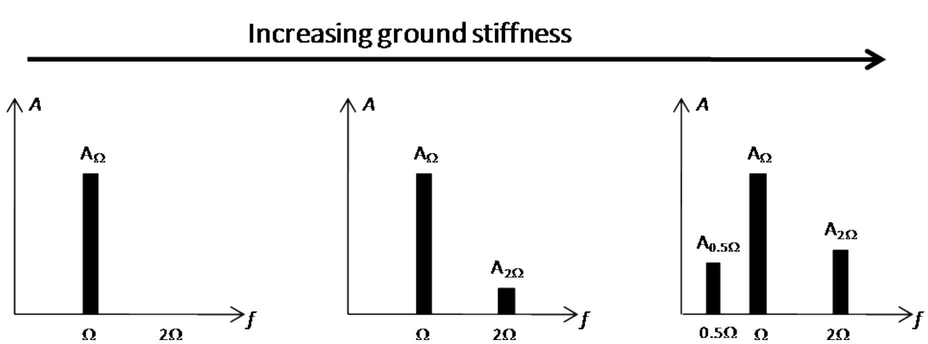


Figure 2. Changes in amplitudes of harmonics with increasing ground stiffness (Thurner and Sandström 1980).

CMV is calculated using Equation 1 (Sandström and Pettersson 2004).

$$\mathrm{CMV} = \mathrm{C}_1 \cdot \frac{\mathrm{A}_{2\Omega}}{\mathrm{A}_{\Omega}} \tag{1}$$

Where

C_1: a constant (e.g., 300);

$A_{2\Omega}$: amplitude at the second order harmonic frequency;

A_{Ω}: amplitude at fundamental frequency.

The Geodynamik system also measures the resonant meter value (RMV) 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. Dynapac reports this value as bouncing value (BV). Under the drum jumping condition, the drum behavior affects the CMV measurements (Brandl and Adam 1997) and therefore must be interpreted in conjunction with the ICMV measurements (Vennapusa et al. 2010).

$$\mathrm{RMV} = \mathrm{C}_2 \cdot \frac{\mathrm{A}_{0.5\Omega}}{\mathrm{A}_{\Omega}} \tag{2}$$

Where

C_2: a constant;

$A_{0.5\Omega}$: acceleration at a sub-harmonic frequency caused by drum jumping movement (i.e., the drum skips every other cycle).

Dynapac uses a preselected threshold BV as an indicator of roller jumping to adjust the amplitude in compaction under the auto-feedback control (AFC) mode. Similarly, Caterpillar uses RMV to adjust amplitude in compaction (White et al. 2009b). It was found that CMV increases monotonously with the stiffness of soil.

Compaction Control Value (CCV)

CCV is developed by Sakai based on a similar concept 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 displayed in Figure 3.

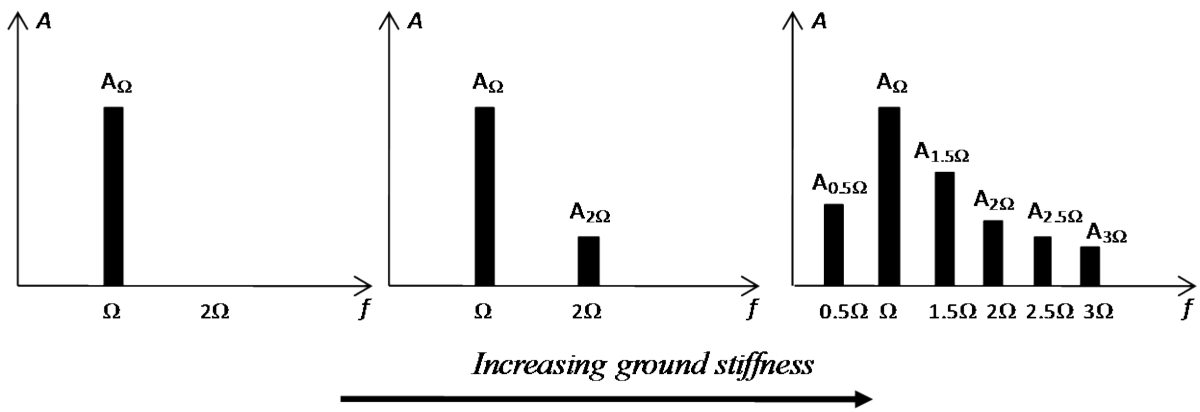


Figure 3. Changes in amplitude of spectrum with increasing ground stiffness (Scherocman et al. 2007).

CCV is calculated using Equation 3.

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

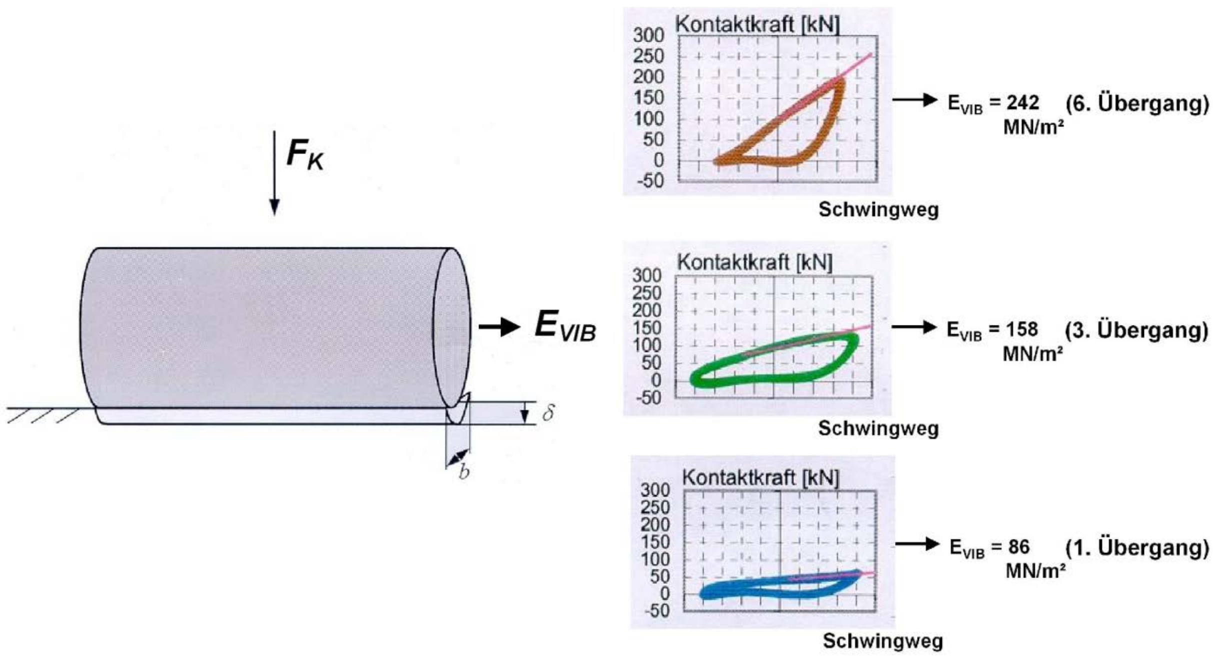
Where

$A_{1.5\Omega}$, $A_{2.5\Omega}$: amplitudes at sub-harmonic frequencies;

$A_{3\Omega}$: amplitude at the third order harmonic frequency.

Vibration Modulus (E_{VIB})

Vibration modulus (E_{VIB}) value is developed by BOMAG based on the one-degree-of-freedom lumped parameter model and Lundeberg's theoretical solution for a rigid cylinder sitting on an elastic half-spaced earth, displayed in Figure 4 (Hertz 1895; Lundberg 1939; Kröber et al. 2001).



(Courtesy of BOMAG)

Figure 4. The drum-on-grade model and changes of slopes of the drum loading curves.

The E_{VIB} value is back-calculated using Equation 4. The E_{VIB} value is related to the modulus determined from a static plate load test (Kröber 1988; Kröber et al. 2001).

$$z_d = \frac{(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L} \cdot \frac{2}{\pi} \cdot \left(1.8864 + \ln \frac{L}{Wd}\right) \quad (4)$$

Where,

η: Poisson's ratio of the material;

L: length of the drum;

F_s: roller-soil interaction force;

W_d: contact width of the drum, $W_d = \sqrt{\frac{16}{\pi} \cdot \frac{R'(1-\eta^2)}{E_{VIB}} \cdot \frac{F_s}{L}}$

R' : radius of the drum.

IC Data Basics

IC data are geospatial data that all measurements at a time and a location are associated with a GPS location in either latitude/longitude or northing/easting. Elevation data may be recorded but they are not currently used for analysis. IC data are generally in two forms: *Raw Data* and *Gridded Data*.

Raw Data: Raw data are recorded during compaction operations prior to the gridding process. Raw data consists of one data point for a roller drum at approximately 10 Hz or 1 ft. interval. Therefore, the data mesh or data foot print is about the drum width by 1 ft. Both vibratory and non-vibratory data are normally recorded.

Gridded Data: Gridded data are processed from raw data by refining the data mesh. Raw measurement data are duplicated over the meshes for the entire drum width (i.e., multiple data points cover the drum width). The refined data mesh size is generally 1 ft. by 1 ft. in horizontal directions. One of the purposes of this process is to track partial drum overlaps among passes. It is anticipated that the gridding rule will be included in a future standard.

The raw data and gridded data are illustrated in Figure 5.

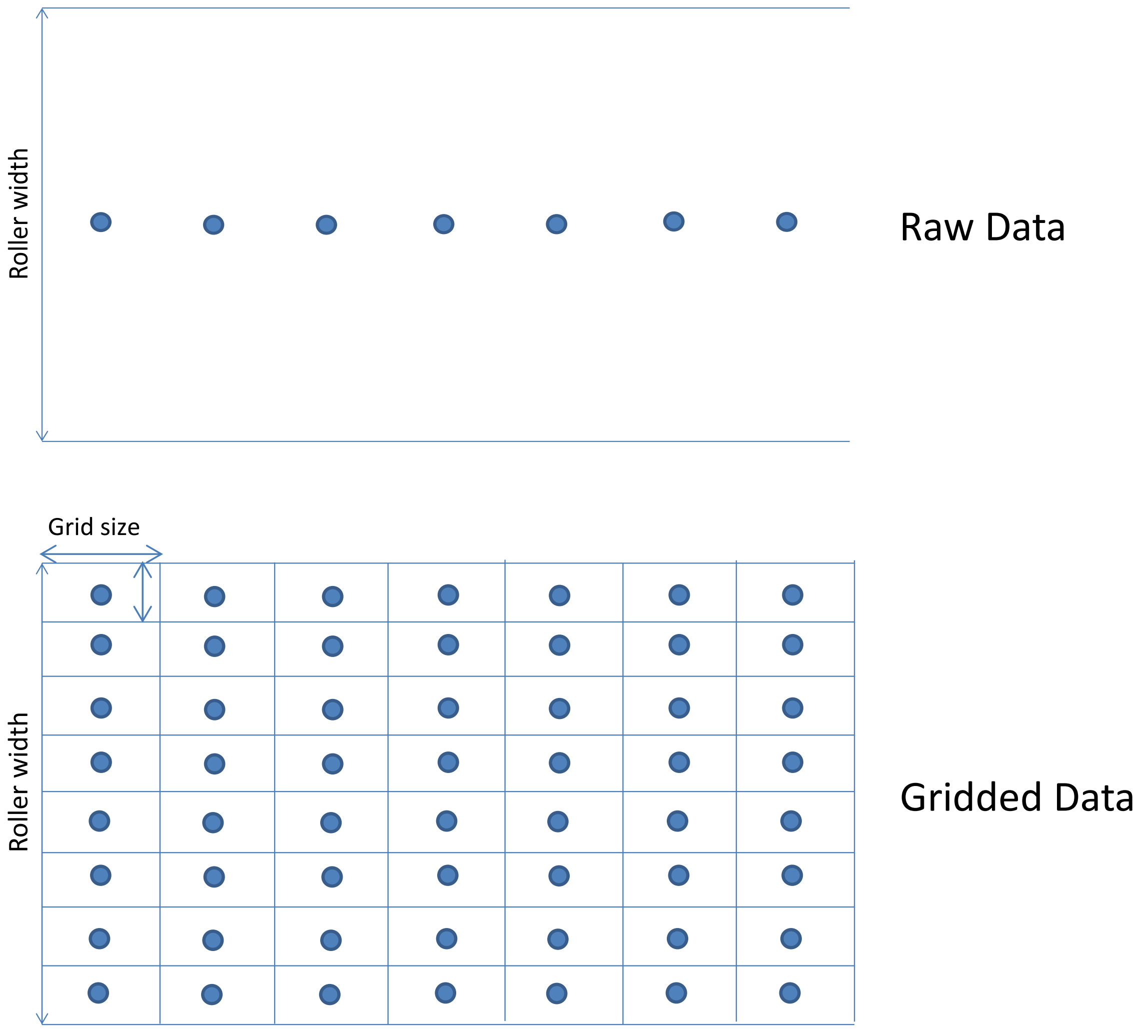


Figure 5. Raw data vs. gridded data.

The gridded data are in two sub-forms:

All-Passes Data: All-passes data include all measurements within a given mesh. All passes are generally used to build compaction curves in order to establish rolling patterns.

Final Coverage Data: Final coverage data contain measurements from the last passes within a given mesh. Final coverage data can be used to assess the end results of compaction.

Gridded all-passes data and final coverage data are illustrated in Figure 6. The all-passes data include entire time history of compaction while the final coverage data is a subset of the all-passes data to signify the last passes.

Further information regarding IC data can be found in the Intelligent Compaction Data Guideline document (Chang et. al, 2014).

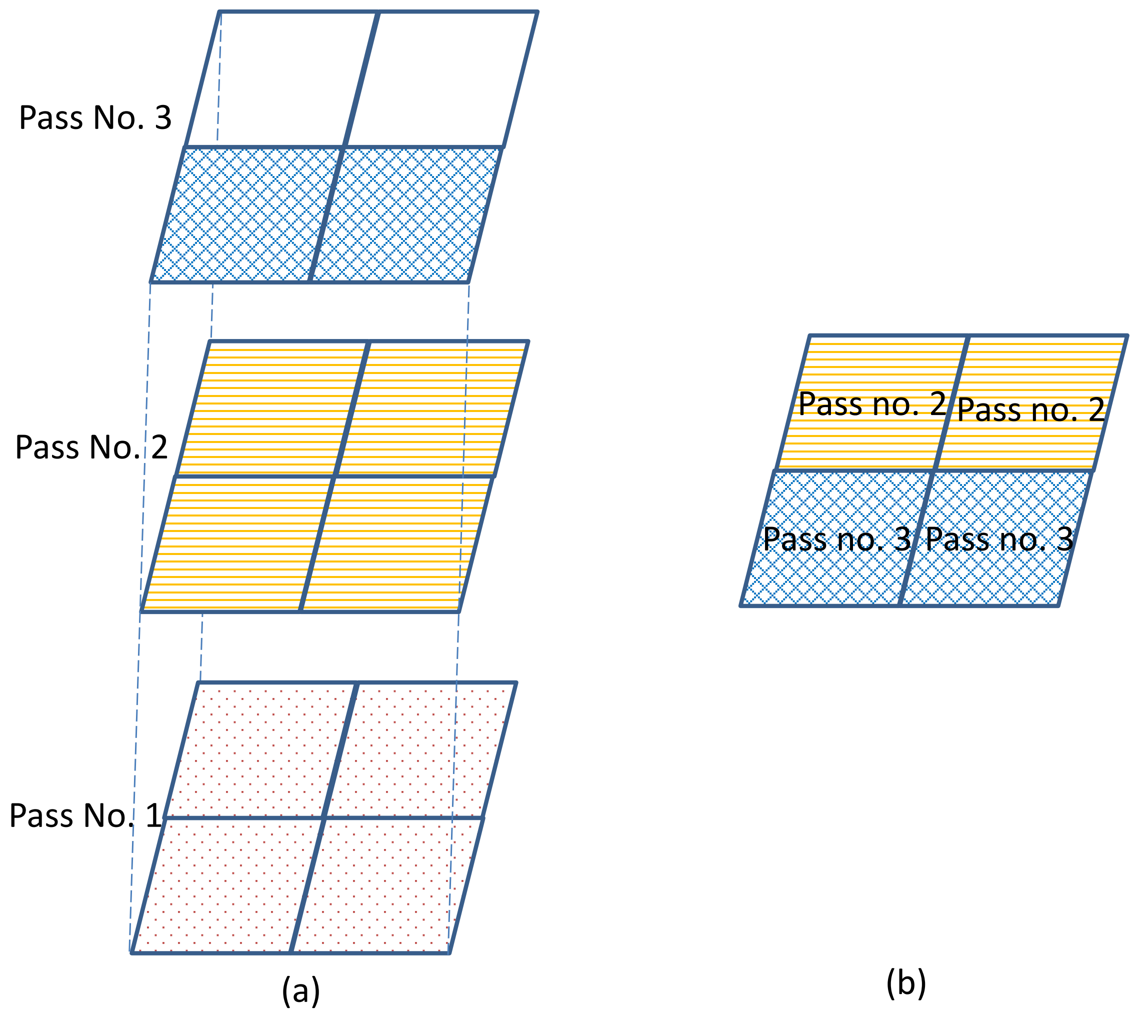


Figure 6. (a) Gridded all-passes IC data and (b) final coverage IC data.

Correlation Studies

When performing regression analysis and model development between IC data and point test data (such as core densities), care shall be taken to understand the mechanism, footprints, and influence depths of different measurements displayed in Figure 7. Depending on its weight and operational settings, a full size IC roller may measure up to 4 ft. (1.2 m) of influence depth with a 6 ft. (2 m) wide footprint based on past studies on soils IC. There are not known study on influence depths for asphalt IC.

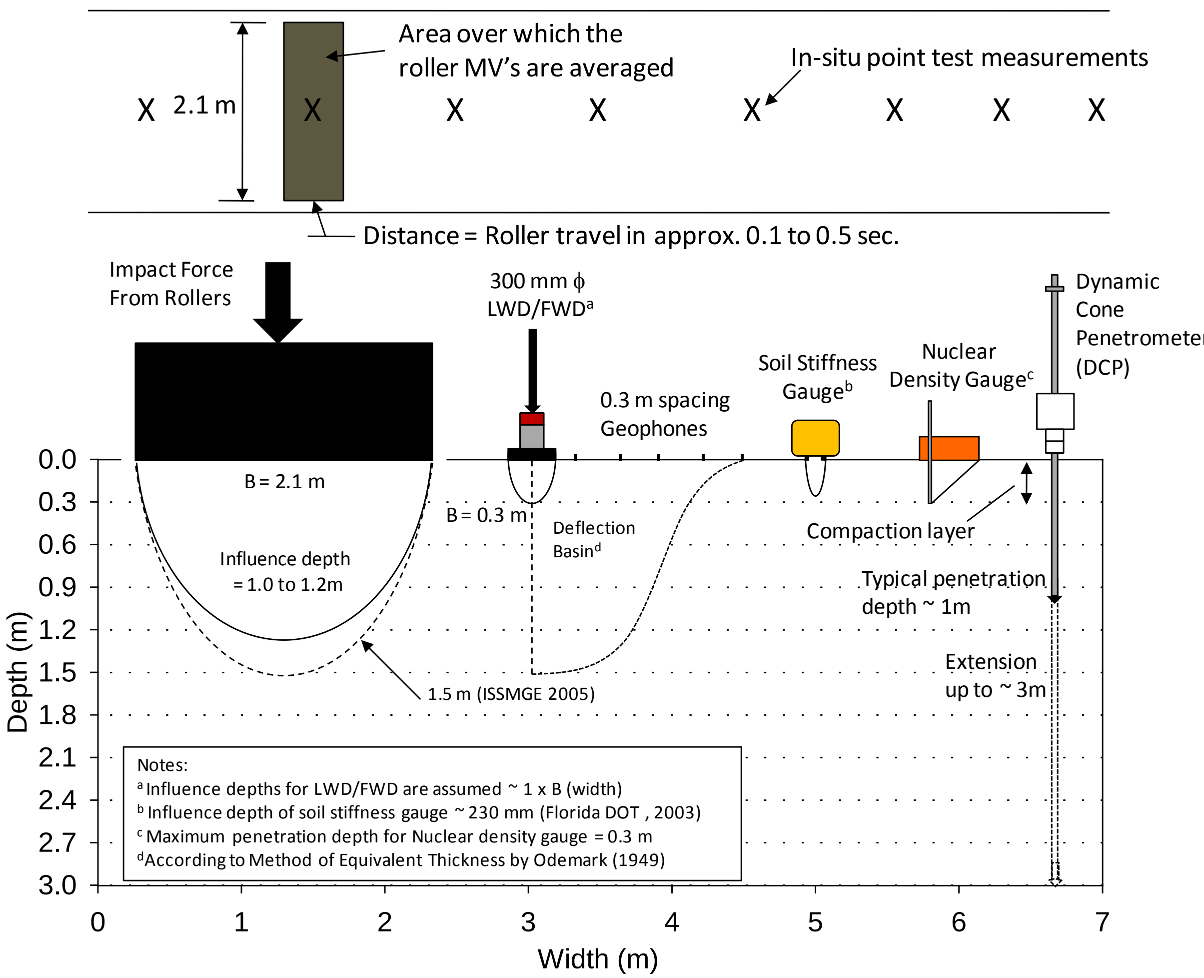


Figure 7. Influence depths for different measurements.

It is prudent to recognize the different nature of ICMV and density measurements. ICMV is related to stiffness of materials, while density is related to proportioning of materials. In-place asphalt density can be affected by many factors including mixture design (aggregate gradation and binder type), paving thickness (thus, thickness to nominal aggregate size ratio), mixture production/transport, paving equipment (especially whether the use of material transfer vehicle or MTV), confinement of paving lanes, compaction equipment (sizes of roller drums and operation weight), type of compaction (static/vibration/oscillation), number of roller passes, and operation condition, especially temperatures. There are many research performed by IC vendors to correlate ICMV and asphalt in-place densities in published, unpublished reports or in presentation. For example, good correlation between Evib and NDG measurements was observed within the range of 320°F to 212°F (160°C to 100°C) based on limited data in a past research (Kloubert and Wallrath, 2010).

The above complexity should be considered when interpreting simple linear correlation between in-place asphalt densities with any single measurement, such as ICMV.

Density
Proportion properties measured by laboratory bulk density tests or nuclear density gauge.

Stiffness
Mechanical properties measured by accelerometers to reflect drum rebounds during vibratory compaction.

Figure 8. Differences between density and stiffness measurements.

Chapter 3 Experimental Work

Experimental Design

The experimental framework of this study includes extensive data collection from nine (9) field sites to investigate the correlation of IC measurements and asphalt in-place density as well as to develop an IC-based density model for use. The selection of field sites was based on the diversity of climate, traffic, and construction types as well as availability of project windows. The location and distribution of IC project sites is illustrated in Figure 9. In 2012, field projects were conducted in Utah and Florida; in 2013, Ohio, Maine, and California; in 2014, Idaho, Maryland, Kentucky and Washington State.

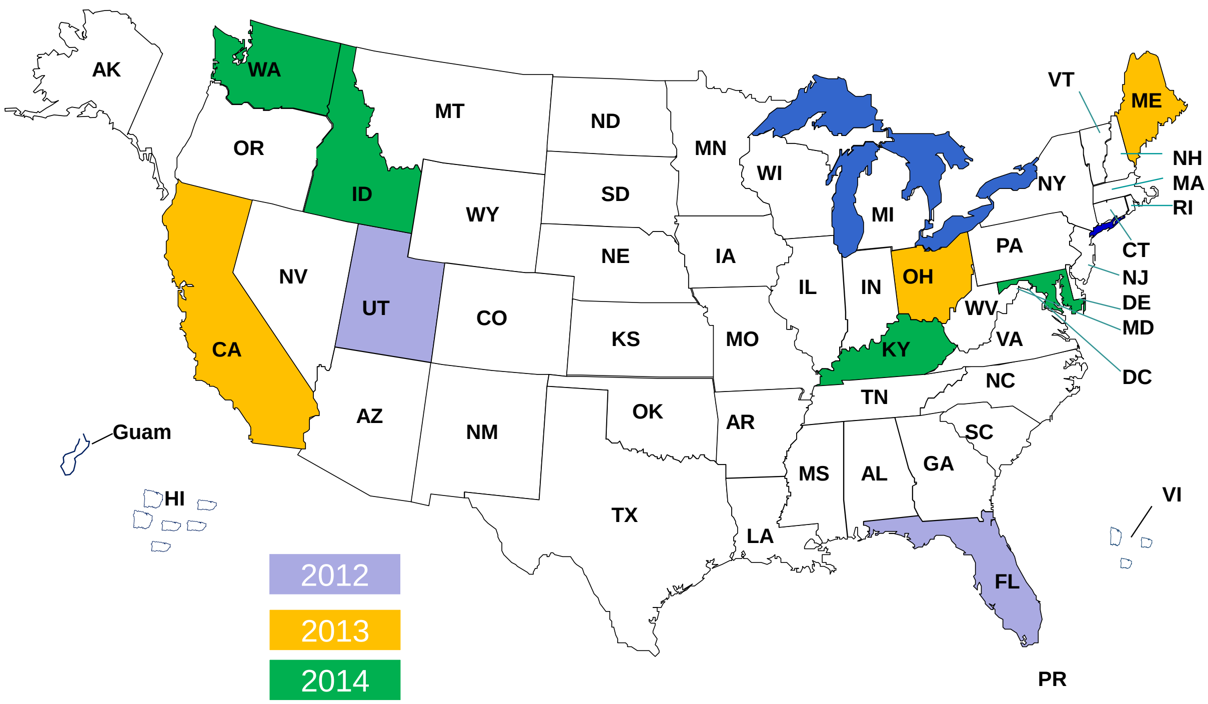


Figure 9. IC field sites.

For each field site, at least two IC rollers were used as the breakdown and intermediate rollers to collect IC measurements. Nuclear density gauges were used to conduct extensive asphalt in-place density measurements after the paver and each roller pass. After the finish rolling, 60 locations were marked for nuclear density gauge testing, temperature measurements, GPS, Light Weight Deflectometer (LWD) testing, and coring. The number of 60 cores was selected to reduce the variability and to approach the true mean value based on the sampling theory of National Bureau of Standard Handbook 91 (Natrella, 1963). The four-inch cores were then tested in asphalt laboratories for bulk density.

The following sections consist of details of the experimental work.

IC Rollers

The IC rollers used in this study include double drum IC rollers by BOMAG, Caterpillar, Hamm, and Sakai. The BOMAG double drum IC rollers are generally equipped with Trimble GPS and BOMAG AsphaltManager hardware and software. The Caterpillar double drum IC rollers are generally equipped with Trimble GPS and Trimble CCS900 hardware and software as well as the wireless data transmission to Trimble Connected Community (TCC) and VisionLink web software. The Hamm double drum IC rollers are generally equipped with Trimble OmniSTAR GPS and Hamm Compaction Quality (HCQ) hardware and software. The Sakai double drum IC rollers are generally equipped with TopCon GPS and TopCon SiteLink3D hardware and web software. The technical specifications, images of IC rollers, and onboard/offline IC software for all IC systems used in this study are presented in the following tables and figures.

Table 1. A typical technical specification of a BOMAG double drum IC roller.

Manufacturer/ Vendor	BOMAG
Model	VarioControl
Model Number	BW 278AD-4
Drum Size	78” (front) and 48” (rear) dia. x 78” wide
Machine Weight	23,900 lbs. (~ 10.84 tons)
Amplitude Settings	0.019” (low) and 0.029” (high)
Frequency Setting/ Range	4,000 (high) 3,400 (low) vpm
Auto-Feedback	Yes
Measurement System	Evib with temperatures and passes mapping
Measurement Value	Evib
Measurement Unit	MN/m^2
GPS Capability	Yes
Documentation System	BCM 05 Office and Mobile with the capability to export to Veda

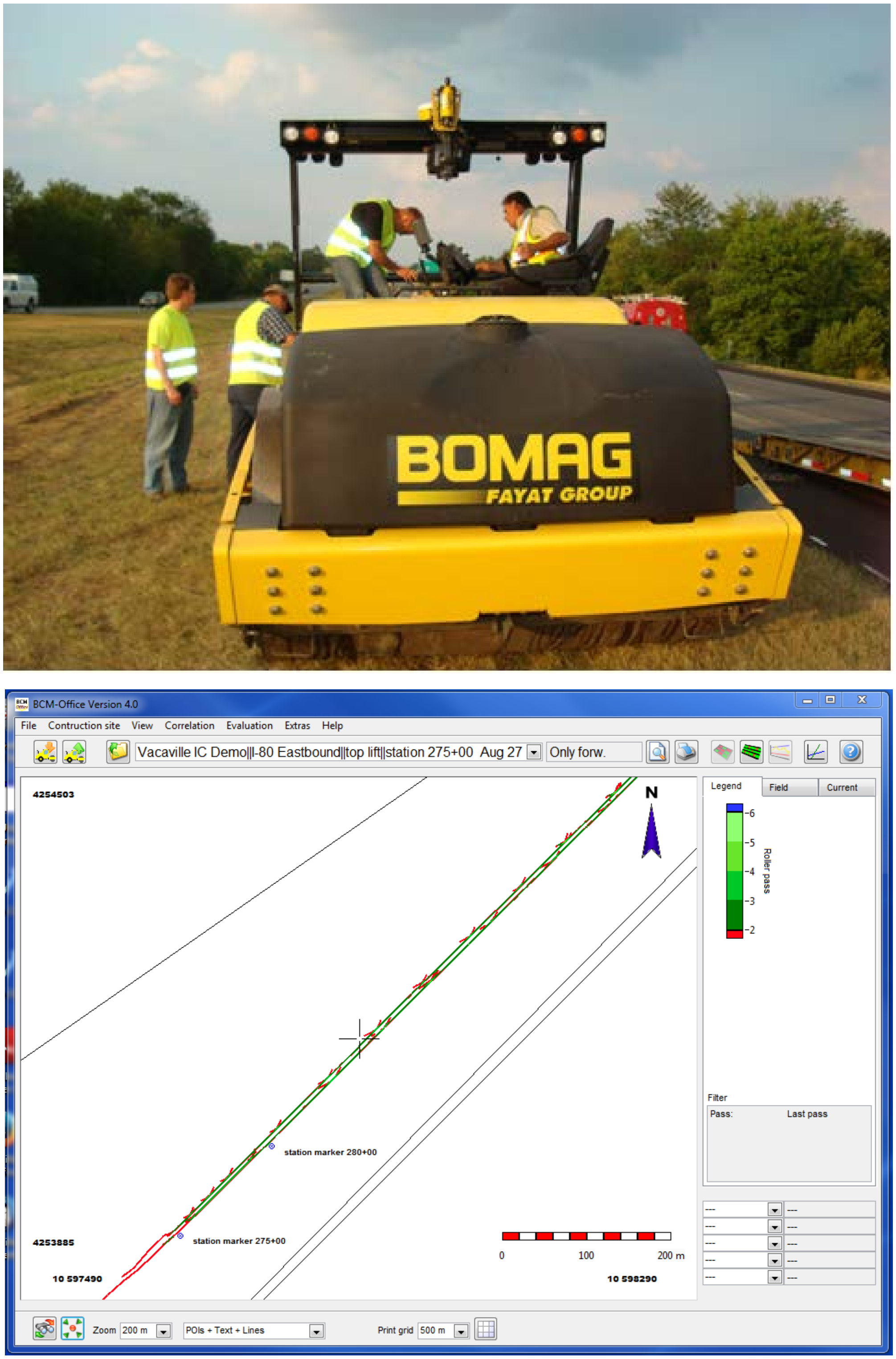


Figure 10. A BOMAG double drum IC roller and AsphaltManager software.

Table 2. A typical technical specification of a Caterpillar double drum IC roller.

Manufacturer/ Vendor	Caterpillar
Model Name	Tandem vibratory rollers
Model Number	CB54XW
Drum Width	79”
Machine Weight	Operating wt. 26,230 lbs.
Amplitude Settings	0.034 – 0.012”
Frequency Settings	2,520 and 3,800 vpm
Auto-Feedback	NA
Measurement System	Compaction Meter Value (CMV)
Measurement Value	CMV
Measurement Unit	[unitless]
GPS Capability	Yes
Documentation System	VisionLink with the capability to export to Veda

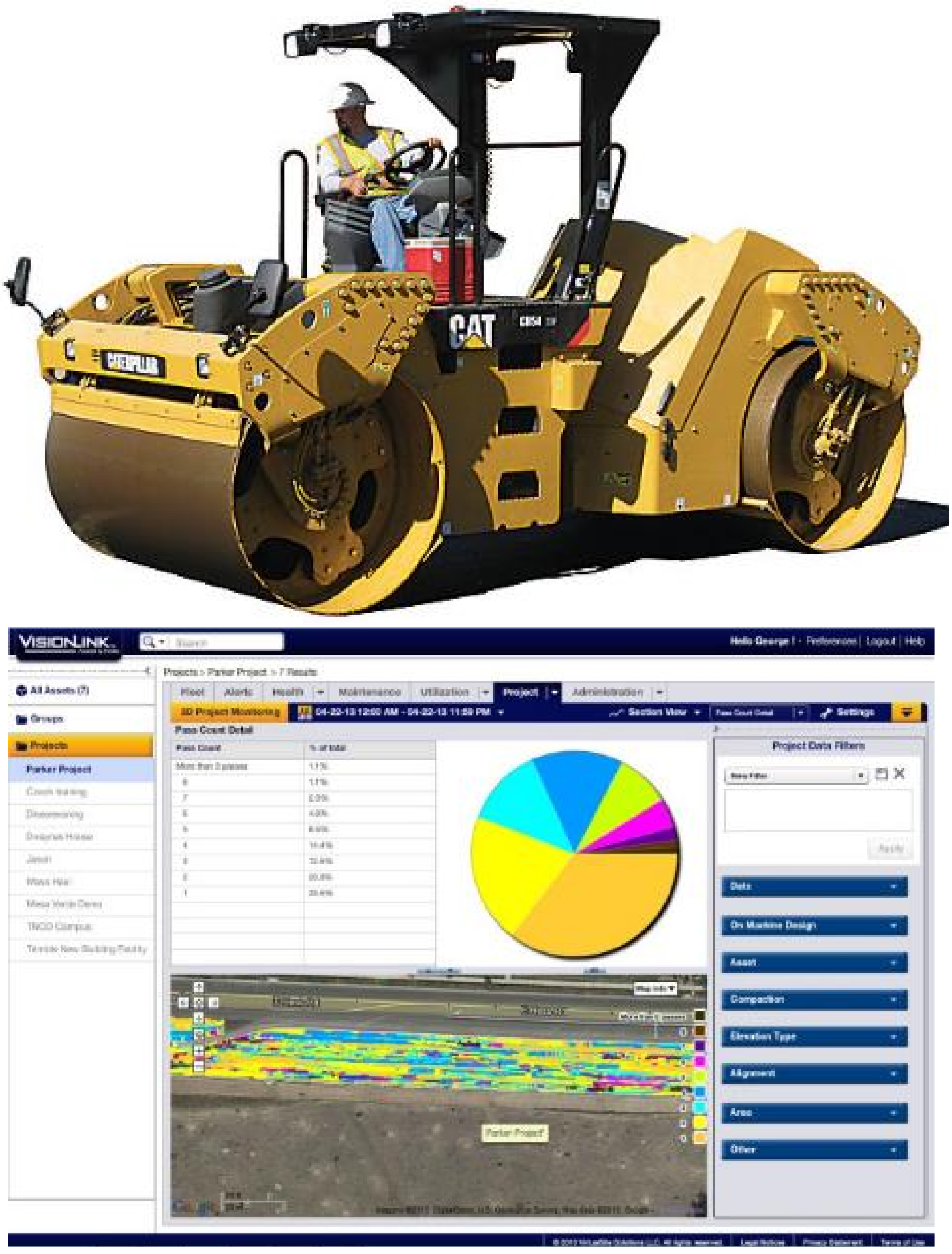


Figure 11. A Caterpillar double drum IC roller and VisionLink web software.

Table 3. A typical technical specification of a Hamm double drum IC roller.

Manufacturer/ Vendor	Hamm/Wirtgen
Model Name	HCQ (Hamm Compaction Quality)
Model Number	HD+140VVHF
Drum Width	84”
Machine Weight	Operating wt. 28,936 lbs. w/ max of 31,509 lbs.
Amplitude Settings	High/Low - .03/.01 in.
Frequency Settings	Variable from 2700 - 4020 vpm
Auto-Feedback	NA
Measurement System	Hamm Compaction Quality (HCQ)
Measurement Value	HMV, density estimator, temperature, passes
Measurement Unit	[unitless, % compaction, °C/, color coded]
GPS Capability	Yes
Documentation System	HCQ with ability to export to Veda

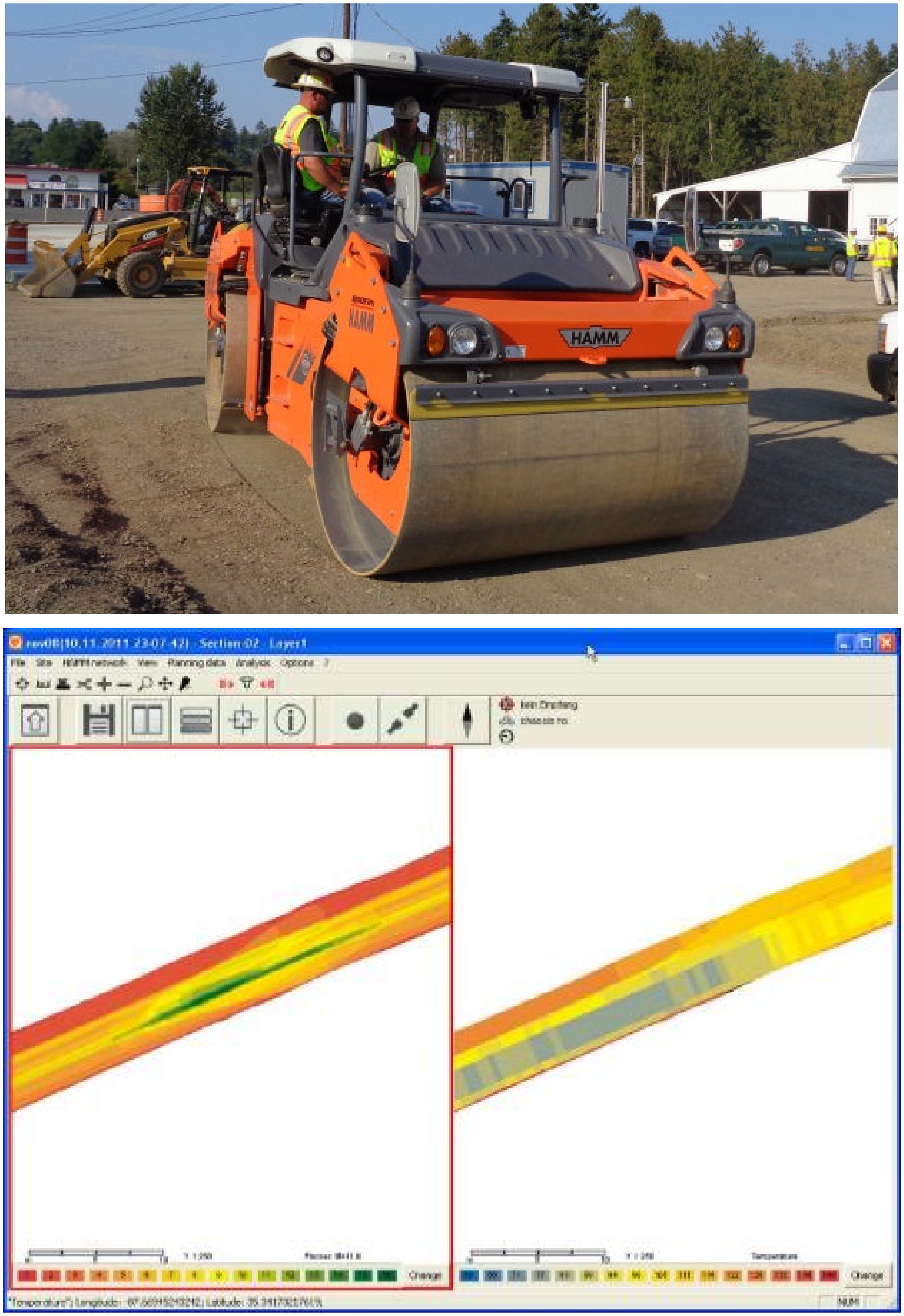


Figure 12. A Hamm double drum IC roller and HCQ software.

Table 4. A typical technical specification of a Sakai double drum IC roller.

Manufacturer/ Vendor	Sakai America
Model Name	Compaction Information System (CIS)
Model Number	SW880
Drum Width	79”
Machine Weight	29,560 lbs (~ 14 tons)
Amplitude Settings	0.013” , 0.025” (0.33 to 0.64 mm)
Frequency Settings	2500, 3000, 4000 vpm
Auto-Feedback	No
Measurement System	CCV with temperature and passes mapping
Measurement Value	Compaction control value (CCV)
Measurement Unit	Unitless
GPS Capability	Yes
Documentation System	TopCon SiteLink web service with the ability to export files to Veda

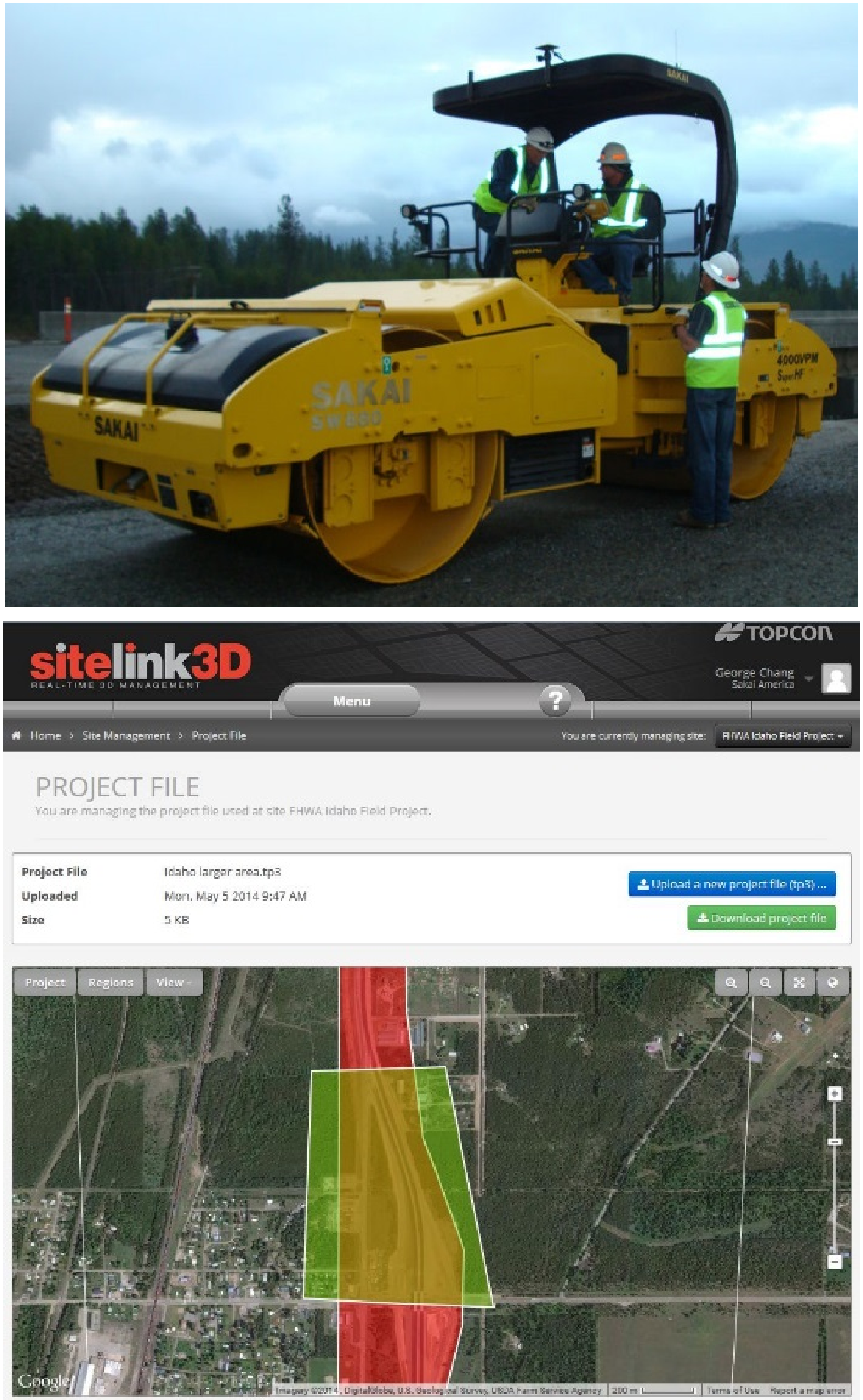


Figure 13. A Sakai double drum IC roller and SiteLink3D web software.

In Situ Test Devices

Nuclear Density Gauge (NDG)

The nuclear density gauge (NDG) was used to measure the densities of HMA materials, as shown in Figure 14. The nuclear density gauge measures the in-place material density based on gamma radiation. A NDG usually contains a small gamma source (about 10 mCi) such as Cesium-137 on the end of a retractable rod.

The device consists of a handle, a retractable rod, the frame, a shielding, a source, and a Geiger-Mueller detector as shown in Figure 14. 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 (see Figure 14). All test sites make use of the back scattering method. Only the Washington State site used the direct transmission method.

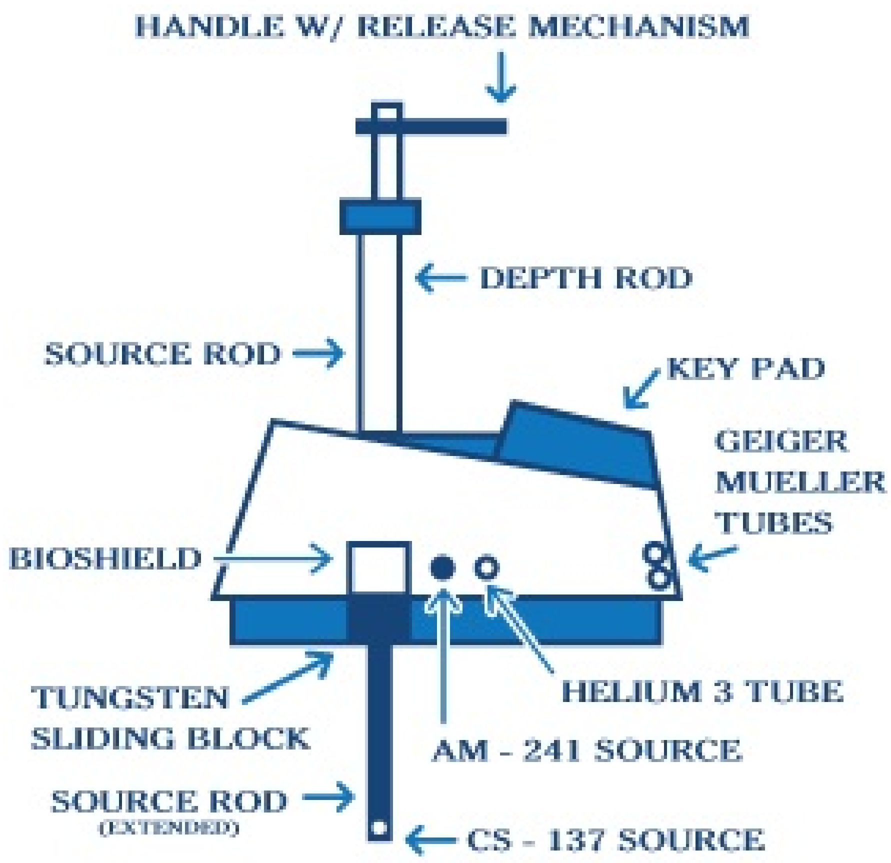


Figure 14. Nuclear density gauge mechanism.

Falling Weight Deflectometer (FWD)

The FWD test data were collected using various devices such as JILS-FWD (Figure 15), if provided by DOTs. The test was performed on the base or intermediate asphalt course. For each test site, there were 30 test locations at 50 foot intervals. The typical test settings were as follows:

- Platen Size: 5.9 inch radius (rigid plate)
- Geophone positions: 0, 8, 12, 18, 24, 36, 60 inches (7 sensors)
- Drops/Loads: 2 drops targeting 9,000 lbs
- File format: *.DAT, and *.THY (time history)

The back-calculation was performed using a Transtec Group software based on the linear elastic layer theory to obtain layer moduli. Deflections at the sensor no.1 were normalized to those w.r.t. 9,000 lbs load.

Figure 15. JILS-FWD equipment.

Light Weight Deflectometer for Asphalt (LWD-a)

The LWD data were collected using a Zorn ZFG 2000A device (Figure 16), if provided by Kessler Engineering. This LWD is designed for testing freshly paved HMA layers. The test settings were as follows:

- Drop mass: 22 lb. (10 kg)
- Drop height: 21.25 inches (54 cm)
- Force: 1,412 lbf (6.28 kN)
- Stamp size: 1.2 or 2.0 inches (30 or 50 mm)
- Pulse time: 17 ms
- Pressure range: 72.5 to 145 ksi (500 to 1,000 MPa)

The collected data for each drop includes the deflections in time series, the drop speed, etc. By using the deflection data collected from these sensors, the modulus of pavement layers were back-calculated by Zorn's software program and normalized to values w.r.t. 78 ºF (20 ºC).

Figure 16. LWD-a equipment.

Description of Field Sites

The description of IC field sites is shown in Table 5. The field sites were selected to maximize the diversity of climate zones, traffic levels, and construction types, and layer thicknesses. Thus, the data collected would not be bias toward certain condition. The IC roller selection was based on the FHWA IC team's recommendation and paving contractors' preferences.

Table 5. Description of IC field sites.

State	Location	Construction Type	Asphalt Layer	IC Rollers
UT	US-89, Lehi	overlay	2.5" base course	Hamm, Sakai
FL	I-95, Brevard	overlay	1.5" base course	Hamm, Sakai
OH	I-71, Morrow	overlay	1.75" base course	Hamm, Sakai
ME	I-95, Island Falls	new construction	2" intermediate course	Caterpillar, Hamm
CA	I-80, Solano	overlay	3" intermediate course	BOMAG, Caterpillar, Hamm
ID	US 95, Garwood	new construction	2" base course	Hamm, Sakai
MD	MD 170, BWI	overlay	2" base course	Caterpillar, Hamm
KY	I-65, Hart County	new construction	4" base course	Caterpillar, Hamm
WA	SR 539, Lynden-Aldergrove	new construction	4.5" base course	Caterpillar, Hamm

The Utah site is an asphalt overlay project on US-89 in Lehi, UT. Nighttime paving was conducted. The project consists of a mill-and-fill of one lane in each of the northbound and southbound directions. Four inches (100 mm) of the existing pavement were milled from the existing pavement prior to the asphalt overlay. The new layers include an asphalt base course (2.5 in. or 64 mm) and a stone matrix asphalt (SMA) wearing course (1.5 in. or 38 mm) with a cross slope of 2%. IC was used for the construction of the base course only. Approximately three miles (4.8 km) of this construction was identified as a test section for data collection. This section was further divided into test beds and labeled numerically. Test Bed 02 includes the coring section and is located on the northbound lane of US-89. A Hamm IC roller (HD+120VVHF) was used at the breakdown position and a Sakai IC roller was used at the intermediate position. Further details are in the Utah IC Demonstration Report (Chang et al., 2012).

The Florida site is located on I-95 in Brevard County, FL. The project consists of a mill-and-fill of the travel lane (outside lane) in the northbound direction. Paving was conducted in two lifts at night behind construction barrels between Stations 2432 and 2452 for 2,000 feet (610 m). Based on the core information of the existing pavement before paving, the average asphalt layer thickness was 7.81 inches (198 mm), and the base layer thickness was seven inches (175 mm). It was a mill-and-fill operation with two 1.5-inch (37 mm) lifts of HMA base course. The bottom lift of the base course was the focus of this study. Test Bed 02 includes the coring section and is along the northbound travel lane of I-95. A Hamm IC roller (HD+120VVHF) was used at the breakdown position and a Sakai IC roller was used at the intermediate position. Further details are in the Florida IC Demonstration Report (Chang et al., 2013).

The Ohio site is located on I-71 in Morrow County, OH. Paving was conducted on the northbound lanes between junctions SR 95 and Mt. Gilead-Fredericktown road during day time hours. The project consisted of new asphalt construction for two sections 24 feet (7.3-m) wide and an inside shoulder in the northbound direction. The pavement layers are (from the bottom up): six to eight inches (150 to 200 mm) of 304 aggregate stone base, 10 inches (250 mm) of 302 asphalt concrete base, 1.75 inches (19 mm) of intermediate course, and 1.5 inches (12.5 mm) of surface course. The IC technology was used to construction the 1.75 inch (19 mm) intermediate course, which was the focus of study for this site. The Test Bed 02 location that includes the coring section is in the northbound direction of I-95. The Sakai IC roller was used as the breakdown roller with the front drum vibrating at the high frequency and low amplitude settings. The Hamm IC roller (HD+120VVHF) was used as the intermediate/finish roller with the front drum vibrating at the high frequency and low amplitude settings. Further details are in the Ohio IC Demonstration Report (Chang et al., 2013).

The Maine site is located on I-95 from Island Falls to Oakfield, ME. This project is new asphalt construction in the northbound direction. Two main lane sections, each 25 feet (7.6-m) wide, and an outside shoulder 10 feet (3 m) wide were paved. The total paving length was approximately 12,000 feet or 2.3 miles (3657.6 m or 3.7 km). The pavement layer information is as follows: 12 inches Aggregate Base (hard, crushed stones), two inches (12.5 mm) intermediate course, and two inches (12.5 mm) surface course. The intermediate course consists of a 12.5 mm – coarse-graded HMA mix with 20% RAP from drum mix plant No. 32 in Smyrna. The binder grade is PG64-28. IC technology was used to construct the two-inch (12.5 mm) intermediate course. A test section and test beds were identified for data collection. The Test Bed 01 location is on the northbound outside shoulder and the main lane. The Test Bed 3 location is on northbound main lane. The Hamm IC roller (HD+120VVHF) was used as the breakdown roller while the Caterpillar IC roller (CB54B split drum) and a conventional pneumatic roller were used alternatively as intermediate and finish rollers. Both IC rollers were operated at low amplitude and high vibration frequency. Further details are in the Maine IC Demonstration Report (Chang et al., 2013).

The California site is located on I-80 in Solano, CA. Three main lane sections were paved. The total paving length was approximately 6,634 feet or 1.26 miles (2022 m or 2.0 km). This project is a long-life asphalt pavement in the eastbound direction of I-80. The pavement layer information is as follows (from bottom up):

- Existing cracked-and-seated PCC or HMA
- HMA leveling course (PG 64-10)
- 0.25 ft intermediate HMA (25% RAP Long Life) (PG 64-10)
- 0.2 ft HMA (15% Max. RAP Long Life) (PG 64-28PM)
- 0.1 ft HMA- overlay

A geosynthetic pavement interlayer was placed on top of the HMA leveling course prior to the intermediate HMA course paving. IC was used to construct the intermediate HMA course of the eastbound lanes. A test section and test beds were identified for data collection. The Test Bed 01 location is on eastbound lanes 1 and 2. The Test Bed 02 location is on eastbound lane 3. The Hamm (HD+120VVHF) and Caterpillar (CB54B) IC rollers were used as the breakdown rollers in echelon. The BOMAG IC roller was used as the intermediate roller while a conventional steel drum roller was used as the finish roller. Further details are in the Florida IC Demonstration Report (Chang et al., 2013d).

The Idaho site is located on the main lanes of US 95, north of Coeur d'Alene, ID. This project is a new construction with a two-inch base course. The Test Bed 02 location is on northbound lane 3 which is the focus of this field study. The Hamm IC roller (HD+120VVHF) was used as the breakdown roller. The Sakai IC roller (SW 880) was used as the intermediate roller. A conventional steel drum roller was used as the finish roller. A premapping on the granular base was also performed with the Hamm and Sakai IC rollers. Further details are in the Idaho IC Demonstration Report (Chang et al., 2014).

The Maryland site is located on MD 170 next to the Baltimore Washington International (BWI) Airport. It was a mill-and-fill project with a two-inch base course. The Test Bed 02 location is on the southbound travel lane which is the focus of this field study. The Caterpillar IC roller (CB54 XW) was used as the breakdown roller. The Hamm IC roller (HD+120VVHF) was used as the intermediate roller. After half of Test Bed 01 was compacted, the Hamm IC roller was used as the breakdown roller while the Caterpillar IC roller was switched to the intermediate position. The majority of Test Bed 02 areas were next to trees that blocked GPS reception. Further details are in the Maryland IC Demonstration Report (Chang et al., 2014).

The Kentucky site is new construction of additional lanes on I-65 in Hart County between Horse Cave and Munfordville (MP 58 – MP 65). The following is the typical section for this portion of the project. IC technology was used to construct the 4.5-inches base course on top of asphalt stabilized granular base.

- 1.5 inches 0.38A CL4 76-22
- 3.0 inches 1.0D CL4 76-22
- 3.5 inches 1.0D CL4 64-22
- 4.5 inches 1.5D CL4 64-22
- 4.5 inches 1.5D CL4 64-22

- 6 inches ATDB
- 7 inches DGA

The Test Bed 02 location is on both the southbound traveling lane and northbound traveling lane which is the focus of this field study. The Hamm IC roller (HD+120VVHF) was used as the breakdown roller. The Caterpillar IC roller (CB54 XW) was used as the intermediate roller. Further details are in the Kentucky IC Demonstration Report (Chang et al., 2014).

The Washington State site is located on SR 539 in Whatcom County, WA from MP 14.34 to MP 15.16. It was a new constructions with a 4.5-inches base course. The total length of this project is 2,500 feet with three lanes of construction. The lane widths range from 13 to 14 feet. The paving direction was from the north to the south. IC technology was used to construct the base layers for all three lanes. Test Bed 02 is located on the base course of the northbound left lane and middle lane which is the focus of this field study. The Hamm IC roller (HD+140VVHF) was used as the breakdown roller. The Caterpillar IC roller (CB54 XW) was used as the intermediate roller. Either a conventional Sakai roller or Ingersoll Rand roller was used as the finish roller. Further details are in the Washington State IC Demonstration Report (Chang et al., 2014).

Field Activities and Roller Settings

On-site activities for each field site started with a half-day IC setup and GPS validation followed by three days of IC field operation (construction with IC, testing, and data collection) and a half-day Open House activity. A typical schedule of on-site activities for each field site is listed in Table 6.

Table 6. A schedule of typical on-site activities for a field site.

Schedule	Activities
Day 0	• Conduct IC rollers/GPS setup and trial runs (equipment vendors and FHWA IC team only) at the staging area (2PM-4PM). • Conduct project briefing at the staging area and IC training for roller operators (4PM-5PM).
Day 1	• Conduct project and safety briefing at the staging area (5:30AM). • Set up the GPS base station and IC roller/GPS system (6AM). • Start paving with one IC roller at breakdown and another IC roller at intermediate positions. • Select a 500-ft section as a test strip to establish the rolling pattern. Conduct NDG/GPS/LWD-a testing immediately behind the paver and at selected locations after each breakdown and intermediate roller pass within the test strip. • Perform production compaction using the rolling pattern. • Conduct NDG/GPS/LWD-a at selected locations after the finish rolling.
Day 2	• Set up the GPS base station and IC roller/GPS system (by 6AM). • Start paving with one IC roller at breakdown and another IC roller at intermediate positions. • Conduct NDG/GPS/LWD-a testing immediately behind the paver and at selected locations after each breakdown roller pass within the 1500-ft section. • Conduct NDG/GPS/LWD-a testing at selected locations after each intermediate roller pass within the 1500-ft section. • After the finish rolling, mark 60 locations within the 1500-ft paved section. Conduct NDG/GPS tests at marked locations. Conduct FWD, GPS, and LWD-a tests at designated locations.
Day 3	• Set up the GPS base station and IC roller/GPS system (by 6AM). • Start paving with one IC roller at breakdown and another IC roller at intermediate positions. • Select a 500-ft section. Conduct NDG/GPS/LWD-a testing immediately behind the paver and at selected locations after each breakdown and intermediate roller pass within the test strip. • Perform production compaction using the rolling pattern. • Conduct NDG/GPS/LWD-a at selected locations after the finish rolling.
Day 4	• Conduct the Open House event including presentation and equipment demonstration.

- GPS: Hand-held GPS rover and a base station.
- NDG: Nuclear density gauge and an operator.
- LWD-a: Lightweight deflectometer for asphalt tests.
- FWD: Falling weight deflectometer and an operator.
- Coring: 60 X 4” cores will be taken with two coring rigs.
- Core tests: Bulk density testing of cores.

Normally, UTM was used as the coordinate selection for IC as GPS data collection. State plane system was used if the local surveyors were not familiar with UTM. GPS validation was conducted prior to the field work to ensure consistency between IC GPS and rover GPS.

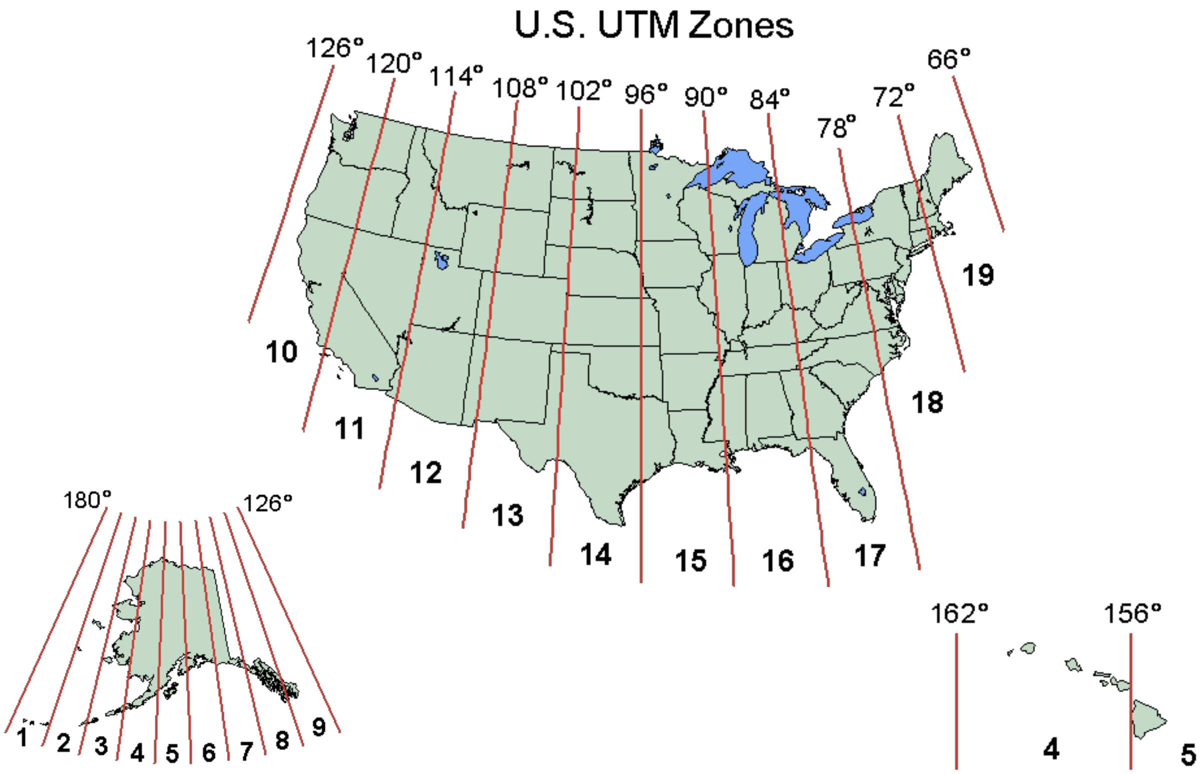


Figure 17. UTM zones in the US.

GPS validation was conducted via the following procedures:

1. Move the IC roller around until the GPS header computation is initialized.
2. Move the IC roller and park at a selected location.
3. Record the GPS measurements from the IC roller ensuring the distance offsets are applied so that the GPS coordinate is at the center or at left/right edges of the front drum.
4. Mark two locations on the ground adjacent to the right and left edges of the front drum contact patch.
5. Move the IC roller from the marked locations.
6. Use a hand-held rover to measure at the marked locations.
7. Average the rover GPS measurements if the roller GPS measurement is at the center of the front drum.
8. The differences between the roller GPS and rover measurements shall be within 12 inches (300 mm) for northing and easting. The tolerance may be adjusted when comparing GPS measurements with different correctional signals.

Two IC rollers were used alternatively at the breakdown position and intermediate positions. The rollers may be operating at a low amplitude and high frequency. Depending on the asphalt mixture type and thickness, the settings may be adjusted to optimize the compaction. A third, conventional roller is often used to smooth out the roller marks on the surface at the finish position. Typical machine settings and in situ testing are described in Table 7.

Table 7. Typical machine settings and in situ testing for a field site.

Date	TB	Machine	Setting	Spot Tests	Notes/Comments
Day 1	1A	IC 1	Low amp at 4000 vpm	NDG, GPS, LWD-a	Breakdown compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day1	1B	IC 2	Low amp at 4000 vpm	NDG, GPS, LWD-a	Intermediate compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day1	1C	Conventional Roller	Static	NA	Finish rolling. 1. Compact with normal roller passes.
Day 2	2A	IC 2	Low amp at 4000 vpm	NDG, GPS, LWD-a	Breakdown compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day 2	2B	IC 1	Low amp at 4000 vpm	NDG, GPS, LWD-a	Intermediate compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day 2	2C	Conventional Roller	Static	NDG, GPS, LWD-a, FWD, Coring	Finish rolling. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a/FWD/Coring tests after the finish rolling at marked locations within the test section.
Day 3	3A	IC 1	Low amp at 4000 vpm	NDG, GPS, LWD-a	Breakdown compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day 3	3B	IC 2	Low amp at 4000 vpm	NDG, GPS, LWD-a	Intermediate compaction for asphalt base course. 1. Compact with normal roller passes. 2. NDG/GPS/LWD-a tests after each roller pass at selected locations within the test section.
Day 3	3C	Conventional Roller	Static	NA	Finish rolling. 1. Compact with normal roller passes.

On Day 1 or Day 3 of the field work, nuclear density measurements were taken right after the paver (considered as pass number 0) and after each roller pass of the breakdown roller, intermediate roller, and finish roller at one or two designated locations. GPS measurements were also made at these locations. LWD-a tests were performed after the intermediate or finish roller to avoid making a dent on the asphalt surface by the metal stamp of the device.

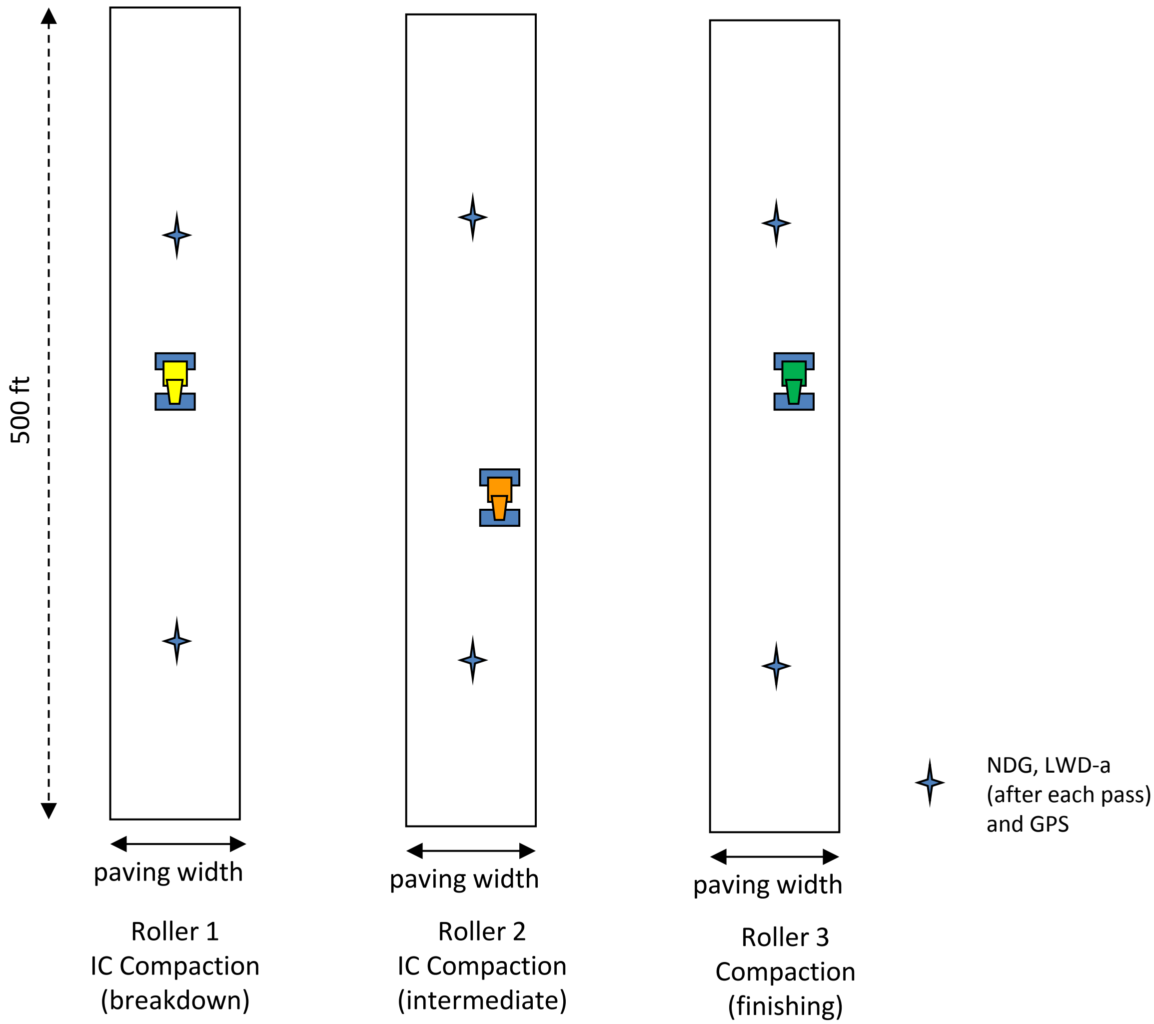


Figure 18. Schematic of a typical Day 1 & 3 testing.

On Day 2 of the field work, nuclear density measurements were taken right after the paver (considered as pass number 0) and after each roller pass of the breakdown roller, intermediate roller, and finish roller at one or two designated locations. GPS measurement was also made at these locations. LWD-a tests were performed after the intermediate or finish roller to avoid making a dent on the asphalt surface by the metal stamp of the device. After the finish rolling, 60 locations were marked with pairs at a 50 ft spacing to facilitate the subsequent coring operation. Nuclear density gauge measurement, GPS, and LWD measurements were conducted at the marked locations. If available, FWD tests were performed between the paired marked locations. Finally, cores were taken at the marked locations after the asphalt was cooled down below a designated temperature in order to obtain intact samples.

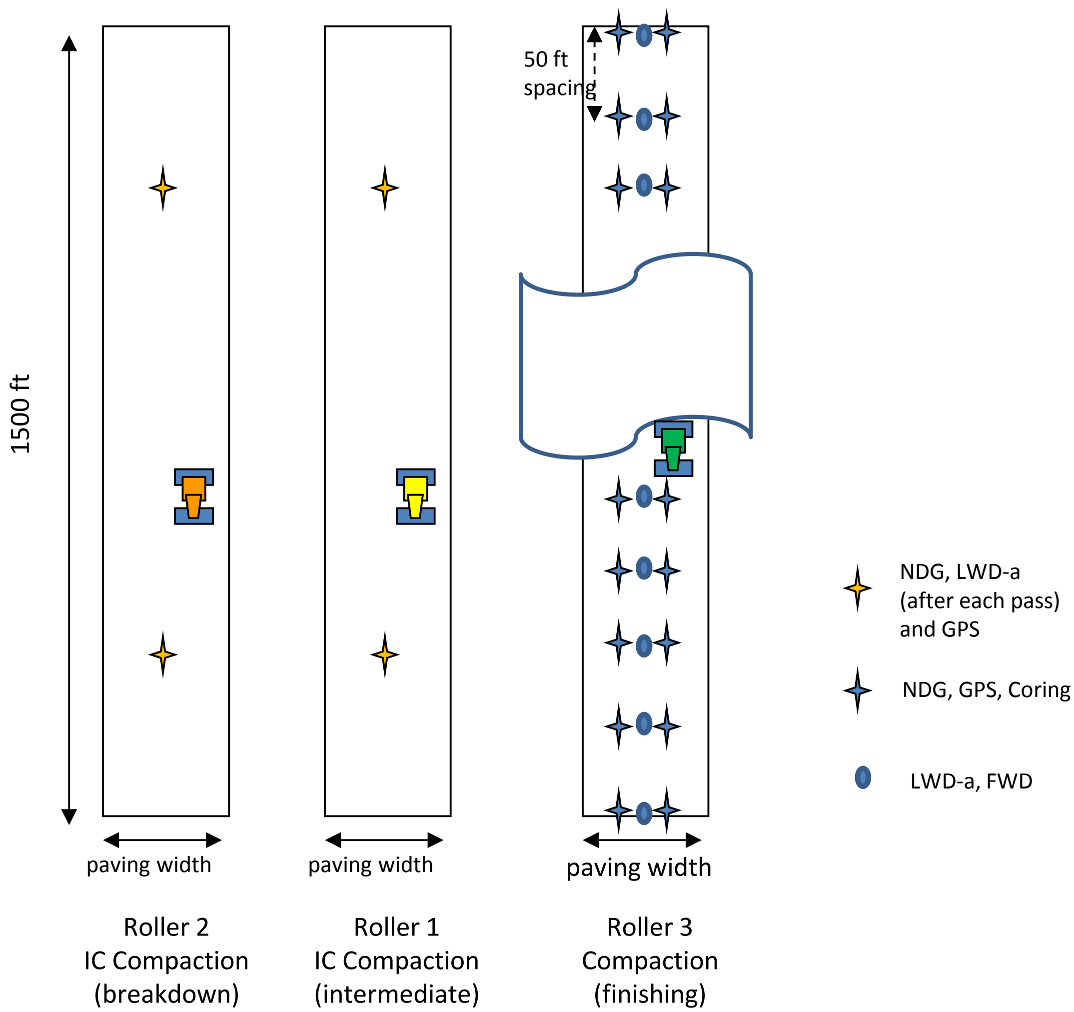


Figure 19. Schematic of a typical Day 2 testing.

Figure 20. A typical paving, compaction, and QC operation for an IC field site.

Figure 21. Typical spot tests and coring for an IC field site

Chapter 4 Data Analysis

Methodology

The IC data were obtained by using vendor-specific IC software to export data in Veda-compatible forms. GPS data were obtained by exporting the measurements from GPS devices to text format. Nuclear density gauge (NDG) data were recorded manually during the measurements onsite. Asphalt core data were provided by DOT laboratories in either PDF or Excel forms. LWD-a data and back-calculation results were provided by Kessler in either PDF or Excel forms. FWD data, if performed, were provided by DOT in raw data forms.

The IC data were imported to Veda for viewing and statistical analysis. The in situ test data were added to the Point Test feature of Veda for correlation analysis. The Veda results were extracted for further processing with Excel to perform regression and charting.

The data analysis focused on the following:

- Statistical Analysis of IC Data: The IC data were analyzed with Veda to produce basic statistics and histogram reports.
- Density Compaction Curves and Pass-by-Pass IC Data Analysis: Based on detailed observation of density growth curves, the influencing factors on in-place density can be better understood.
- Correlation between Core Density and Final Coverage IC Data Analysis: This is a one-to-one simple correlation analysis to evaluate the relationship between core densities and ICMV, even though each measures different properties.

GPS Validation

GPS validation is the first step of any IC field work. The purpose is to ensure all GPS devices (on IC rollers and handheld rover) produce consistent results. It is crucial for the correlation analysis under this study to extract IC data at specific in-place density measurements and coring locations. The target tolerance is within one foot. The default radius for extracting IC data around the in-place measurement location is three feet.

Table 8. An example of GPS validation, Caterpillar IC vs. SITECH hand-held GPS rover, KY site (KY State Plane coordinate).

Point ID	Caterpillar Northing (U.S. ft)	Caterpillar Easting (U.S. ft)	Differences in Northing (U.S. ft)	Differences in Easting (U.S. ft)
1R	3634177.45	4876895.3	-0.02	-0.56
1L	3634178.05	4876901.85	-0.12	-0.57
2R	3634187.55	4876889.65	0	-0.65
2L	3634188.4	4876896.15	-0.02	-0.66
3R	3634205.85	4876890.25	-0.13	-0.58
3L	3634206.8	4876896.75	-0.08	-0.61

Even with GPS validation before the start of field work, care should be taken to monitor any possible GPS “drift” due to various factors such as the GPS base station setup and signal strength/coverage and the GPS mode status of the IC roller systems. The GPS quality check was performed by overlaying GPS spot measurements on IC maps (Figure 22).

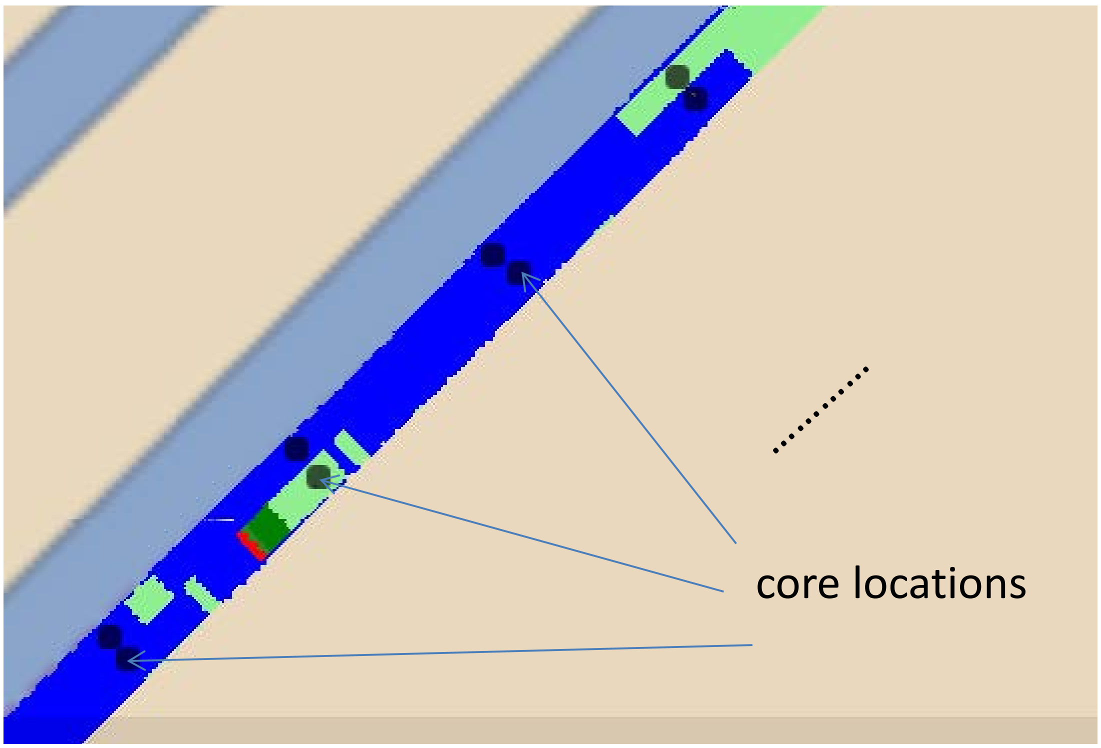


Figure 22. Example of GPS checks, BOMAG IC map, CA site.

The GPS quality checks not only validate whether the GPS devices are producing consistent results but also whether vendors' IC data "gridding process" is correct. The gridding process turns one-point per drum width measurements to one-foot-by-one-foot grids in order to better track roller drum locations and overlaps. An example of GPS quality checks that identify the GPS shift between two rovers is shown in Figure 23. All IC and GPS data were carefully checked prior to the subsequent analysis.

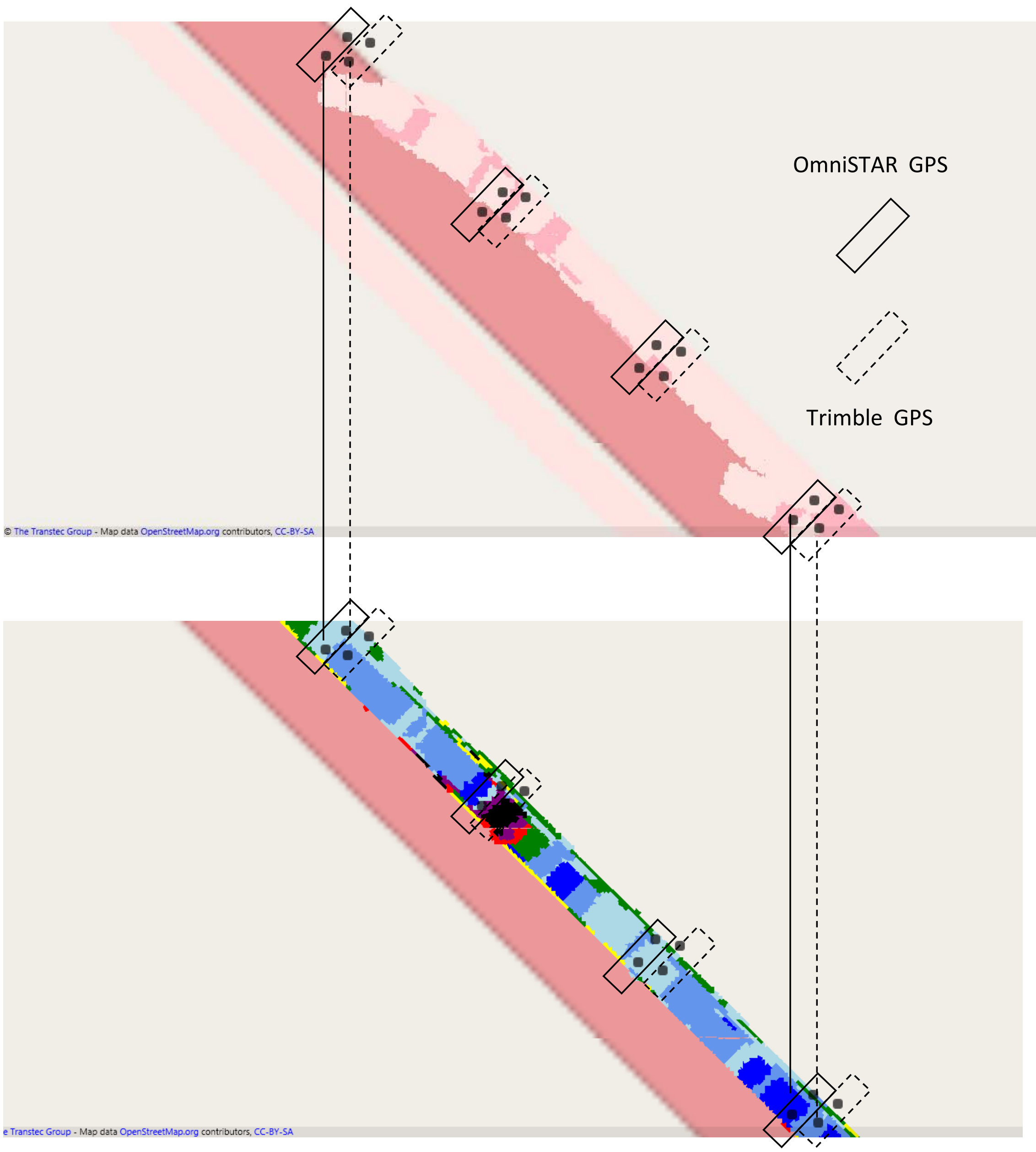


Figure 23. Example of GPS checks, Hamm and Sakai IC maps with two types of GPS rovers, UT site.

Statistical Analysis of IC Data

The IC maps and statistics of Day 2 testing where coring took place for all field sites are included in Appendix A - IC Data Analysis due to its large volume. The IC data analysis results were examined to determine their adequacy for subsequent data analysis.

The following example, for the Idaho site, shows a typical IC data analysis for a given field site. The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 24 and Figure 25.

Comments on Hamm Data:

- ICMV: The mean HMV value is 36 with standard deviation of 7.9.
- Temperature: The mean surface temperature is 222°F with standard deviation of 35°F.
- Pass counts: The recorded mean roller passes is 3.
- Frequency: The mean frequency is 3,016 vpm (50 Hz).
- Compaction curve: The ICMV curve grows parabolic with an asymptote at 38 of HMV and pass count of 4.

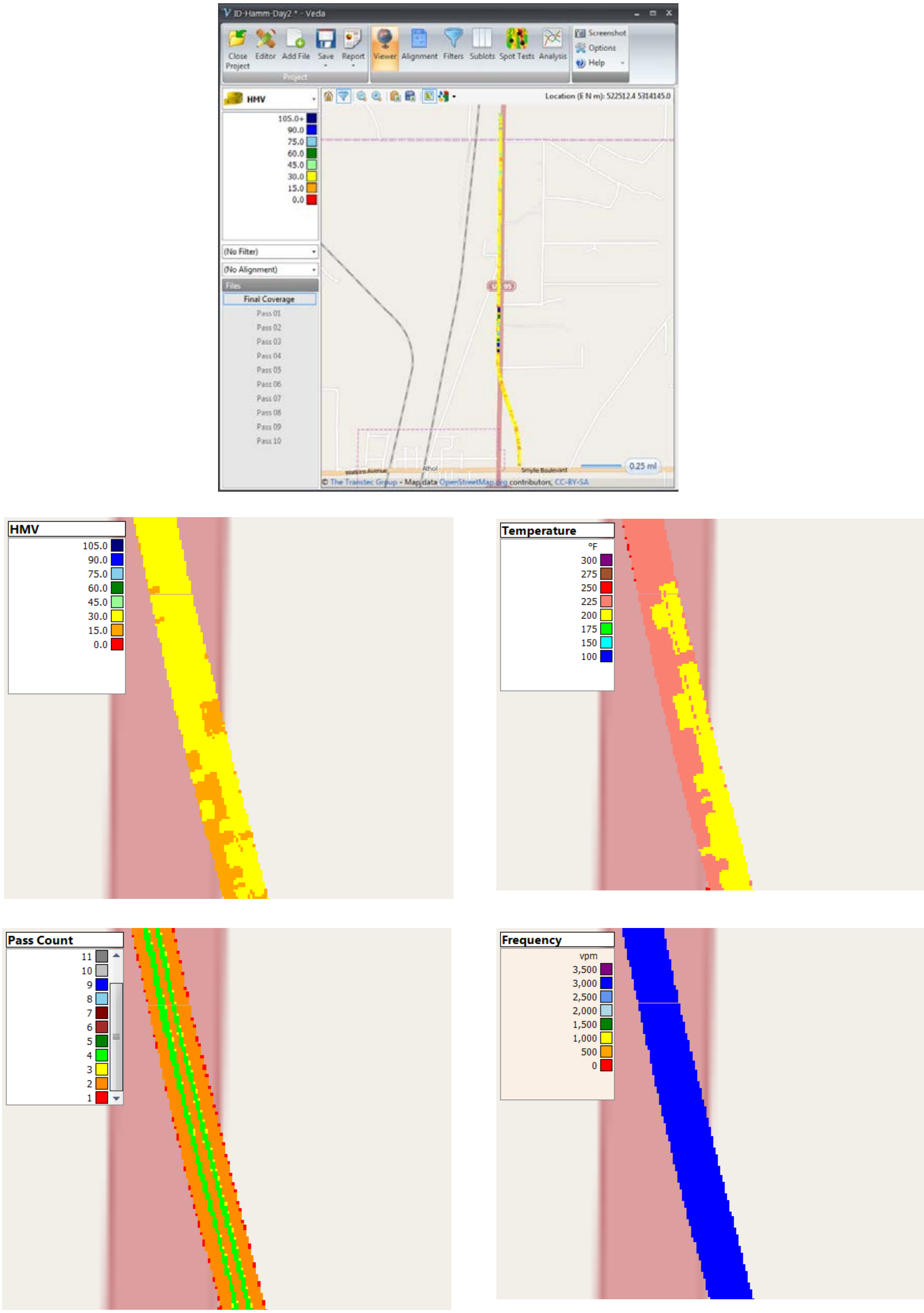


Figure 24. Hamm IC maps (breakdown), TB02, ID site.

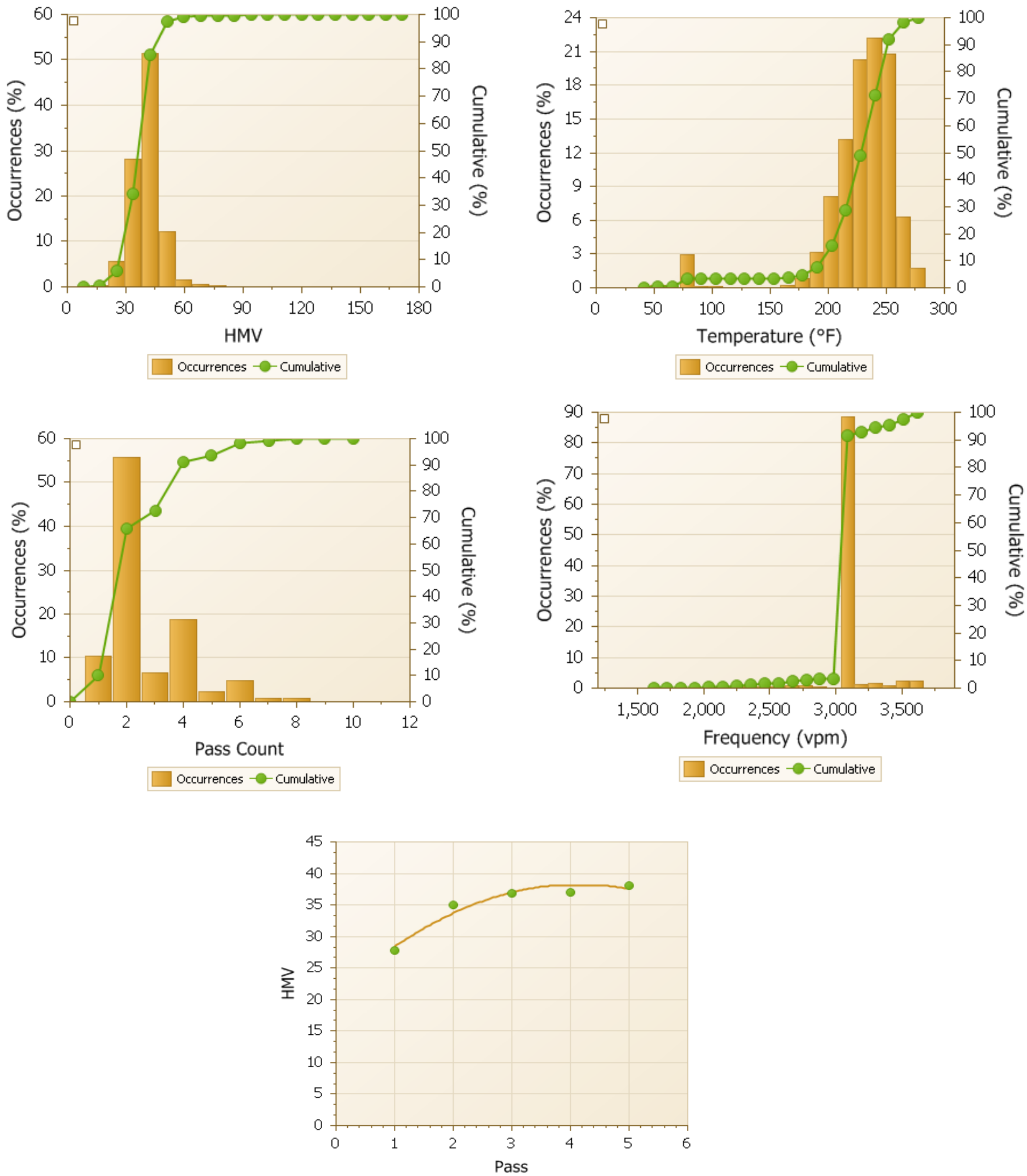


Figure 25. Hamm IC statistics (breakdown), TB02, ID site.

The IC maps and statistics for the Sakai IC data (intermediate position) are presented in Figure 26 and Figure 27.

Comments on Sakai Data:

- ICMV: The mean CCV value is 10.7 with standard deviation of 14.7. The high CCV values may be due to acceleration and deceleration at start and stop locations.
- Temperature: The mean surface temperature is 188°F with standard deviation of 29.6°F. Some lower temperature values may be due to mobilization and sensor malfunctioning.
- Pass counts: The recorded mean roller passes is 3.
- Frequency: The mean frequency is 3,880 vpm (65 Hz).
- Compaction curve: The curve grows monotonically without an apparent optimal value. Being monotonically means the values are either increasing or decreasing, not both.

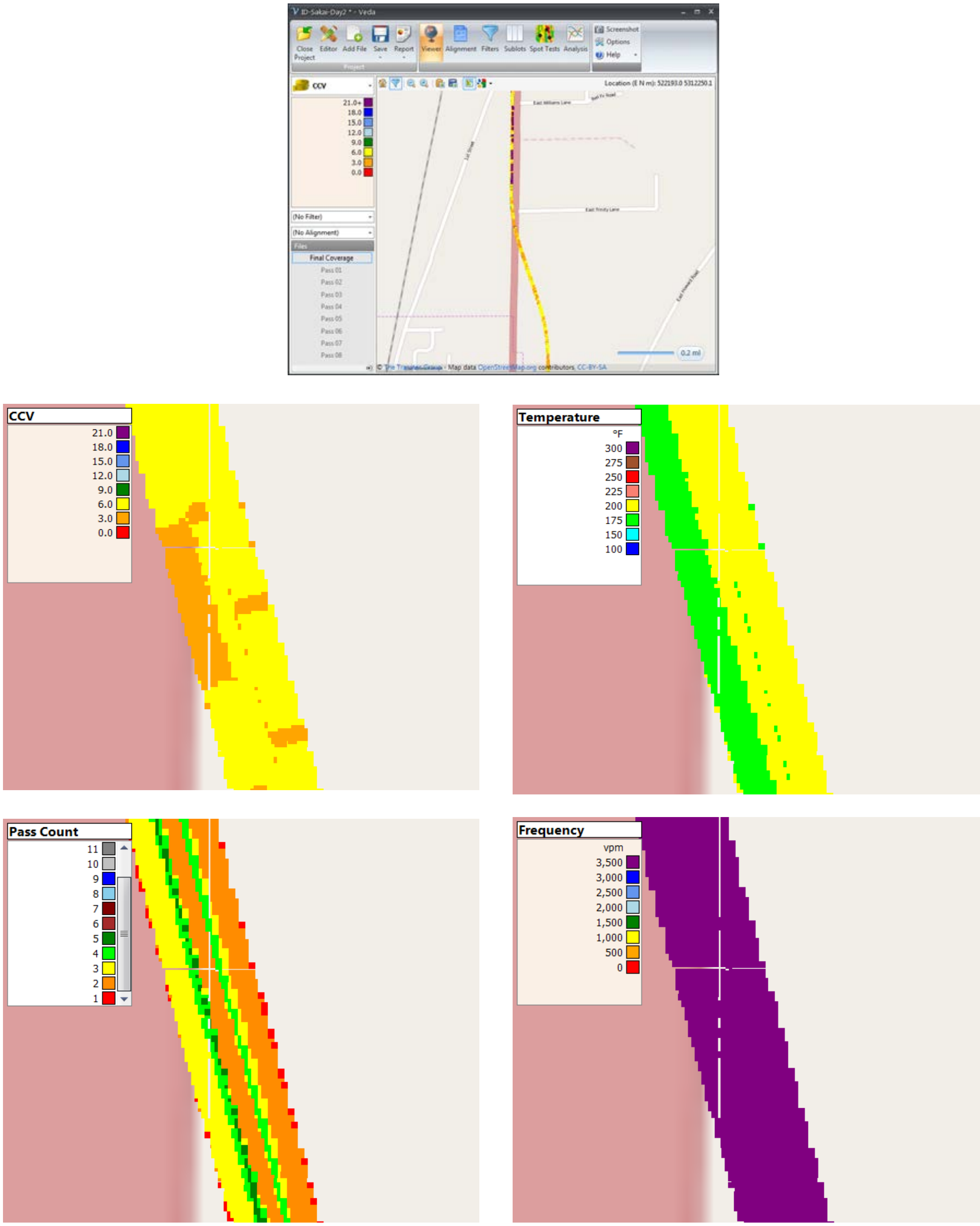


Figure 26. Sakai IC maps (intermediate), TB02, ID site.

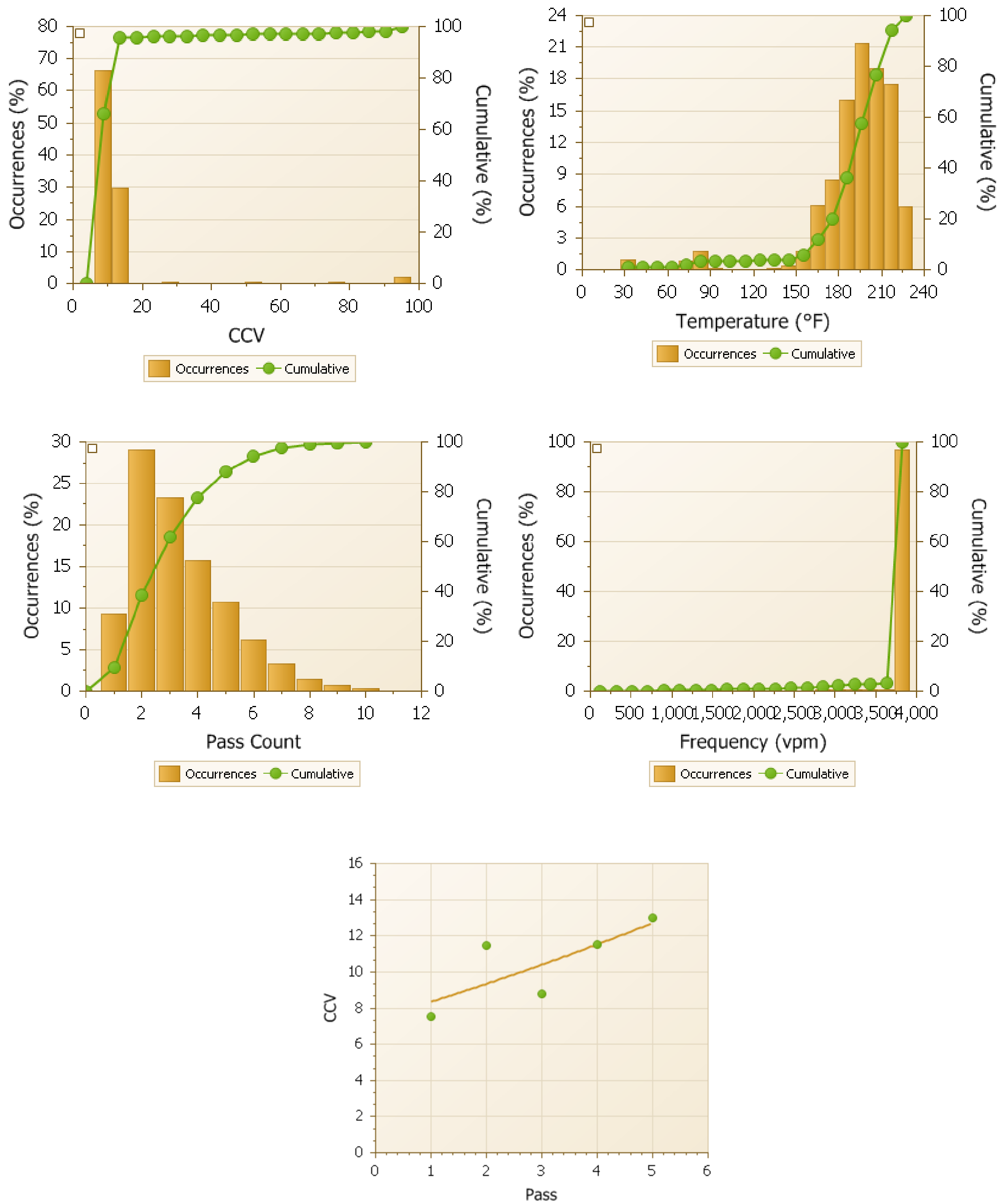


Figure 27. Sakai IC statistics (intermediate), TB02, ID site.

Summary of IC Data Issues

Based on the Day 2 IC data analysis for all field sites, the followings conclusions for adequacy for subsequent analysis can be made:

- UT site: The rolling patterns were erratic. There was a lack of Hamm data within some coring locations.
- FL site: The rolling patterns were erratic.
- OH site: There was a lack of Hamm data within some coring locations.
- ME site: There were no significant issues.
- CA site: There was a lack of Hamm breakdown data due to GPS accessibility. There was also a lack of Caterpillar breakdown data correlation analysis due to GPS shifts. The core numbers were reduced due to lack of time before opening the site to traffic.
- ID site: There were no significant issues.
- MD site: The tree coverage affected the GPS reception, especially for the Caterpillar data. The Caterpillar CMV pattern was unusual.
- KY site: The Caterpillar CMV pattern and the compaction curve were unusual.
- WA site: There were no significant issues.

As can be seen from the above data issues, the IC field work is still challenging as the technology evolves. Therefore, the following recommendations are provided based on the lessons-learned:

- Planning: Thorough planning among all parties is crucial for the success of any IC field work. The state agency, contractors, and IC equipment suppliers need to plan ahead (at least 30 to 60 days) for details of all field operations, especially the responsibility of each party, specific IC rollers and systems to be used, pre-construction briefing, and daily briefing, etc.
- IC Setup: IC roller setup and components mounting need to be completed at least one day prior to the field work. A trial run needs to be performed and IC data storage/transmission

need to be checked. Then, the IC data need to be exported with the vendors' software to the Veda-compatible format for quality checks.

- GPS Recon: Surveyors need to recon the project site to identify whether there are any GPS "shadows" or locations that create cover such as overpasses/trees, and horizontal curves that block the transmission of GPS correction signals, etc. GPS repeaters may need to be installed at selected locations to relate the GPS correction to resolve the GPS shadows. Otherwise, a laser-based technology (such as TotalStation) needs to be employed to overcome issues such as tree coverage. Note that using laser-based equipment would add significant cost.
- GPS Checks: To ensure all GPS records from all devices are compatible, GPS validation needs to be performed at least one day prior to the field work based on the recommended procedures in the FHWA Generic IC Specification (FHWA, 2014). All GPS devices need to use the same GPS datum and coordinate system (either UTM or State Plane). The tolerance for the GPS validation should be with 12 inches. The tolerance may be adjusted when different correctional signals are used. It is also recommended an alternative check for positioning to make the field process practical.
- Daily Data Submission and Checks: IC data needs to be transferred from the IC rollers to other computing devices either via an USB flash drive or wireless infrastructure (such as: VisionLink, SiteLink3D, and etc.) on a daily basis. The raw IC data needs to be checked with IC vendors' software and IC data needs to be exported to Veda-compatible formats. Caution needs to be taken during the export procedures using vendors' software to ensure correct data types (Veda-compatible final coverage and all-passes data), time periods, coordinate system, and file naming with appropriate extension are completed correctly. The exported IC data needs to be imported to Veda to check:
    a) if the GPS locations correctly displayed on the Veda map viewer with the aids of underlying street maps, imported plan file, or comparison maps automatically launched by Veda such as Google Maps or Google Earth;
    b) if the IC roller operation (speed, vibration frequency/amplitude) meet the requirements set by the QC managers;
    c) if the roller passes meet the required rolling patterns set by the QC manager;
    d) if the ICMV and temperature maps display any issues.

- Daily Briefing: Daily briefing prior to the start of the operation will identify the previous days' issues and will allow for making adjustments if necessary. It maintains the proper communication if any unexpected issues occur.

NDG Density Compaction Curves and Pass-by-Pass IC Data Analysis

NDG measurements after each roller pass were used to build density compaction curves that show the growth trend of asphalt densification. The main purpose of compaction curves is to identify the compaction characteristic for specific materials and roller(s) used in a paving project in order to determine the optimal rolling pattern. The NDG measurements can also be correlated to ICMV to evaluate whether there is a linear relationship between the two.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Utah site are presented in Figure 28 and Figure 29. The compaction curve from the breakdown compaction indicates a monotonic growth of densification. A monotonic growth follows a trend of increasing values. The temperature drop also follows a similar monotonic but reverse trend. The R^2 for the correlation between NDG measurements and HMV from the breakdown compaction is 0.50, which is consistent with the observations by IC vendors.

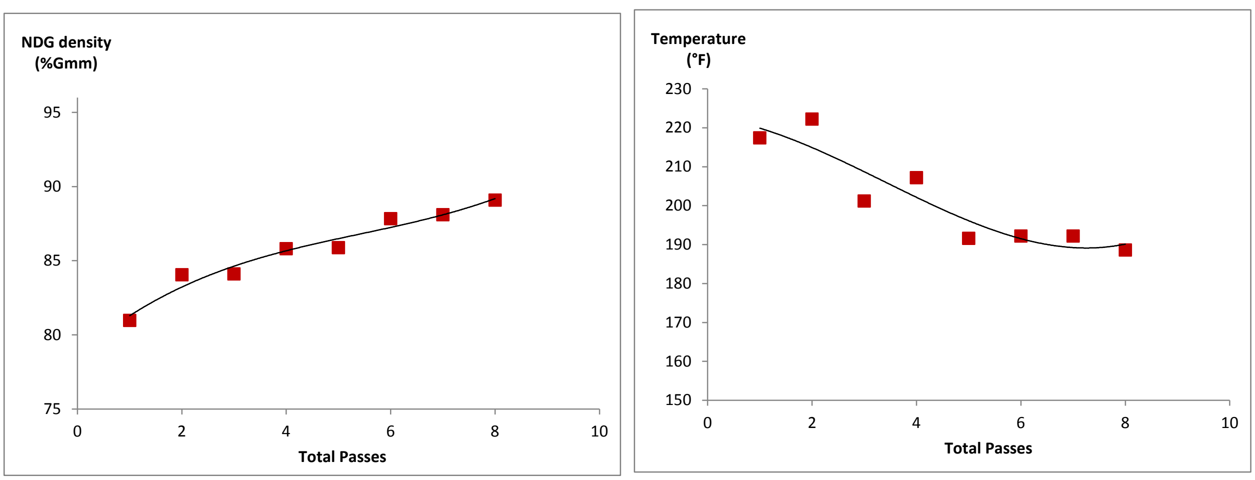


Figure 28. NDG density compaction curves at T1 location of Test Bed 03, UT site.

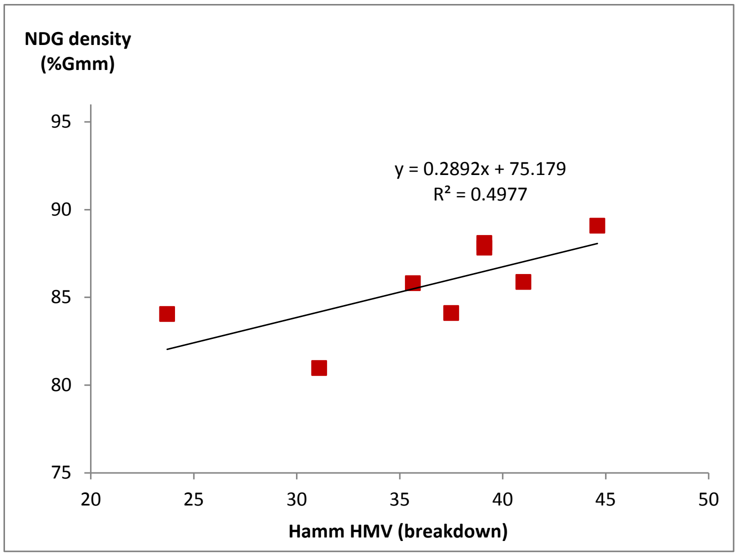


Figure 29. Correlation between NDG density and ICMV at T1 location of Test Bed 03, UT site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Utah site are presented in Figure 30 and Figure 31. The compaction curve indicates a rapid growth of densification during the breakdown compaction then levelling off during the intermediate compaction. The temperature drop also follows a similar, but reverse trend. The R^2 for the correlation between NDG measurements and CCV during the breakdown compaction is 0.97 while R^2 for the NDG measurements and asphalt during the intermediate compaction is 0.20. The significant difference between the two correlations is due to the nature of accelerometer-based ICMV that reflects the changes of internal aggregate structure or densification during breakdown compaction at elevated temperatures, but reflects the hardening of asphalt binder during the cooling off stage of intermediate compaction.

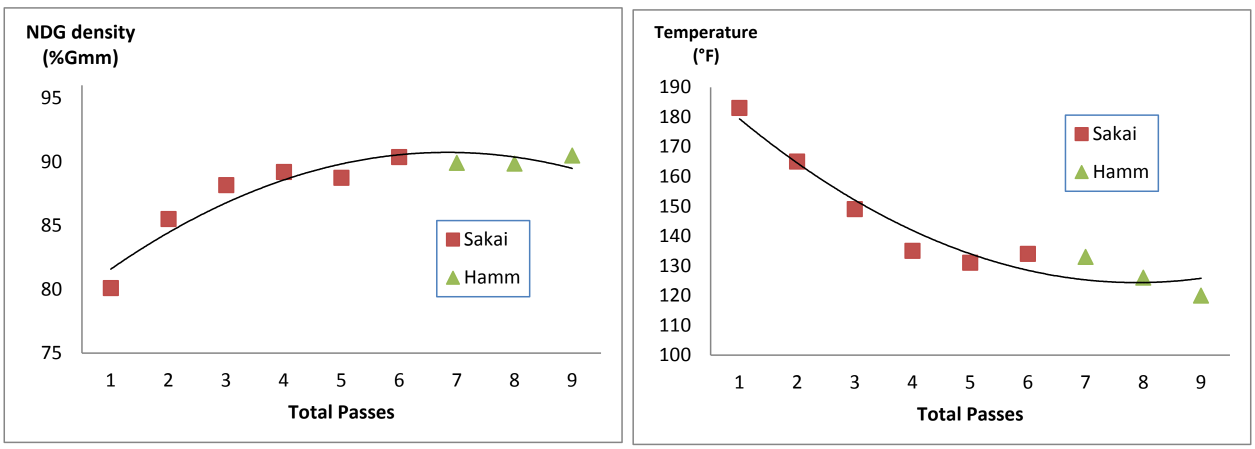


Figure 30. NDG density compaction curves at T1 of Test Bed 03, FL site.

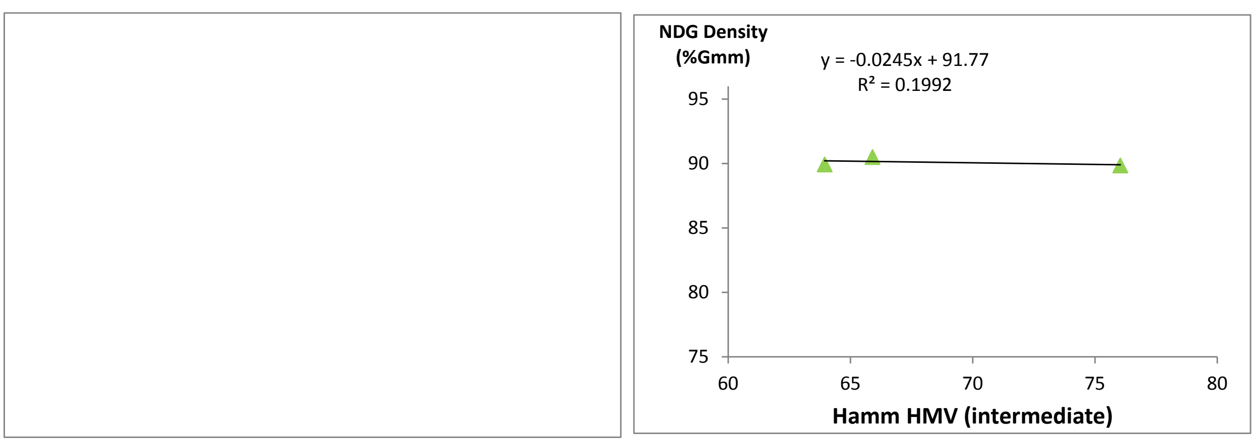


Figure 31. Correlation between NDG density and ICMV at T1 of Test Bed 03, FL site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Ohio site are presented in Figure 32 and Figure 33. Three test locations within a 100-foot (30 m) section were labeled as T1, T2, and T3. The compaction curves indicate different patterns even though the same equipment, materials, and compaction method were used. The temperature drop also follows a similar, but reverse trend. At T1, the pattern of the compaction curve is similar to that from the Utah site, which is monotonic growth. At T2 and T3, the pattern is similar to that from the Florida site, in which the density grows rapidly during the breakdown compaction then levels off during the intermediate compaction. At T1, the density grows at a slower rate during breakdown compaction than those at T2 and T3. However, it reaches higher density values after the intermediate compaction than those at T2 and T3. Therefore, compaction behavior is more complex than it was previously thought. This phenomenon also poses challenges to modelling efforts for predicting asphalt density. As for the ICMV- NDG relationship, the R^2 for the correlation between NDG measurements and CCV during the breakdown compaction is 0.59, while it is 0.24 between the NDG measurements and HMV during the intermediate compaction. The comparison is consistent with that from the Florida site.

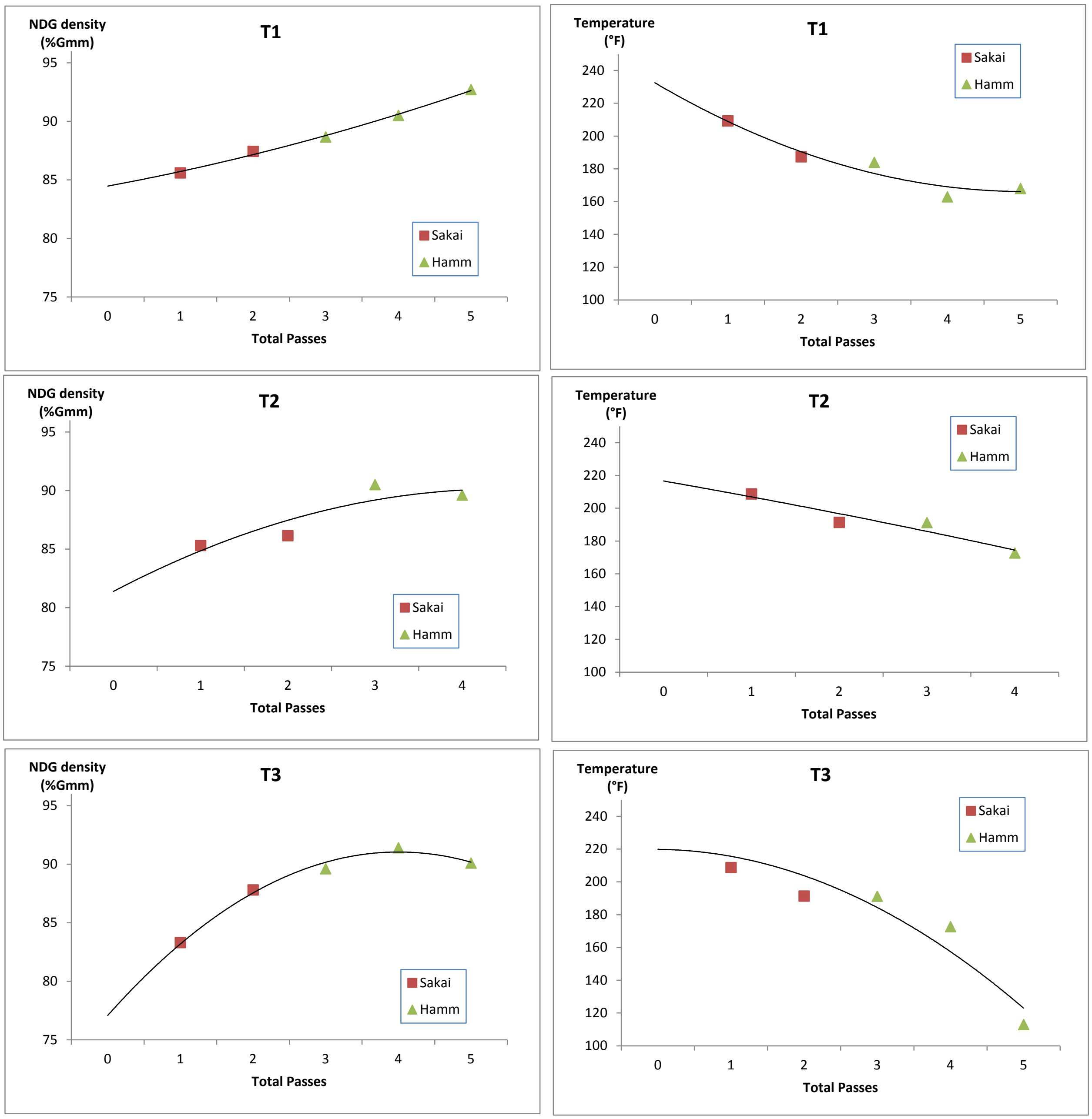
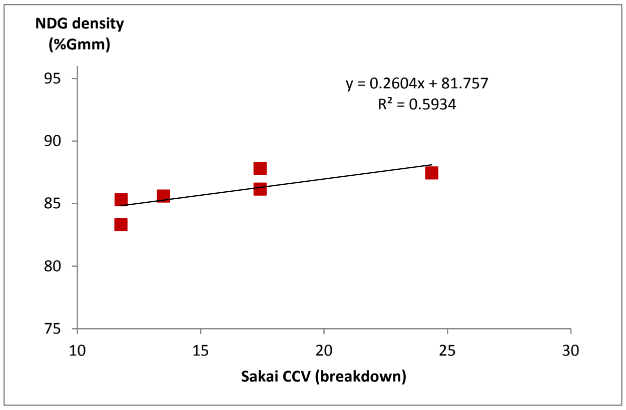


Figure 32. NDG density compaction curves at T1 of Test Bed 01, OH site.



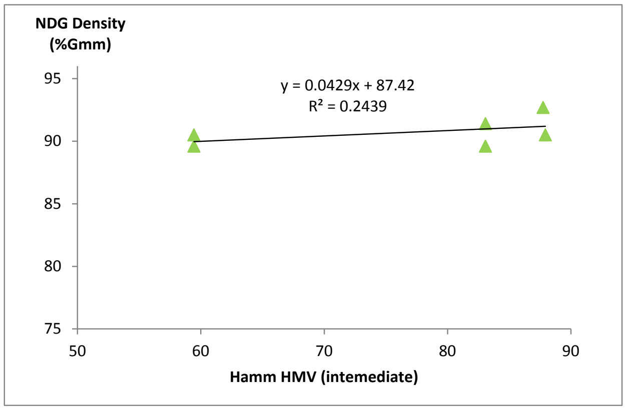


Figure 33. Correlation between NDG density and ICMV at T1 of Test Bed 01, OH site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Maine site are presented in Figure 34 and Figure 35. In Figure 34, the density increases with a similar trend at T2 and T5, reaching 90 %G_{mm} after breakdown compaction then around 92 %G_{mm} after intermediate compaction. In Figure 35, the R^2 values of correlation between NDG density and ICMV are 0.71 and 0.38, for breakdown compaction and intermediate compaction, respectively.

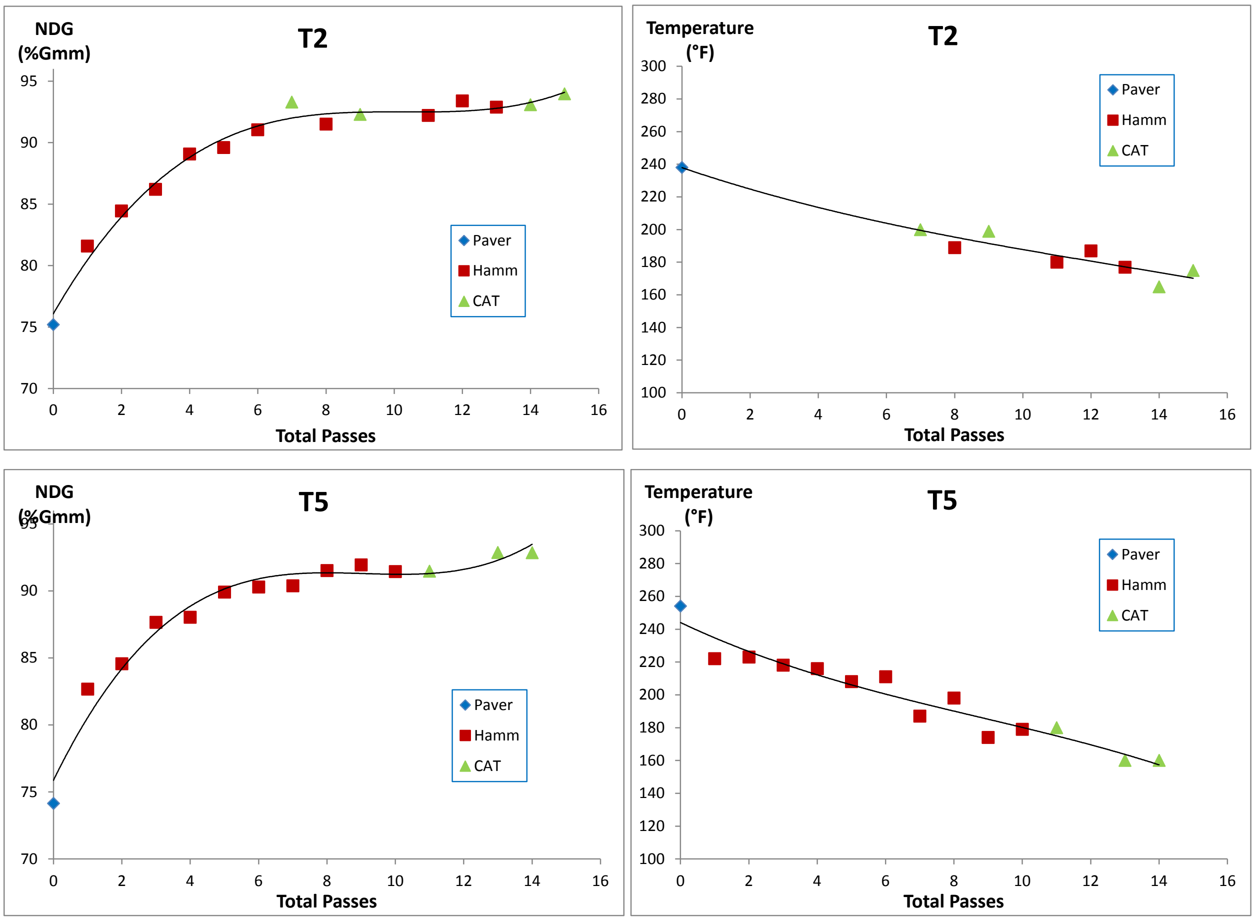


Figure 34. NDG density compaction curves at T2 of Test Bed 01B and T5 of Test Bed 03, ME site.

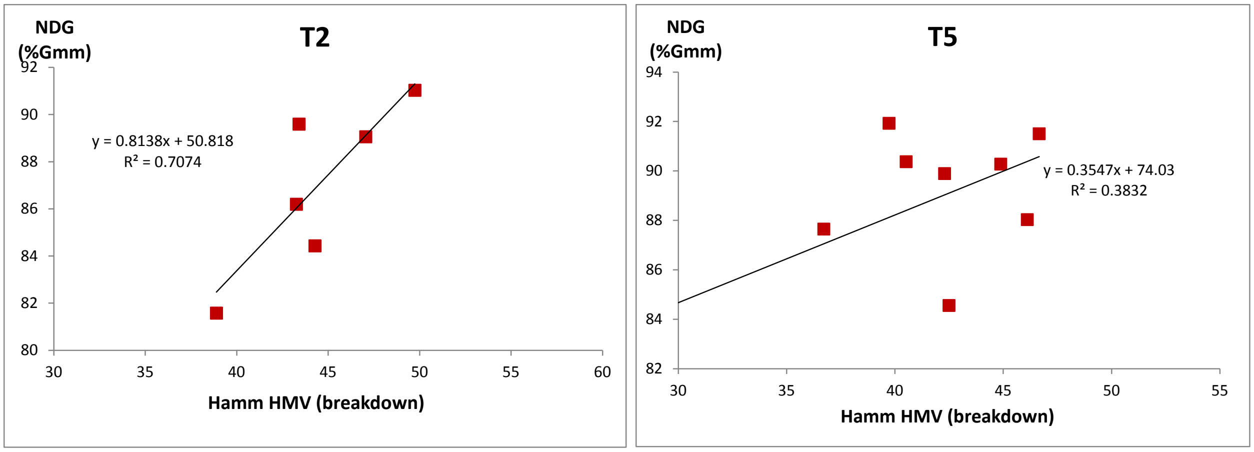


Figure 35. Correlation between NDG density and ICMV at T2 of Test Bed 01B and T5 of Test Bed 03, ME site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the California site are presented in Figure 36 and Figure 37. In Figure 36, the density increases with a slightly different trend then at T1 and T3, starting at different density values behind the paver. In Figure 37, the R^2 values of correlation between NDG density and ICMV are both unusually high at 0.96, for breakdown compaction and intermediate compaction.

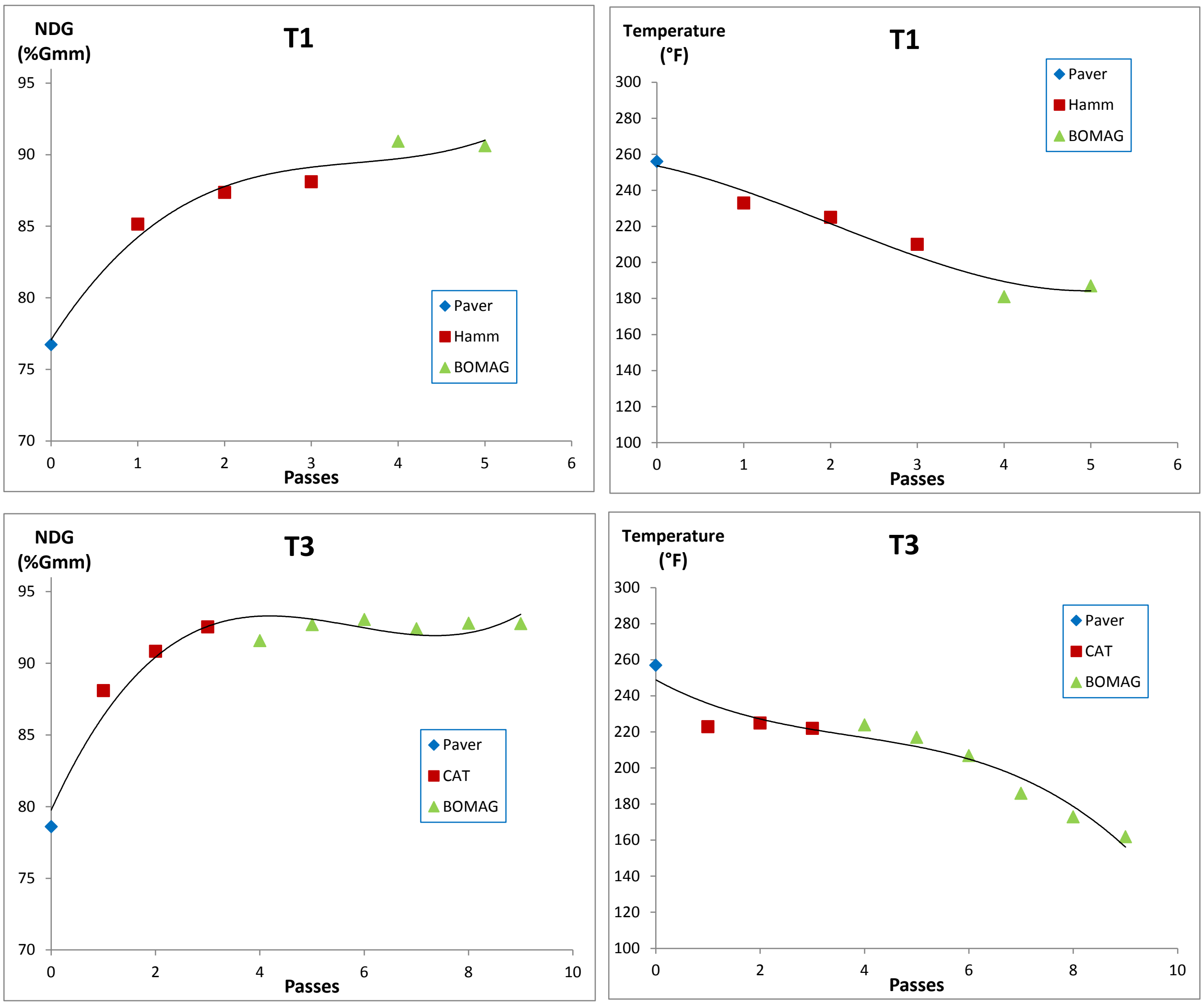


Figure 36. NDG density compaction curves at T1 of Test Bed 01 and T3 of Test Bed 02, CA site.

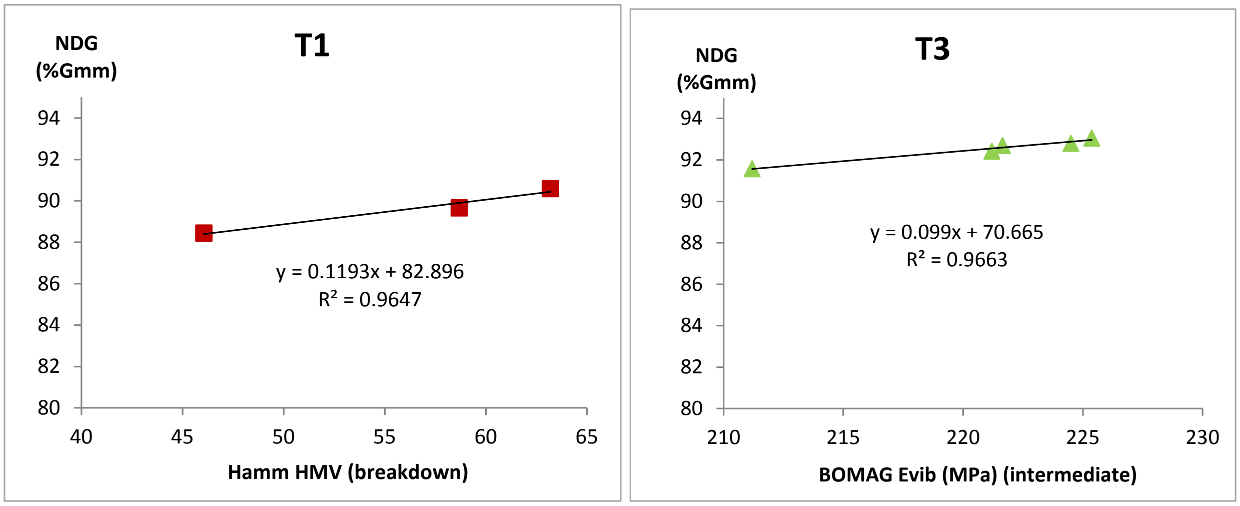


Figure 37. Correlation between NDG density and ICMV at T1 of Test Bed 01 and T3 of Test Bed 02, CA site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Idaho site are presented in Figure 38 and Figure 39. In Figure 38, the density increase with a similar trend at T1 and T2, starting at usually low densities behind the paver and reaching below 90 %G_{mm} after the intermediate compaction. In Figure 39, the R^2 values of correlation between NDG density and ICMV are both low at 0.32 and 0.07, for breakdown compaction and intermediate compaction, respectively.

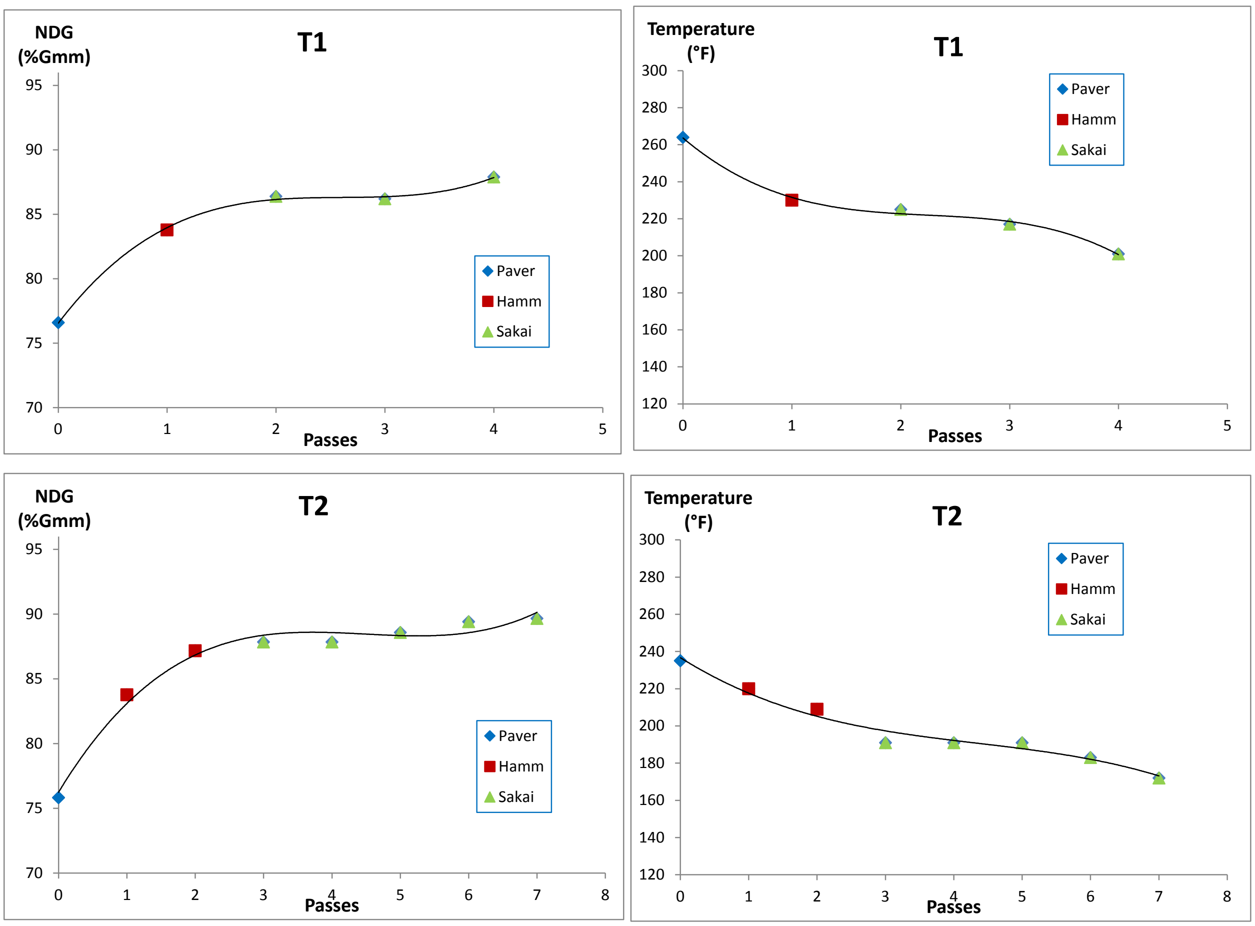


Figure 38. NDG density compaction curves at T1 of Test Bed 01 and T2 of Test Bed 02, ID site.

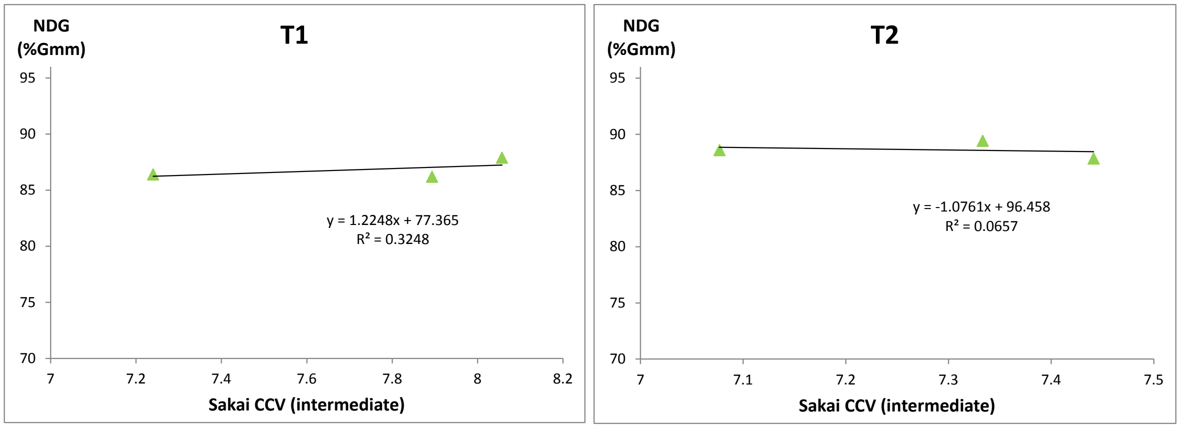


Figure 39. Correlation between NDG density and ICMV at T1 of Test Bed 01 and T2 of Test Bed 02, ID site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Maryland site are presented in Figure 40 and Figure 41. In Figure 40, the density increase with different trends at T1, T2 and T3, starting at different low densities behind the paver and reaching around 91 to 92 $\%G_{mm}$ after the intermediate compaction. In Figure 41, the R^2 values of correlation between NDG density and ICMV are all low values for breakdown compaction and intermediate compaction. The trend at T2 is reversed. The erratic trends and correlation may be due to the NDG measurement issues.

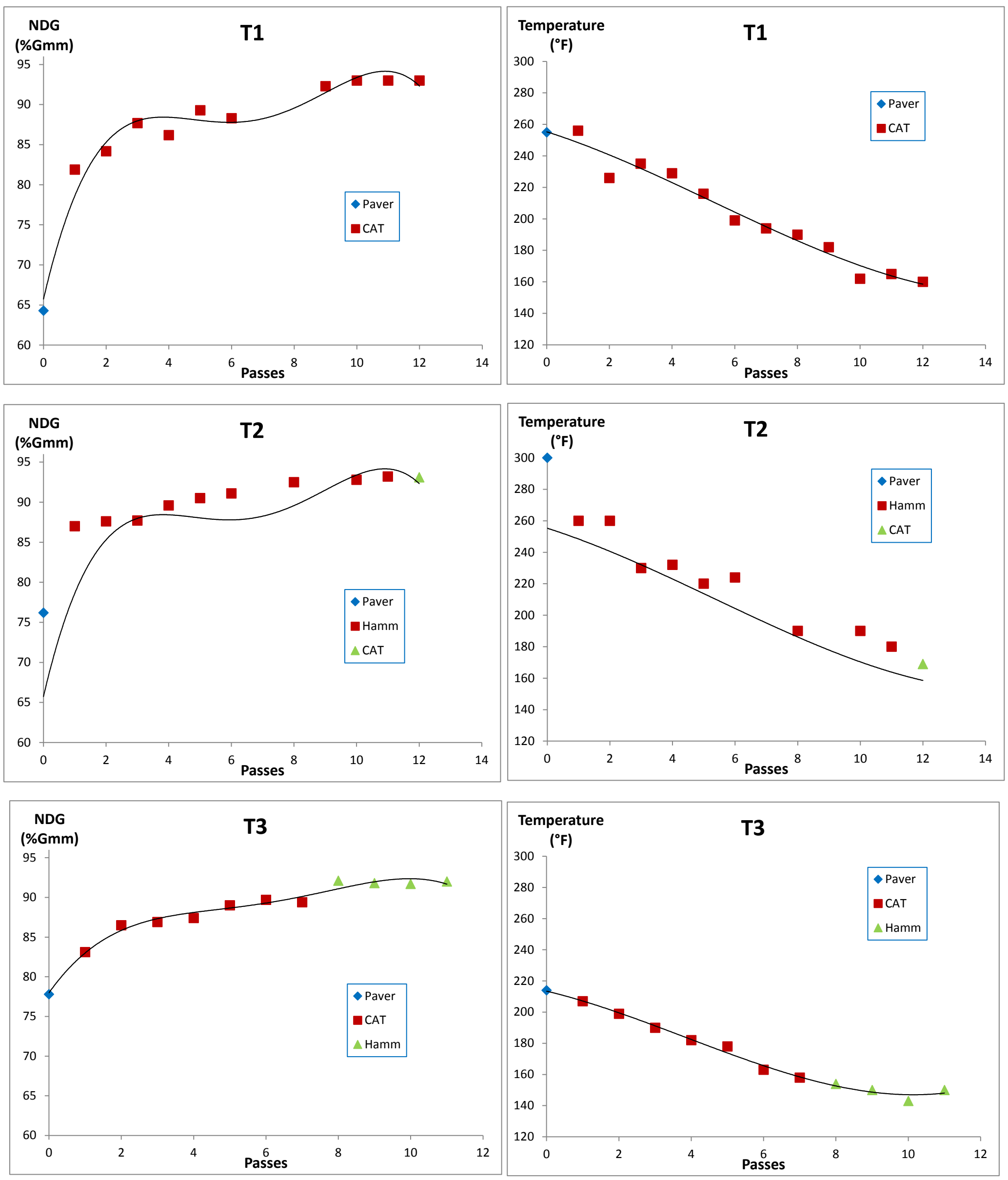


Figure 40. NDG density compaction curves at T1 of Test Bed 01, T2 of Test Bed 02, and T3 of Test Bed 03, MD site.

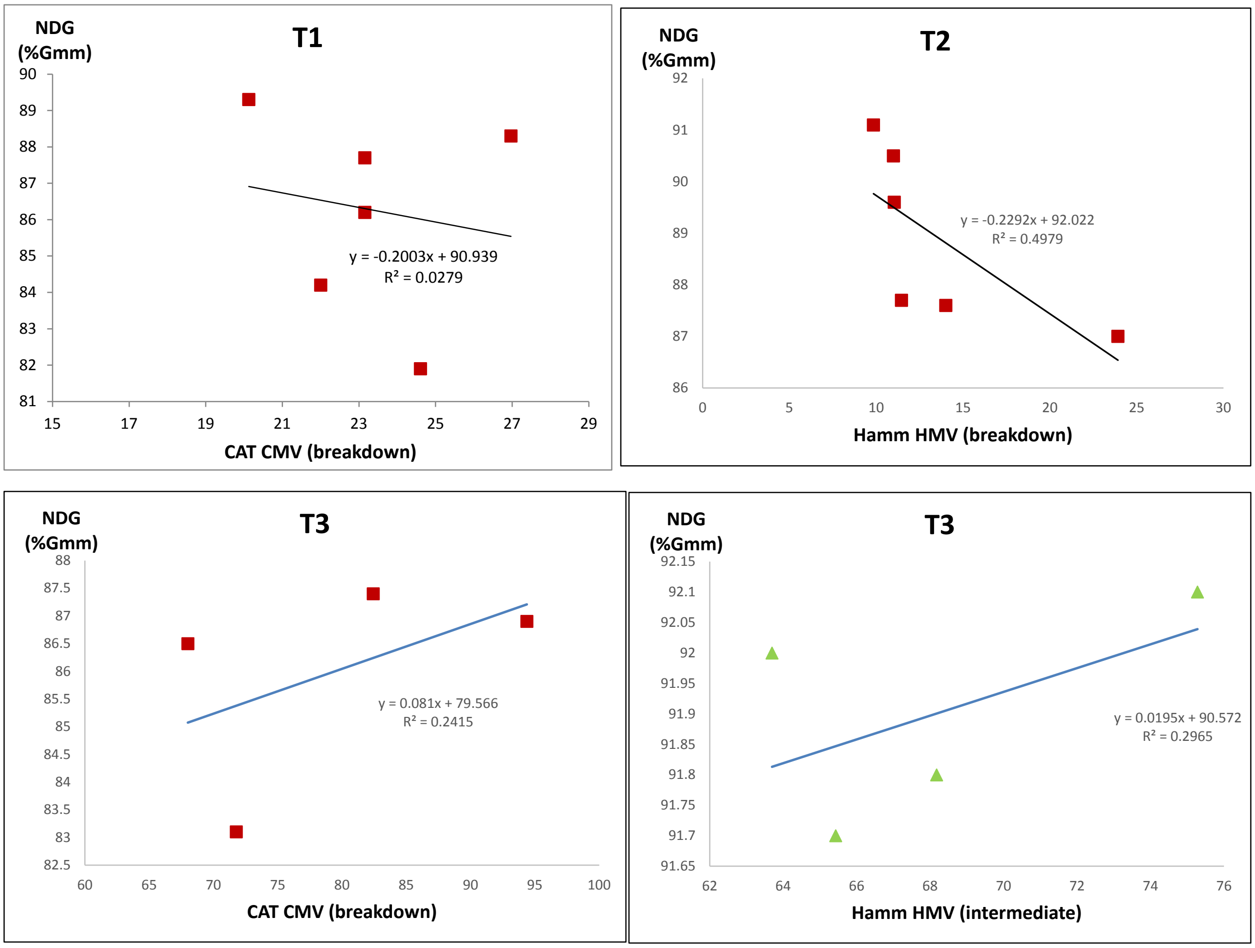


Figure 41. Correlation between NDG density and ICMV at T1 of Test Bed 01, T2 of Test Bed 02, and T3 of Test Bed 03, MD site.

The NDG and non-nuclear density gauge (NNDG) density compaction curves for the Kentucky site are presented in Figure 42. The NDG density gauge data were erratic. Therefore, no further analysis of the NDG data were performed for the Kentucky site.

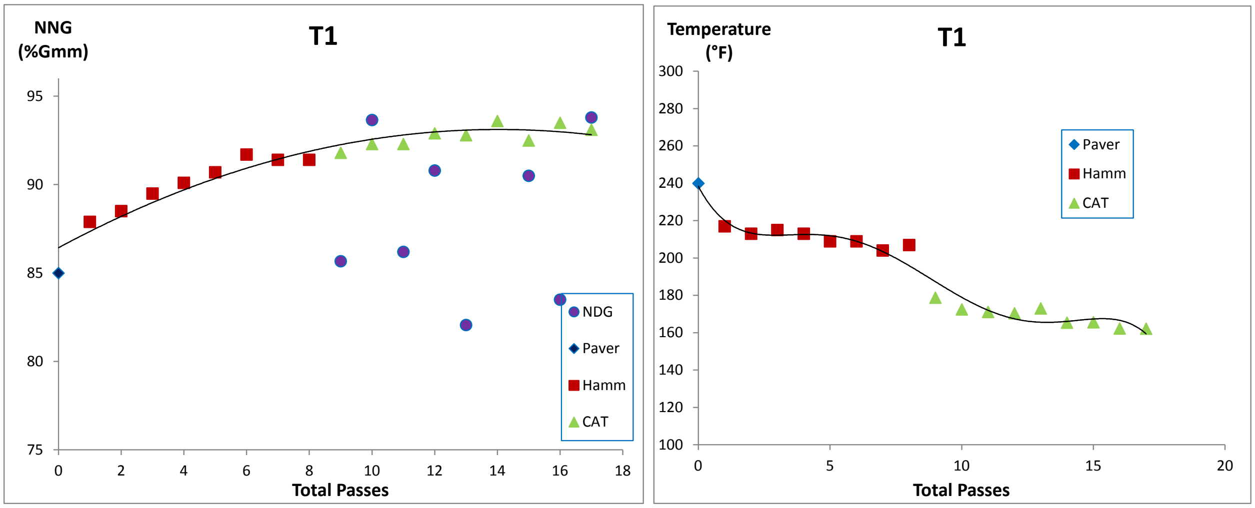


Figure 42. NDG density compaction curves at T1 of Test Bed 01 and T2 of Test Bed 02, KY site.

The NDG density compaction curves and linear correlation between NDG density and ICMV for the Washington State site are presented in Figure 43 to Figure 46. All test points indicate similar trends for NDG density growth and temperature drops. The ICMV from the breakdown rollers correlate well with the NDG density values, with R^2 of linear correlation ranges from 0.5 to 0.9. On the other hand, the ICMV from the intermediate rollers do not correlate well with the NDG density values. The probable causes may include lower mix temperature, narrower range of values, and different methods for NDG measurements (back scatter and direct transmission).

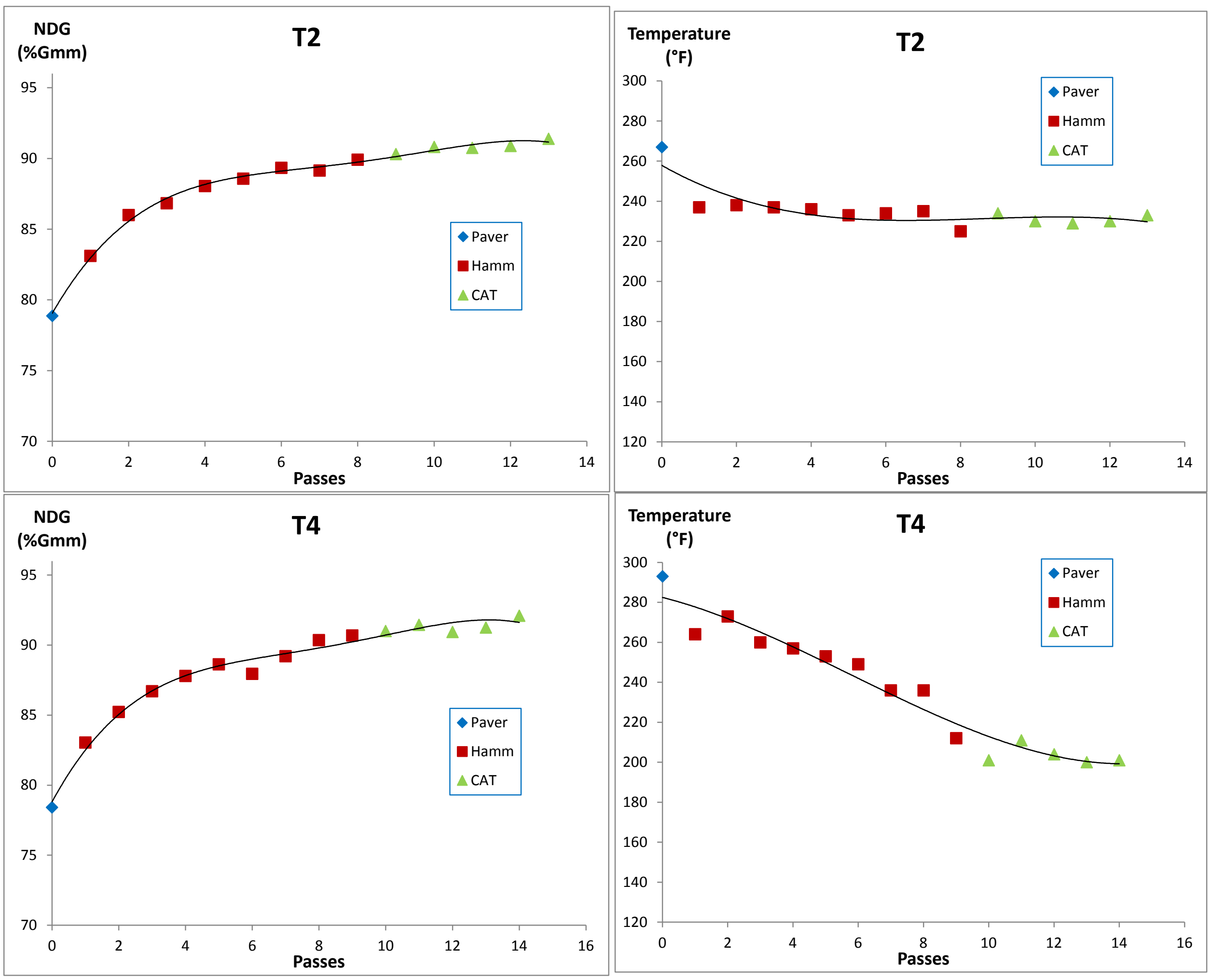


Figure 43. Pass-by-pass NDG densities and temperatures, WA site (1/2).

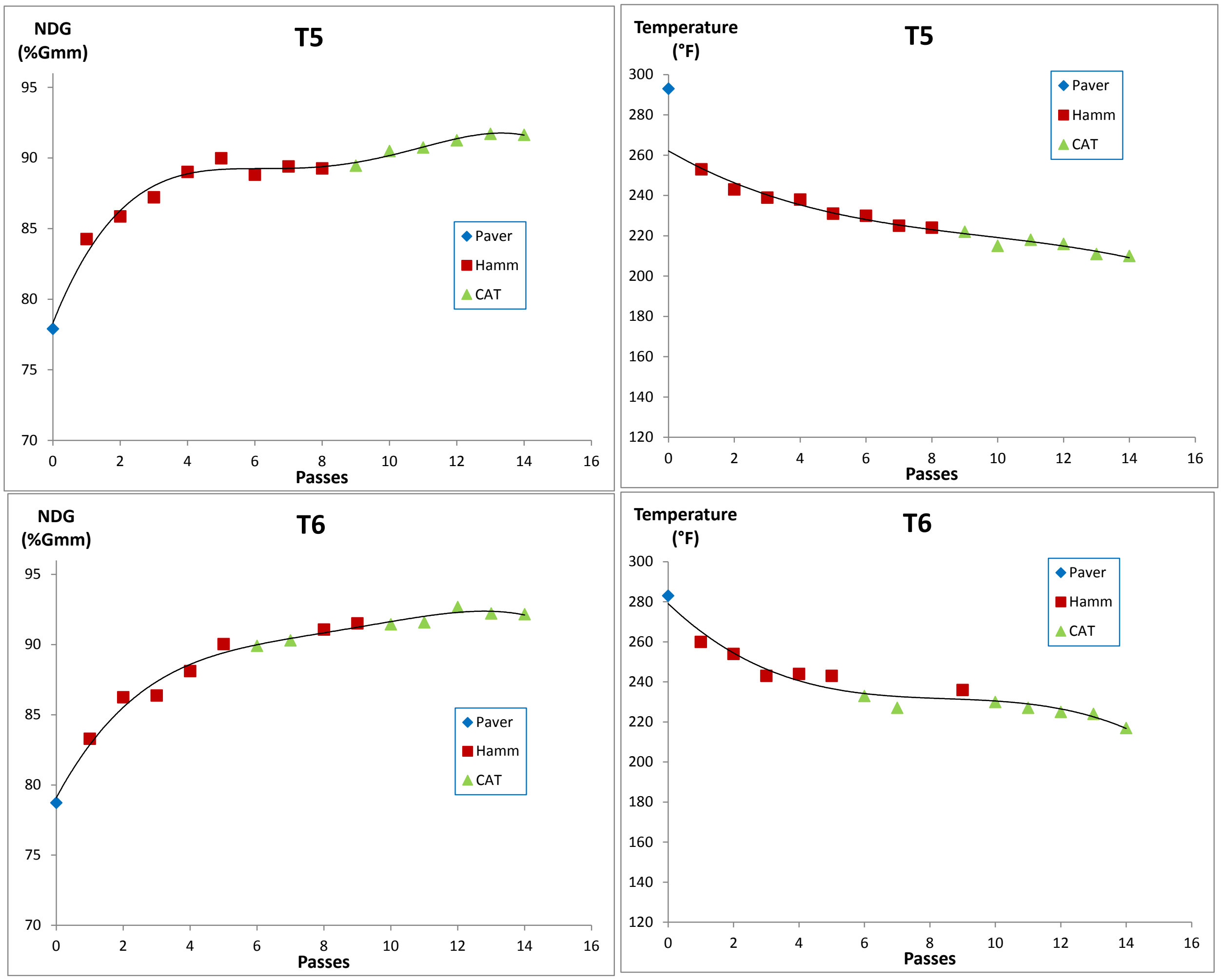


Figure 44. Pass-by-pass NDG densities and temperatures, WA site (2/2).

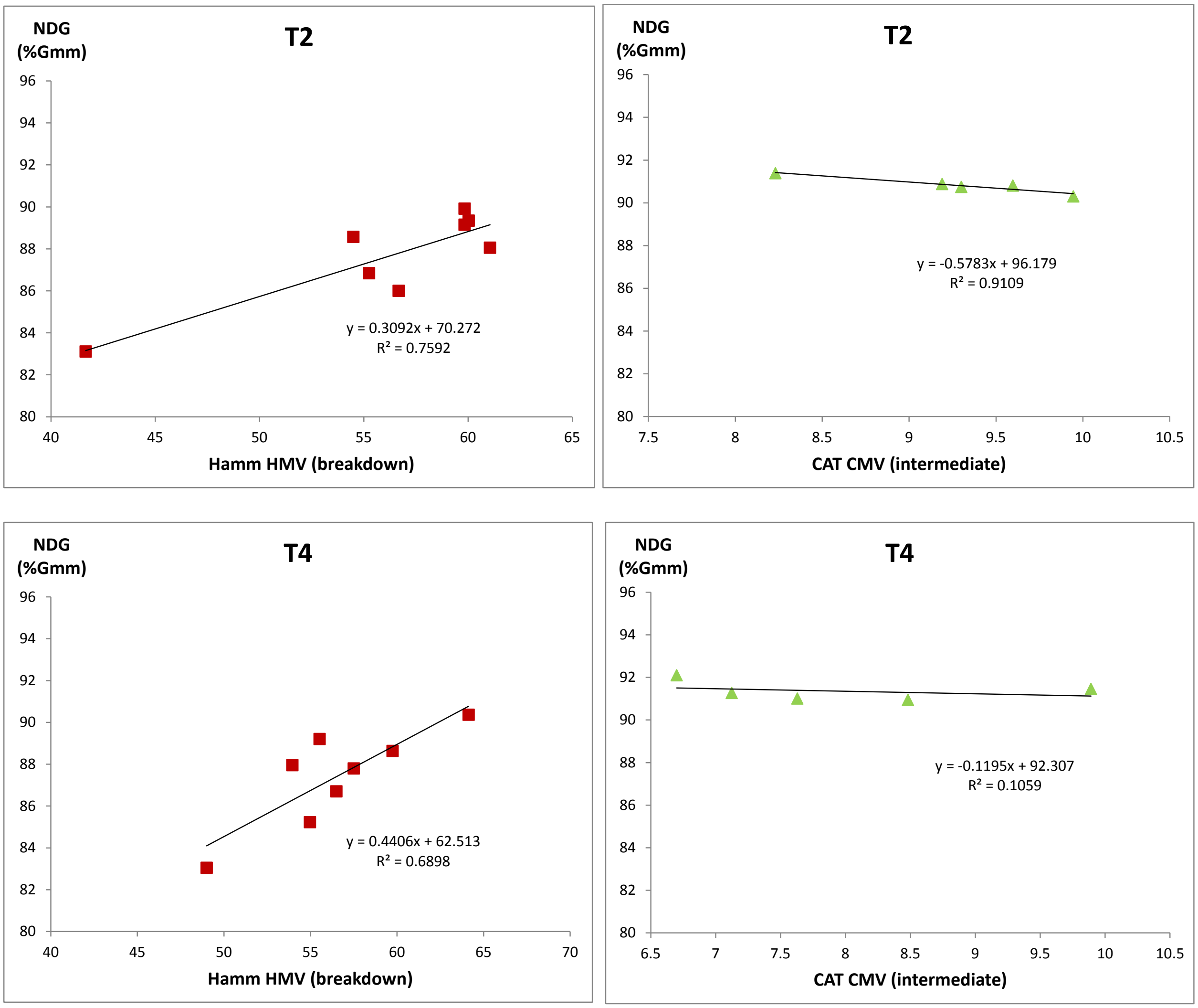


Figure 45. Pass-by-pass NDG densities vs. ICMV, WA site (1/2).

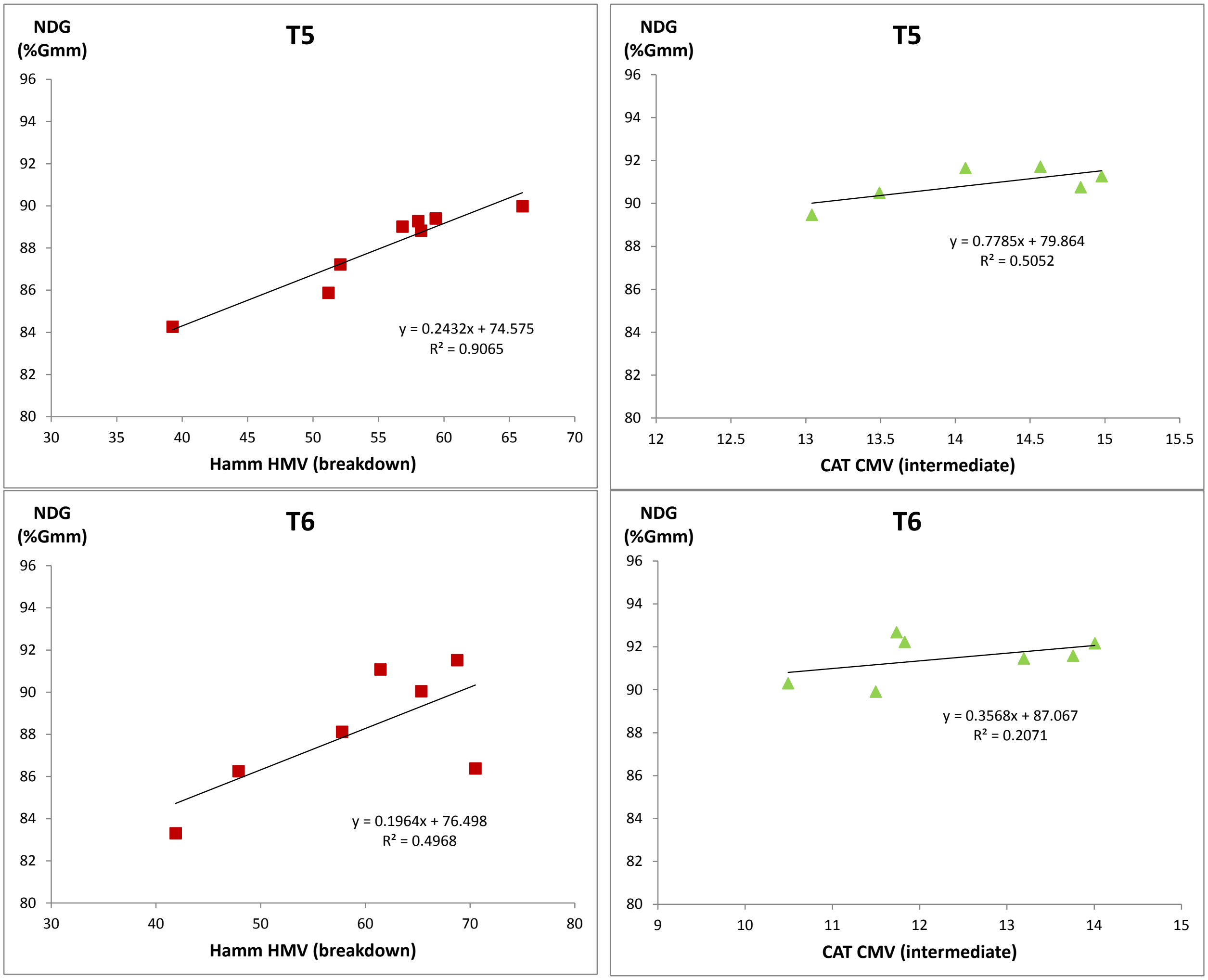


Figure 46. Pass-by-pass NDG densities vs. ICMV, WA site (2/2).

The above compaction curves and correlation analyses show that compaction characteristics may vary even within the same paving operation. It verifies the daily (or nightly) challenges that the paving industry has been facing. It also calls for improved technology in order to achieve better quality control for consistent asphalt paving products. The above correlation analysis also shows that pass-by-pass ICMV and NDG measurements correlate well with R^2 values from 0.49 to 0.97 during breakdown compaction (see Figure 47). The correlation, however, is less satisfactory during intermediate compaction (see Figure 48). Note that the data for UT, ME, and KY sites are not available. The R^2 values for correlation of NDG densities and breakdown ICMV are similar to R^2 values for correlation between NDG densities and core densities (see Figure 49). It is postulated that ICMV during breakdown compaction measures drum rebound as the compacted materials stiffens due to aggregate re-arrangements. During intermediate compaction or later, the stiffening of compacted materials may be due to binder hardening while the density or internal aggregate structure stays mostly constant. Thus, the ICMV would be less correlated to densities at the later stages of compaction. Further research is warranted with techniques such as micromechanics for investigating internal structures of asphalt cores:

- Field cores associated with IC compaction data can be tested with X-rays tomography to obtain information regarding the internal aggregate structure and asphalt film thicknesses.
- Micromechanical study of the above field cores and X-rays tomography data to characterize the mechanical properties associated with the internal aggregate structure and asphalt film thicknesses.
- Conventional bulk density tests can be performed on duplicates of these field cores by properly accredited laboratory and personnel.
- Performance tests can be performed on duplicates of the field cores regarding rutting, cracking, and water sensitivities.
- Comparisons between the above test data (IC data, bulk densities data, micromechanics data, and performance test data) will shed lights on the most relevant tests for performance.

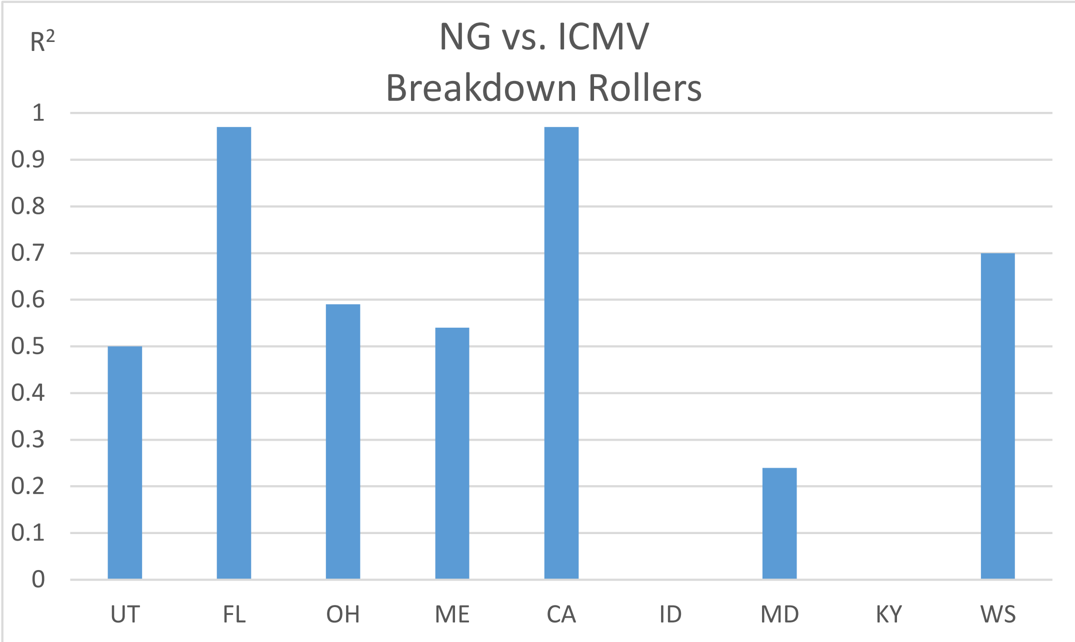


Figure 47. R^2 for correlation of Pass-by-Pass NDG density and ICMV (breakdown rollers).

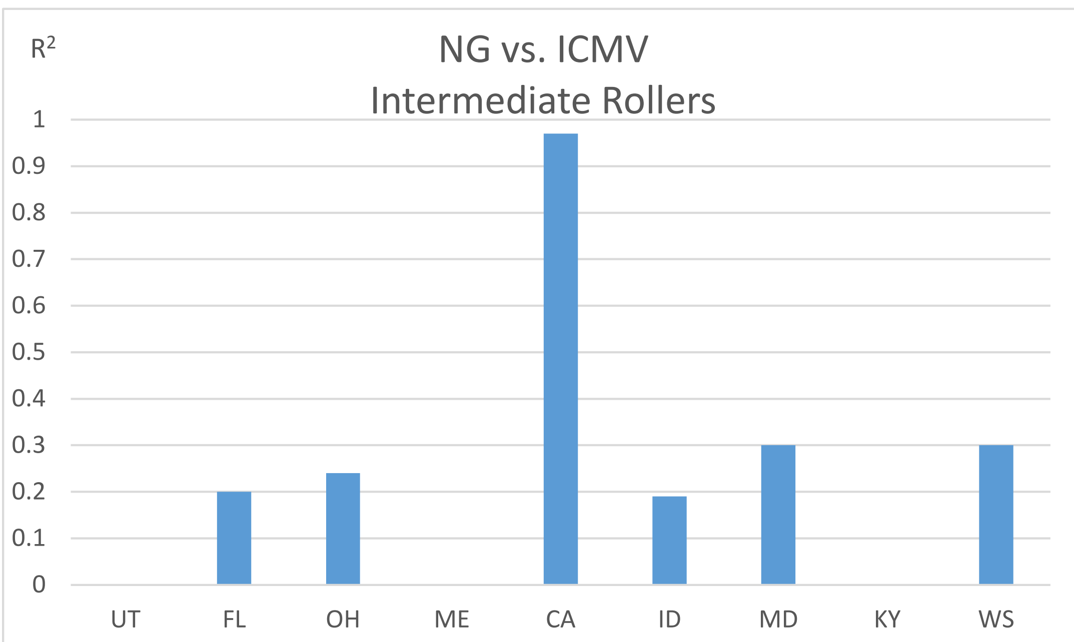


Figure 48. R^2 for correlation of Pass-by-Pass NDG density and ICMV (intermediate rollers).

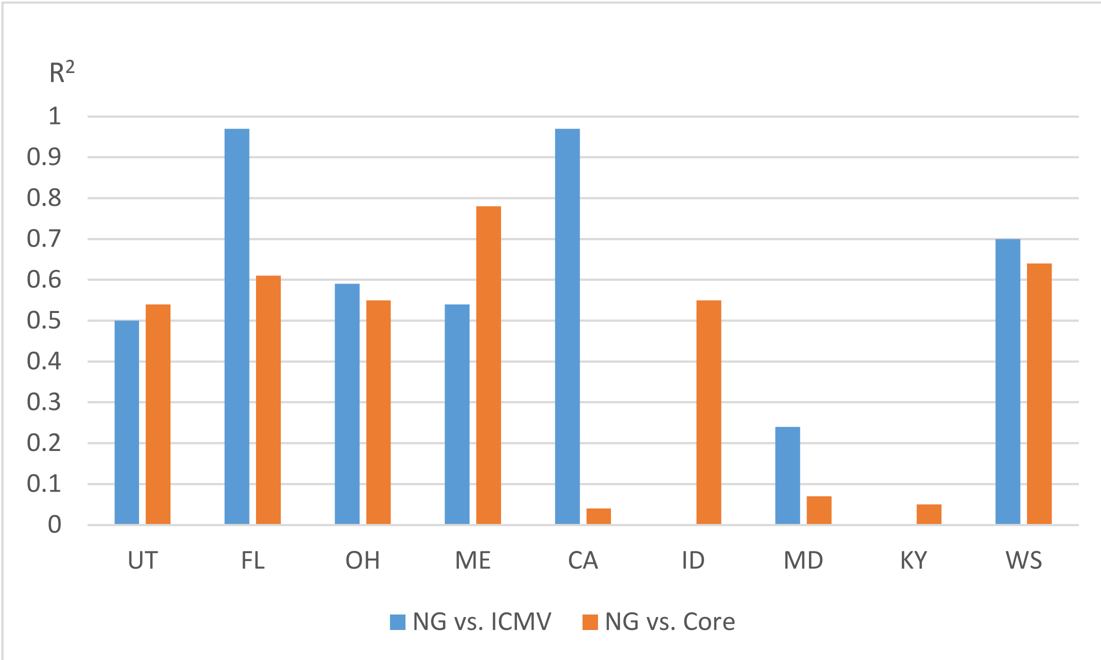


Figure 49. Comparison of correlation of NDG vs. ICMV (breakdown rollers) and NDG vs. cores.

Core Density vs. Nuclear Density Gauge Measurements

The core density data were correlated to NDG density data in order to shed some light on reliability of both data. The cores were taken on the same day after the finish roller. Dry ice was used to cool the asphalt prior to coring at some sites. Core density data were then obtained by state agency testing laboratories except for the CA site where the core density tests were conducted by a QC company. NDG measurements were typically conducted by contractors, but occasionally, by state agency representatives in the field. These data were obtained on site during construction. All NDG measurements were obtained using a back scatter method except at the WA site where NDG measurements were obtained using the direct transmission method.

The core density vs. NDG density analysis results are shown in Figure 50, Figure 51, and Figure 52. The results from the FL, OH, ME, ID and WA sites show relatively good correlation with R^2 ranging from 0.55 to 0.78 without significant bias. However, results from the CA, MD, and KY sites exhibit significant bias and very low correlation. Therefore, caution is to be taken when interpreting any core or NDG density correlation results for the CA, MD, and KY sites. Further investigation is warranted.

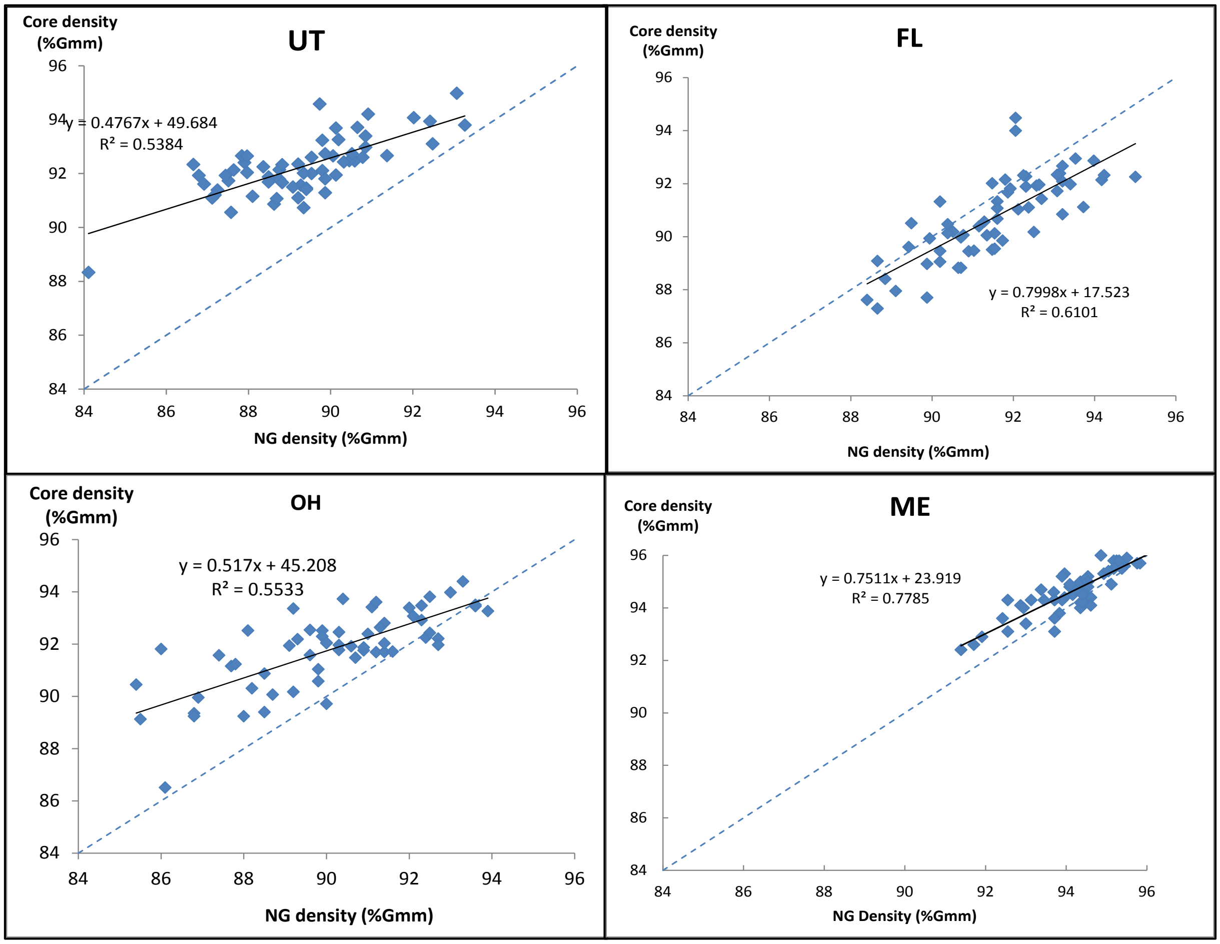


Figure 50. Correlation of Core density and NDG density (1/2).

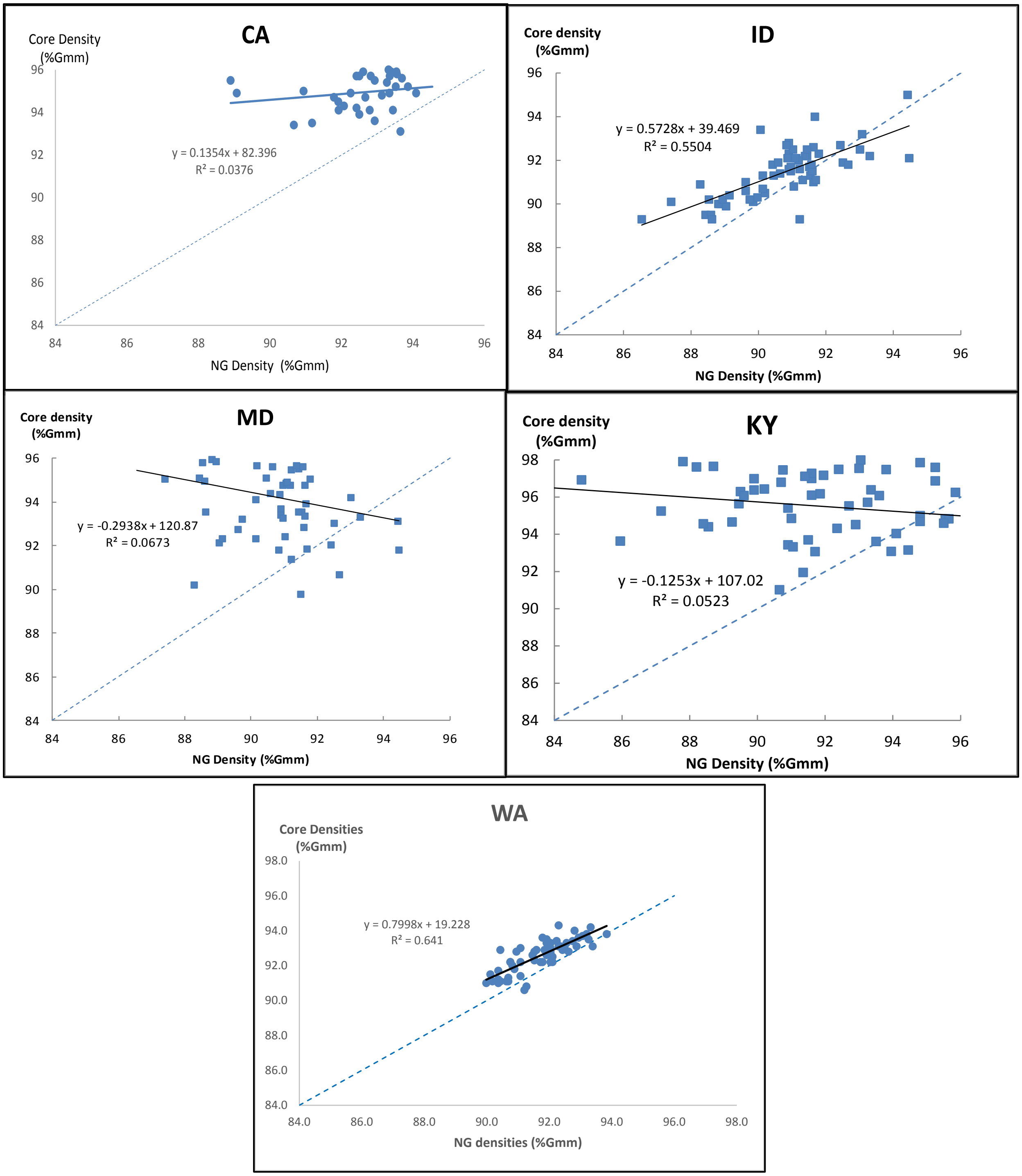


Figure 51. Correlation of Core density and NDG density (2/2).

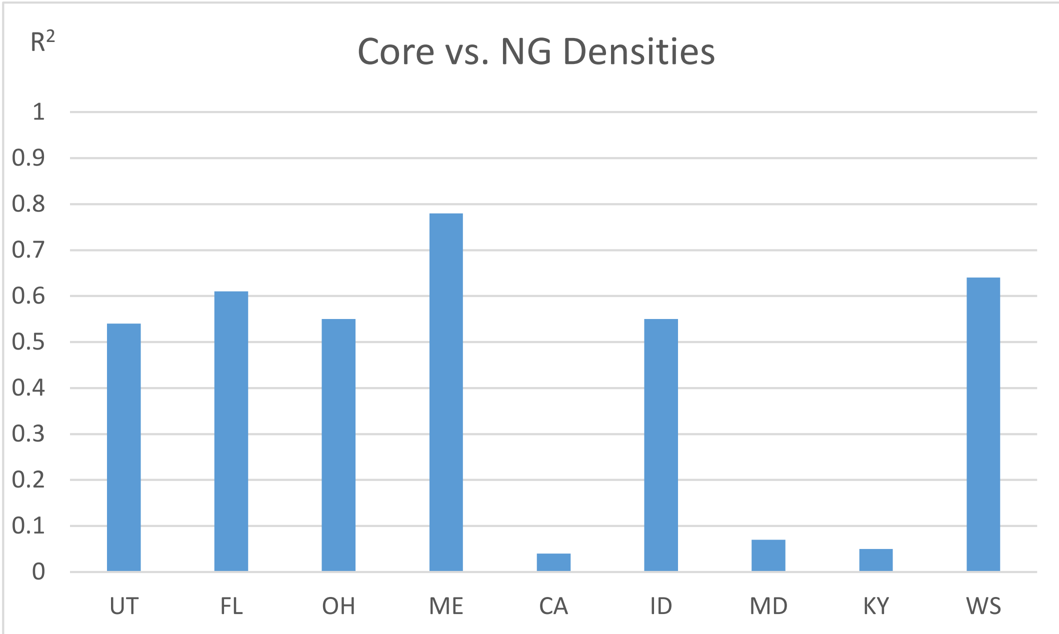


Figure 52. R^2 for correlation of core density and NDG density.

Generally, agencies require one core sample per 1,000 tons of asphalt paving as the conventional acceptance method. For the example of Utah core data, it is a 50% possibility that the density value may be greater than 92% by randomly selecting a location out of 60 samples (the median is 92.1%) (see Figure 53). Therefore, the possibility for passing or failing are approximately the same. Thus, there is always a risk for both state agency and contractor when using random sampling for acceptance.

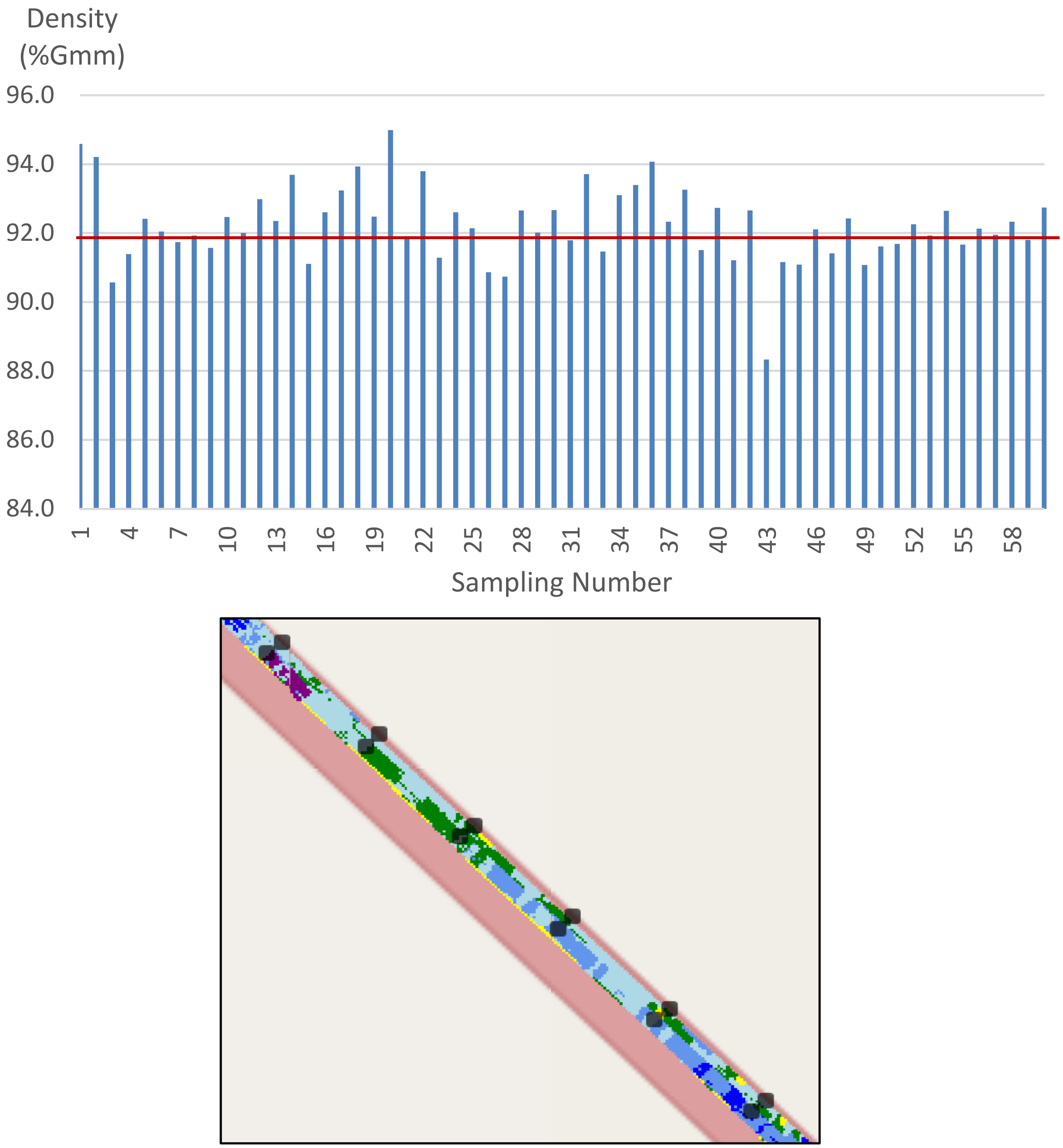


Figure 53. Core density and sampling locations (Utah site).

Core Density vs. LWD-a and FWD Tests

Both the LWD-a data and FWD were analyzed to produce asphalt layer moduli in order to be compared with the core density data. Even though density and moduli are fundamentally different properties, the comparison was used to investigate if there is any association between the two types of measurements. Please note that the load levels are different for LWD-a and FWD though both uses the same falling weight dynamic loading principles.

As mentioned in the Experiment Plan, the collected LWD-a data for each drop includes the deflections in time series, the drop speed, etc. By using the deflection data collected from these sensors, the modulus of pavement layers were back-calculated by Zorn's software program and normalized to values with respect to a referenced temperature, 78 ºF (20 ºC).

Also recalled in the Experiment Plan, the FWD data back-calculation was performed using a Transtec Group software based on the linear elastic layer theory to obtain layer moduli. The back-calculation results from this tool were validated with popular tools such as the MODULI program. Deflections at sensor no.1 were normalized to those w.r.t. 9,000 lbs load. The normalized deflections are an indication of the structural capacity of the entire pavement.

The correlation analysis results between core densities and LWD-a are shown in Figure 54 (for the FL, OH, ME, and CA sites) and Figure 55 (for the KY, MD, ID, and WA sites). As seen in both figures, the correlation between core densities and asphalt layer moduli back-calculated from LWD-a data is poor.

The correlation analysis results between core densities and FWD are shown in Figure 56 (for the FL and CA sites) and Figure 57 (for the ME and WA sites). As seen in both figures, the correlation between core densities and asphalt layer moduli back-calculated from FWD data is poor. As seen in both figures, the correlation between core densities and normalized FWD deflections is also poor.

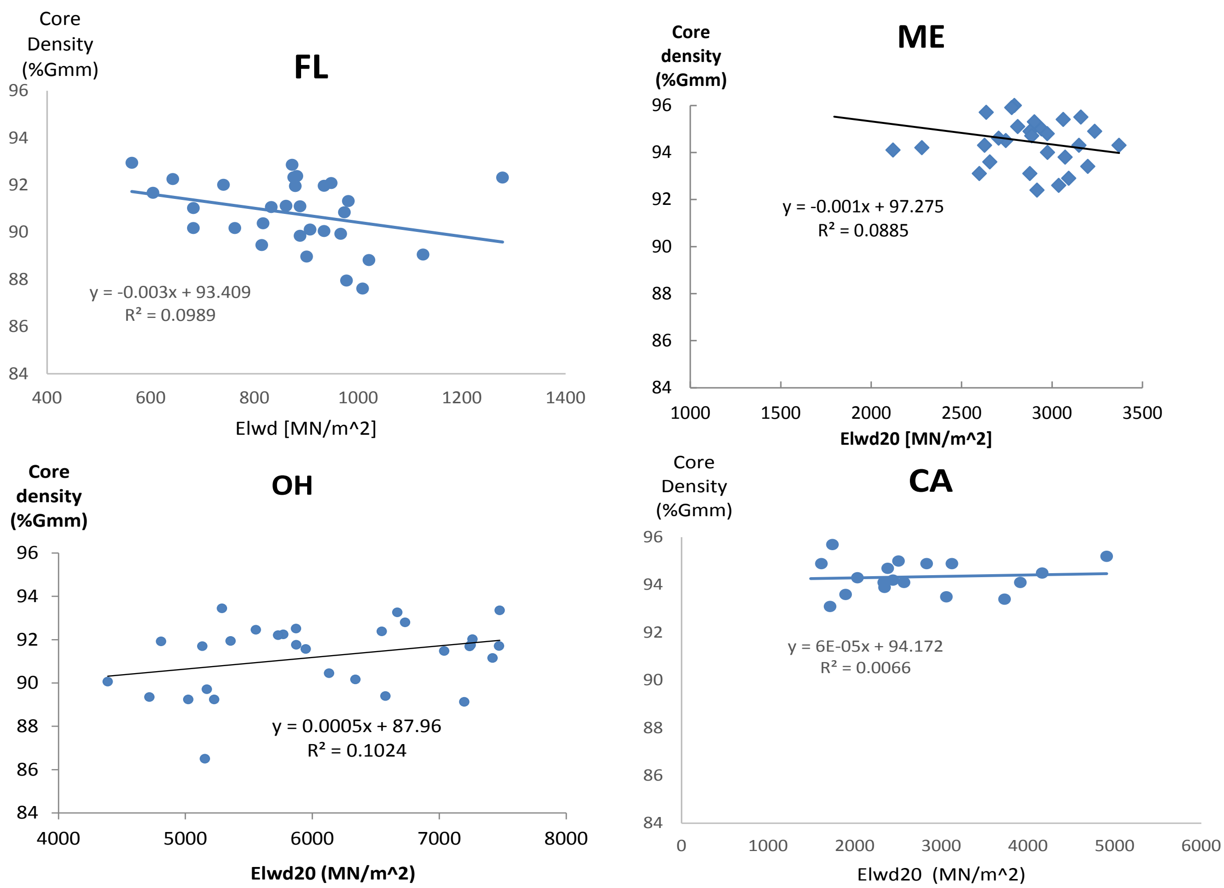


Figure 54. Correlation between core densities and asphalt layer moduli back-calculated from LWD-a test (1/2).

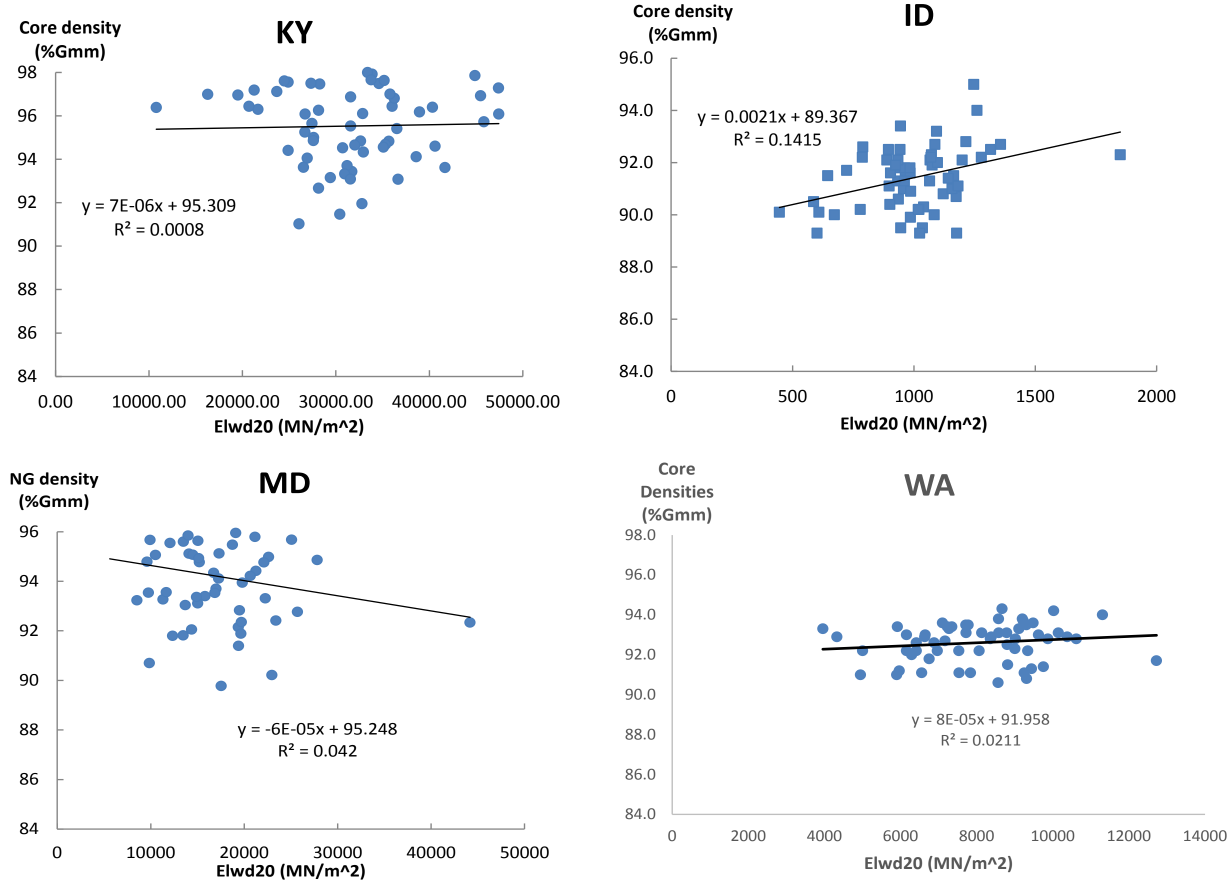


Figure 55. Correlation between core densities and asphalt layer moduli back-calculated from LWD-a test (2/2).

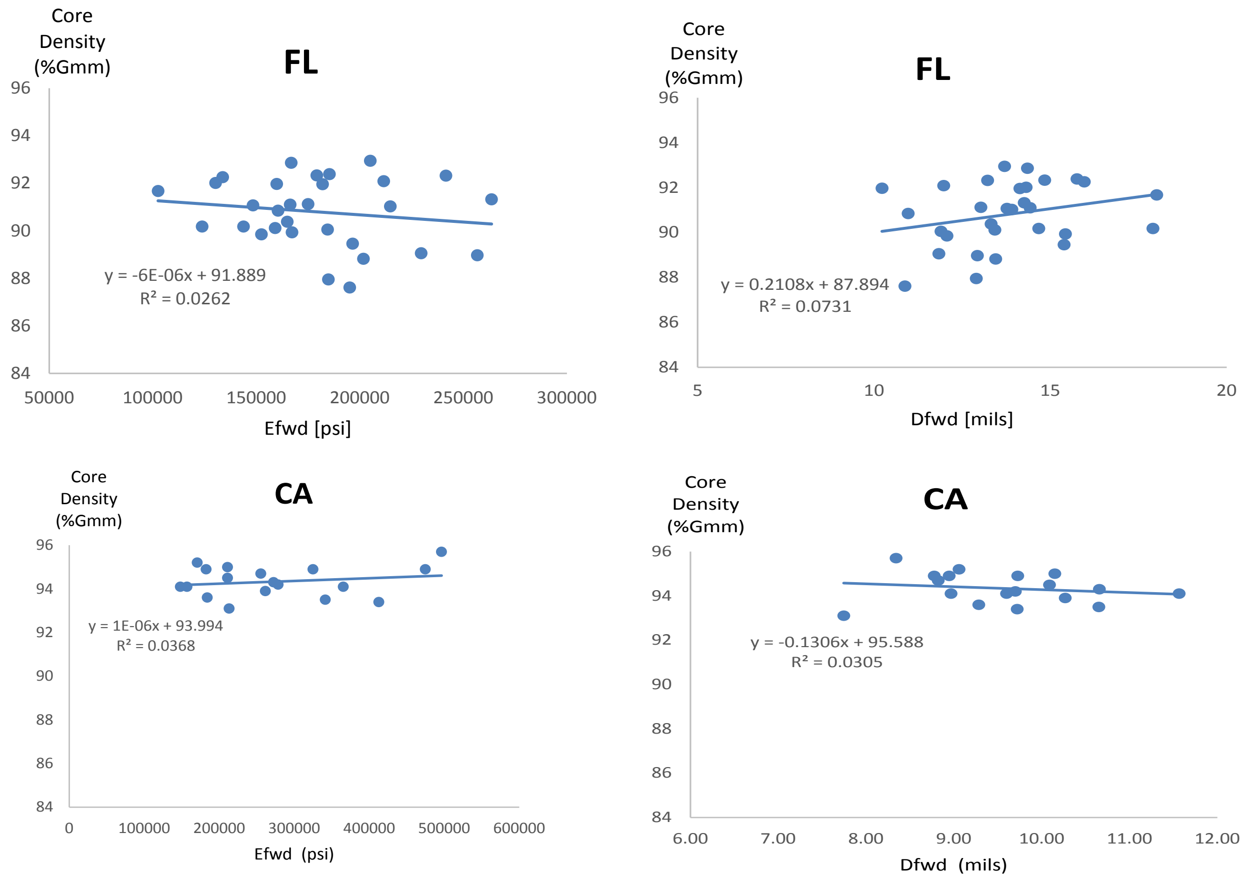


Figure 56. Correlation between core densities and asphalt layer moduli back-calculated from FWD test and normalized FWD Defections (1/2).

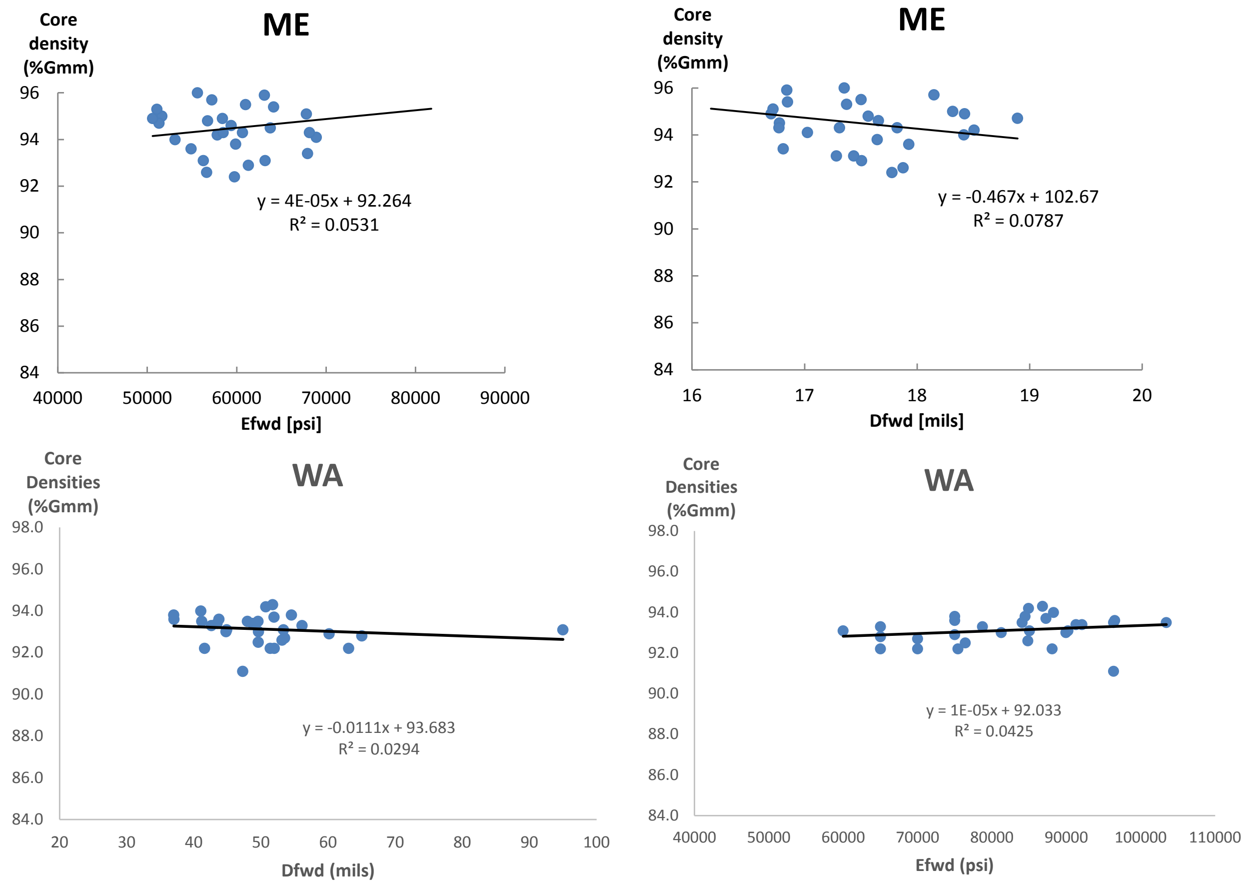


Figure 57. Correlation between core densities and asphalt layer moduli back-calculated from FWD test and normalized FWD Defections (2/2).

Final Coverage ICMV vs. LWD-a

The final coverage ICMV are the last pass values for a given compaction stage. LWD-a test has been considered as a candidate spot test method for correlating conventional measurement values (such as layer moduli) to IC measurements. However, the layer moduli back-calculated from LWD-a data indicate a measure depth much shallower than that of ICMV. Furthermore, the current ICMV from various vendors are not yet de-coupled to represent values corresponding to different layers of a pavement structure. The following analysis is to illustrate the current limitation.

The correlation analysis results between breakdown final coverage ICMV and LWD-a are shown in Figure 58 for the FL, OH, ME, ID, KY, and WA sites. As seen in this figure, the correlation between breakdown final coverage ICMV and asphalt layer moduli back-calculated from LWD-a data is poor. These results reflect the limitations described above. However, it is anticipated improvement of correlation between ICMV and LWD-a once ICMV is de-coupled or broken down to layer responses.

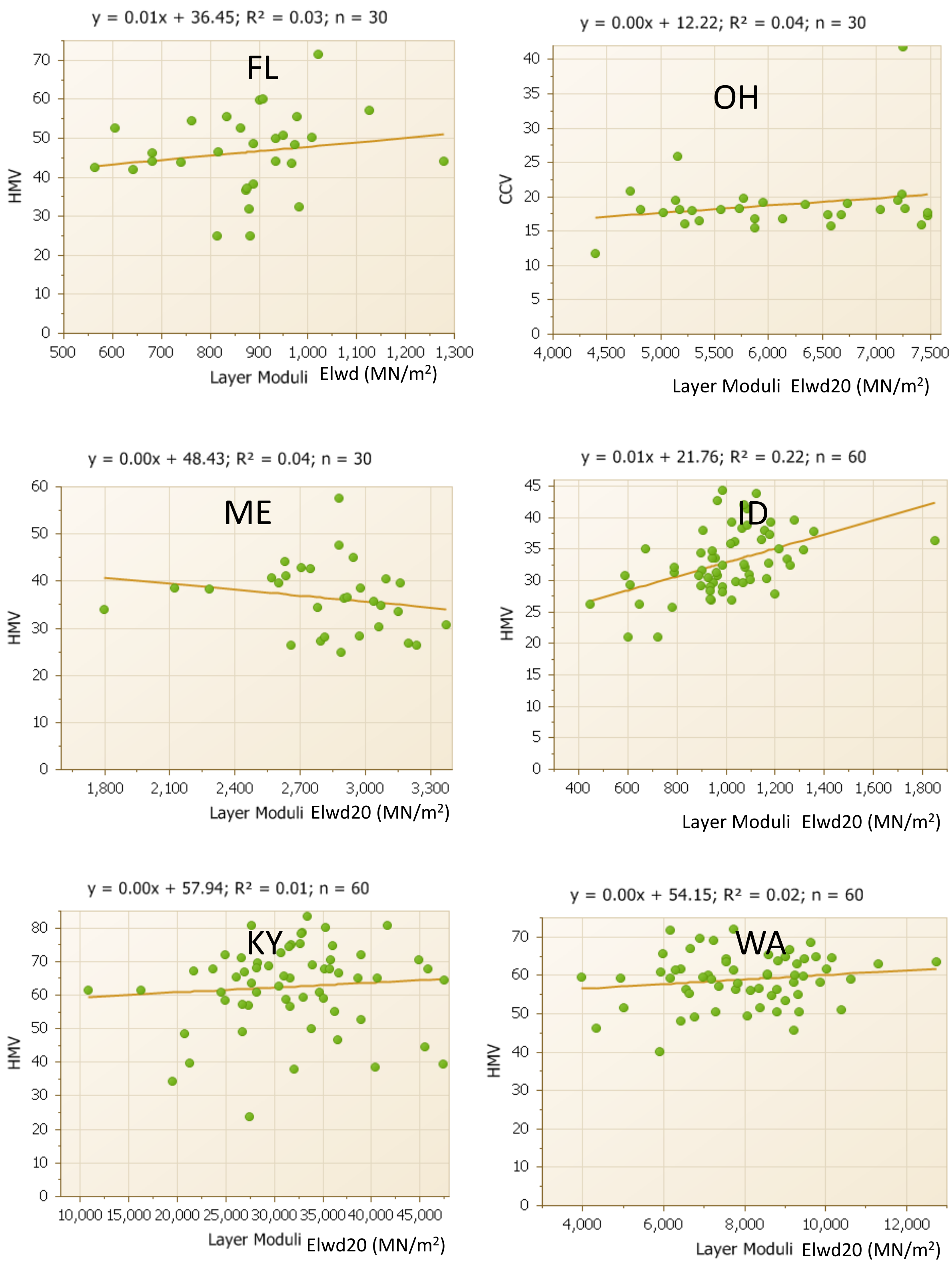


Figure 58. Correlation between breakdown final coverage ICMV and asphalt layer moduli backcalculated from LWD-a data.

Core Density vs. Final Coverage ICMV Data

There were sixty (60) cores taken during each field validation, a total of 515 cores (with a few missed at the CA site), which is considered unprecedented and valuable for a correlation study with IC. The correlation between core densities and final coverage ICMV data from all field sites are presented in Figure 59 and Figure 60 for the breakdown rollers and in Figure 61 and Figure 62 for the intermediate rollers, respectively. The charts within both figures indicate a lack of relationship between core densities and final coverage ICMV data for both breakdown roller data and intermediate roller data. The trends of some correlation are even in the opposite direction.

These results of final coverage ICMV-core density correlation are very different from the analyses for pass-by-pass ICMV and NDG data. This inconsistency may be due to the followings:

- As the asphalt temperatures drop under certain level, such as the glassy temperatures of a specific binder, the correlation between the final coverage ICMV and density become poor. As the asphalt layer stiffens, the roller drum rebounds are associated with deeper pavement structure than the asphalt layer thickness.
- The variability of density compaction curves indicates significant variability exists in density gain patterns even with the same equipment, materials, and crew.
- There is a gap of records between what the IC measures and the final core results including any gains (further compaction) or loss (de-compaction) of density due to subsequent intermediate or finish compaction.
- Due to the relatively narrow range of core densities, the minute gains/loss of density may affect the correlation.
- The ICMV, due to its influence depth, may simply reflect more on the support condition instead of inter-aggregate contacts of the upper layers during compaction and densification.
- Therefore, further research is recommended to perform final mapping on the finished asphalt surface with IC rolling at low vibration amplitude and frequency as roofing measurements to better correlate to the asphalt layer.

With data from more than 515 cores and IC data from all field sites, there is strong evidence that final coverage ICMV alone cannot be correlated to the core densities.

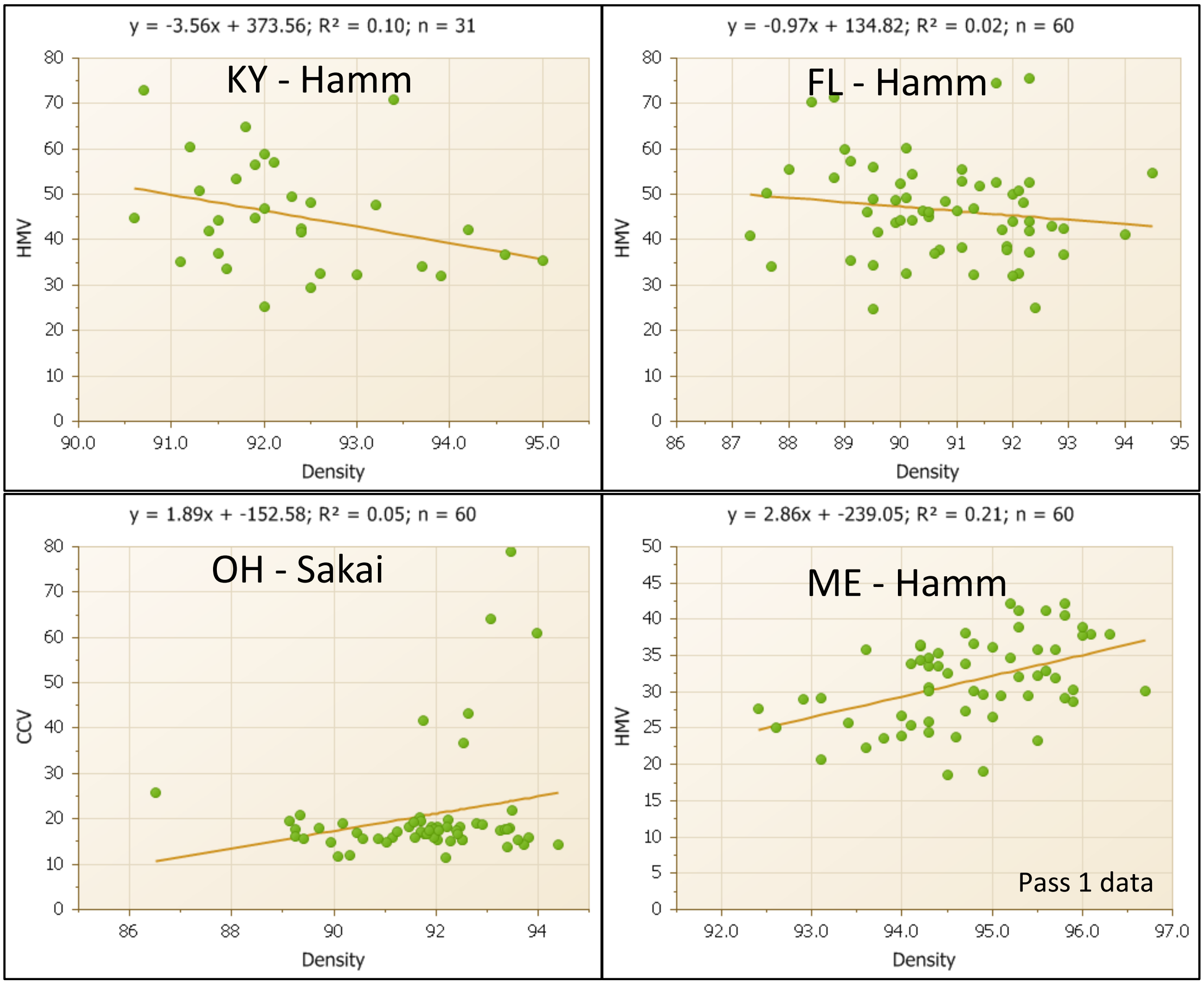


Figure 59. Core density data vs. Final Coverage ICMV from breakdown rollers (1/2).

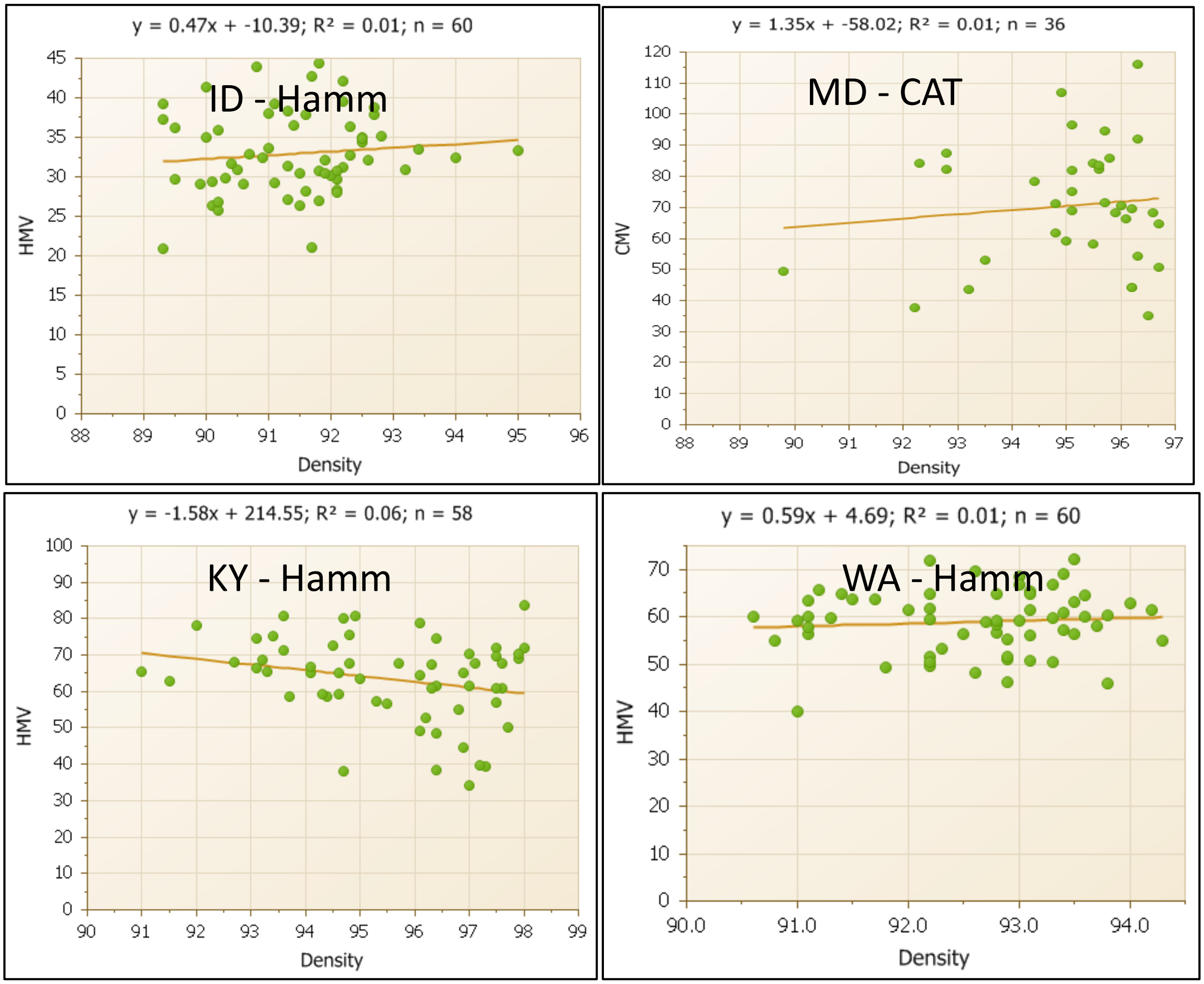


Figure 60. Core density data vs. Final Coverage ICMV from breakdown rollers (2/2).

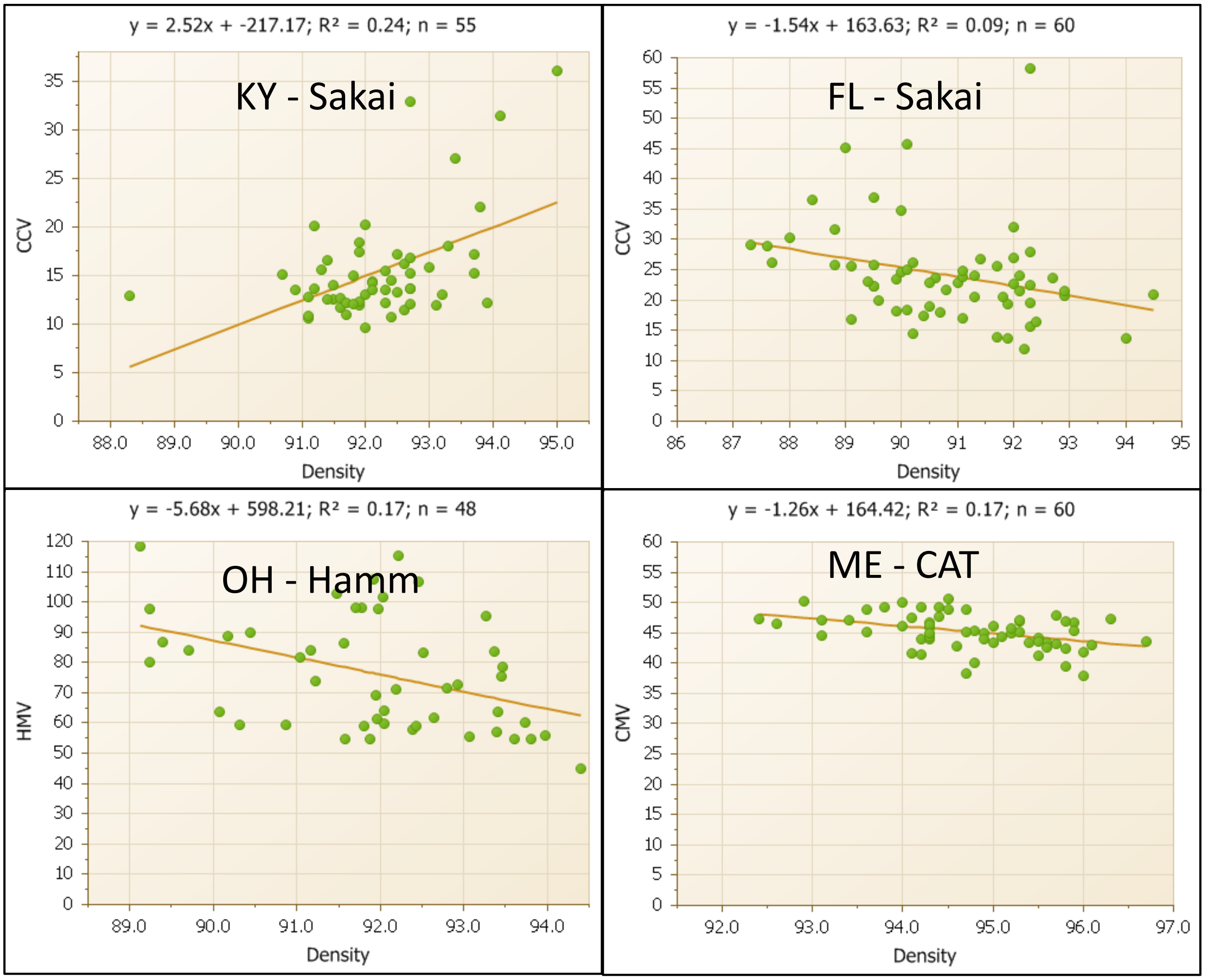


Figure 61. Core density data vs. ICMV from intermediate rollers (1/2).

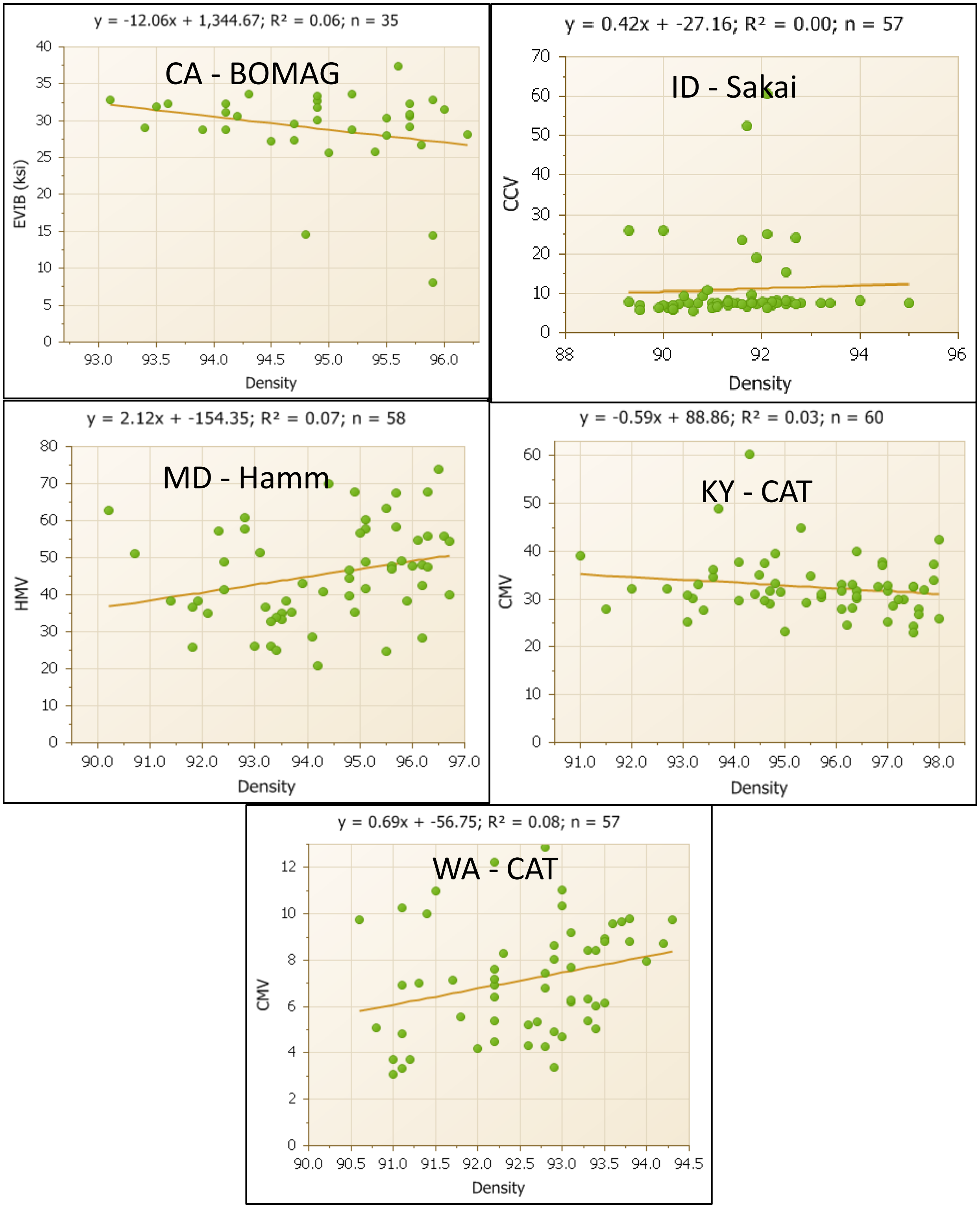
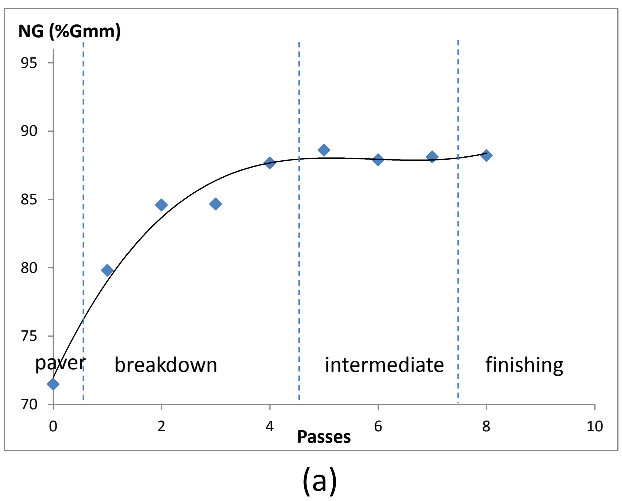


Figure 62. Core density data vs. ICMV from intermediate rollers (2/2).

Chapter 5 IC-Based Density Model

There are many contributing factors in a complex construction environment that affect in-place asphalt densities. The known factors include nominal aggregate size to layer thickness ratios, aggregate shapes and gradation, binder and binder additives, reclaimed asphalt pavements, material transfer vehicles, pavers, etc. In the field, the densification of asphalt is mainly achieved during breakdown and intermediate compaction at elevated temperatures while the increase of density due to finish compaction is minimal. An example of a density compaction curve and temperature drop is shown in Figure 63. As described in Chapter 4, different densification curves were observed at different locations of a field project even though the same equipment and materials were used by the same crew for the construction process. Therefore, the densification characteristic is very complex.



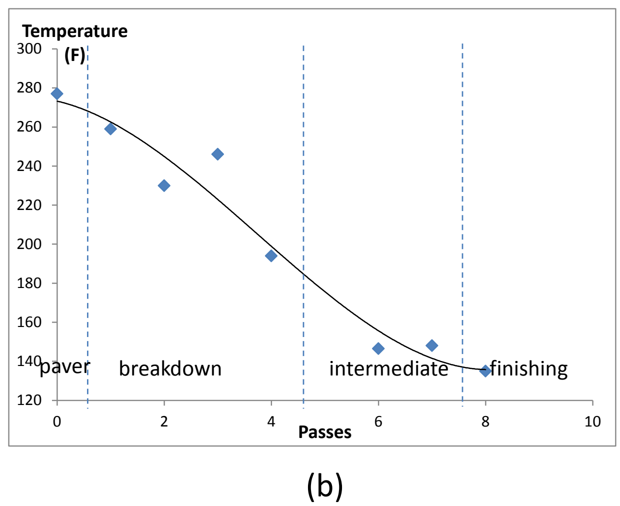


Figure 63. (a) Density compaction curve and (b) temperature drops during compaction, Test Point 1, Maine Site.

As described in Chapter 4, the correlation between asphalt core densities and final coverage ICMV is low. Although the correlation between NDG density measurement and ICMV from the breakdown rollers is satisfactory, there is a need for an IC-based density model to predict the in-place asphalt densities.

This model development effort considers multiple factors during the compaction process and is intended to fill the gap between breakdown/intermediate and finish compaction. The goal of this

IC-based model is to be calibrated for project-specific application in order to be a practical quality assurance tool for real-time in-place asphalt density prediction during production compaction.

The following consists of the details for the development and validation of this IC-based density model to predict in-place asphalt density during production compaction.

Density Model Development

Multivariate Linear Panel Density Model

A heterogeneous panel data model with fixed effects at the geospatial local level was developed as follows. Local level means the area within the foot print of a roller drum. Panel data refers to multi-dimensional data frequently involving measurements over time. The model parameters, such as constants and slope coefficients, vary across different geospatial locations:

$$\rho(i,j) = \rho_0(i) + \sum_{k=1}^{N} \beta_k(i) X_k(i,j) + \varepsilon(i,j) \tag{5}$$

Where

i is the location index associated with GPS coordinates, $\forall\ i = 1,2 \ldots \ldots n$;

j is the time index associated with roller pass numbers, $\forall j = 1,2 \ldots m$;

$\rho_0(i)$ is the individual heterogeneity, an intercept at the i^{th} location;

$X(i,j)$ is the observed independent variable at the i^{th} index and j^{th} index;

$\beta_k(i)$ is the slope of the k^{th} independent variable at the i^{th} location for $k = 1,2,3 \ldots N$ as the number of independent variables;

$\varepsilon(i,j)$ is the idiosyncratic errors or idiosyncratic disturbances at the i^{th} index and j^{th} index due to uncertainty, which is assumed to follow the normal distribution.

Idiosyncratic error is used to describe error from panel data that both changes over time and across units. The idiosyncratic error term refers to the observation-specific zero-mean random-error term. It is analogous to the random-error term of cross-sectional regression analysis.

The initial density, $\rho_0(i)$, is treated as a constant with unobserved effect since it is a parameter to be estimated for each cross section observation at the i^{th} location if measurement is not available (mostly), which could be primarily dependent on the initial material density and other initial conditions including the underlying support before roller vibratory compaction. A Kriging model is proposed to estimate idiosyncratic errors ε as described in a later section.

At the project level, one universal model is used to predict material densities of all locations within the project zone. Therefore, the location effect is dismissed and a homogeneous or pooled panel model with fixed effect can be derived as follows:

$$\rho(i,j) = \rho_0 + \sum_{k=1}^{N} \beta_k X_k(i,j) + \varepsilon(i) \tag{6}$$

Where

ρ_0 is the fixed effect at the initial condition, i.e. the initial density right behind paver;

ε is the fixed-effect error across location, which is assumed to follow the normal distribution.

Using the ordinary least square (OLS) method, the fixed-effect estimated slope $\hat{\beta}_k$ can be determined as follows:

$$\hat{\beta}_k = \left[\sum_{i=1}^{n}\sum_{j=1}^{m}(X_k(i,j) - \bar{X}_k(i))(X(i,j) - \bar{X}_k(i))^T\right]^{-1}\left[\sum_{j=1}^{m}\sum_{i=1}^{n}(X_k(i,j) - \bar{X}_k(i))(\rho(i,j) - \bar{\rho}(i))\right] \tag{7}$$

Where

$\bar{X}(i)$ is the mean value of observations of independent variables at the i^{th} index across all time indexes of j;

$\bar{\rho}(i)$ is the mean density at the i^{th} location across all time indexes of j.

For example, with implementation to one construction project, a fixed-effect project-level multivariate linear panel data model based on IC measurements can be expressed as follows:

$$\rho(i,j) = \rho_0 + \beta_1 ICMV(i,j) + \beta_2 f(i,j) + \beta_3 T(i,j) + \beta_4 V_R(i,j) + \beta_4 A(i,j) + \varepsilon(i) \qquad (8)$$

Where

β_i for $i = 1,2,3,4$ are slopes;

f is vibration frequency;

T is temperature;

V_R is roller speed;

A is vibration amplitude.

ICMV indicates stiffness of materials and underlying support conditions.

Multivariate Nonlinear Panel Density Model

A heterogeneous panel-data multivariate nonlinear model based on IC measurements was developed from multiple trials using different mathematical formulations. Two model types for the local level are proposed as follows, Model I:

$$\rho(i,j) = \rho_0(i) + (\rho_{max} - \rho_0(i)e^{\left[\frac{\sum_k \alpha_k x_k(j)}{j}\right]^{\beta}} + \varepsilon(i,j) \qquad (9)$$

and Model II:

$$\rho(i,j) = \rho(i,j-1) + (\rho_{max} - \rho(i,j-1))e^{-\left[\frac{\sum_k \alpha_k x_k(j)}{j}\right]^{\beta}} + \varepsilon(i,j) \qquad (10)$$

Where

$\rho(i,j)$ is material density at the location i and time index or pass count j;

ρ_{max} is maximum density of the specific material that could be up to 100%.

The physical meanings of the model parameters can be explained as follows:

- Incremental density increase after each roller pass could not exceed the difference between maximum value and the previous or initial density value;
- The exponential term is to restrain the density prediction within 100% Gmm; and
- The β parameter is used to describe how fast the density changes vs. time/pass counts (a higher β value indicates a greater increment across the time index j).

At the project level, the homogeneous panel data-data multivariate nonlinear models with fixed effect can be expressed as follows:

Model I:

$$\rho(i,j) = \rho_0 + (\rho_{max} - \rho_0) \times e^{-\left[\frac{\sum_k \alpha_k X_k(i,j)}{j}\right]^{\beta}} + \varepsilon(i) \tag{11}$$

and Model II:

$$\rho(i,j) = \rho(i,j-1) + (\rho_{max} - \rho(i,j-1)) \times e^{-\left[\frac{\sum_k \alpha_k X_k(j)}{j}\right]^{\beta}} + \varepsilon(i) \tag{12}$$

When implementing this model for a construction project, the material density at the project level is predicted as follows:

$$\rho(i,j) = \rho_0 + (\rho_{max} - \rho_0) \times e^{-\left[\frac{a_1 ICMV(i,j) + a_2 f(i,j) + a_3 V_R(i,j) + a_4 (T(i,j) - T_r)}{j}\right]^{\beta}} + \varepsilon(i) \tag{13}$$

or

$$\rho(i,j) = \rho(i,j-1) + \left(\rho_{max} - \rho(i,j-1)\right) \times e^{-\left[\frac{a_1 ICMV(i,j) + a_2 f(i,j) + a_3 V_R(i,j) + a_4 (T(i,j) - T_r)}{j}\right]^{\beta}} + \varepsilon(i) \tag{14}$$

Where

T_r is reference temperature.

To determine the model parameters for density prediction, a few samples at coring locations are used to determine model parameters.

For the linear model, model parameters are estimated following the OLS method. For the nonlinear model, the Frank-Wolfe algorithm is used for the nonlinear programming for a constrained optimization (Clarkson et al. 2010) as follows:

$$\min \mathcal{L} = \sum_{i=1}^{n} \sum_{j=1}^{m} [\rho(i,j) - \hat{\rho}(i,j)]^2 / mn \quad (15)\text{-a}$$

$$\forall \beta \in (0,2] \quad (15)\text{-b}$$

$$\forall \rho_0 \in (0,100) \quad (15)\text{-c}$$

Where

$\hat{\rho}(i,j)$ is the measured density at location i and time index j;

$\rho\ (i,j)$ is the predicted density.

Equations (15)-b and (15)-c are constrained conditions. To validate the model, the fitted model parameters from a subset of samples (e.g., 5) are used to simulate the large samples measured at all those coring locations (e.g., 60), and the root mean squared (R^2) value is used for evaluation of mode fit.

Kriging Method

The Kriging Method is a geospatial estimation method to guess the missed points. The basic form of the Kriging model as a linear regression estimator can be expressed as follows (Goovaerts 1997):

$$Z^*(u) = m(u) + \sum_{a=1}^{n(u)} \lambda_\alpha [Z(u_\alpha) - m(u_\alpha)] \tag{16}$$

Where

u is location vector for estimation;

$u(a)$ is location vector of the neighboring data points, and a is number of a data point;

$n(u)$ is number of data points in the neighbor;

$m(u)$ and $m(u_a)$ are means of $z(u)$ and $z(u_a)$;

λ_a is kriging weight assigned to the datum $z(u_a)$.

In this study, a Kriging model was used to estimate idiosyncratic errors of density prediction $\varepsilon_\rho(i)$ using those observed errors in calibration location to consider both the geospatial effects and the linear effects of the IC information, as follows:

$$\varepsilon_\rho(u) = \left|1 - \sum_{a=1}^{n(u)} \lambda_\alpha\right| m(\varepsilon_\rho) + \sum_{a=1}^{n(u)} \lambda_\alpha \varepsilon_\rho(u_\alpha) + \sum_k \gamma_k X_k(u) \tag{17}$$

Where

ε_ρ and $m(\varepsilon_\rho)$ are idiosyncratic error of density prediction and its mean value;

$X_k(u)$ is the observed variable (IC information) at the location vector u for $k = 1,2 \ldots N$;

γ_k is the fitted model parameters.

The weight parameter λ_α is determined by minimizing the variance of the error estimation:

$$min\mathcal{L} = \sigma^2\left[\hat{\varepsilon}_\rho(u) - \varepsilon_\rho(u)\right] \tag{18}$$

Where

$\hat{\varepsilon}_\rho(u)$ is the observed error at location u from the experimental data.

Density Model Validation

The density model validation was performed via IC data and in situ density measurements from the nine field sites that are described in Chapter 3. The process for density model validation is illustrated in Figure 64.

IC data and intensive in-place asphalt density measurements using the NDG and cores were collected in a test strip for a given site. The IC data and in-place density data were analyzed using the Veda software (Figure 65). IC data with respect to asphalt density measurements were extracted for both all-passes and final coverage data. Pass-by-pass data and a subset of the final coverage data set were used to fit the IC-density model using the Excel Solver function. During the solving process, all unconstrained variables were made positive and the evolutionary method was used to find a good solution to a reasonably well-scaled model. The fitted model was then validated using the remaining data set.

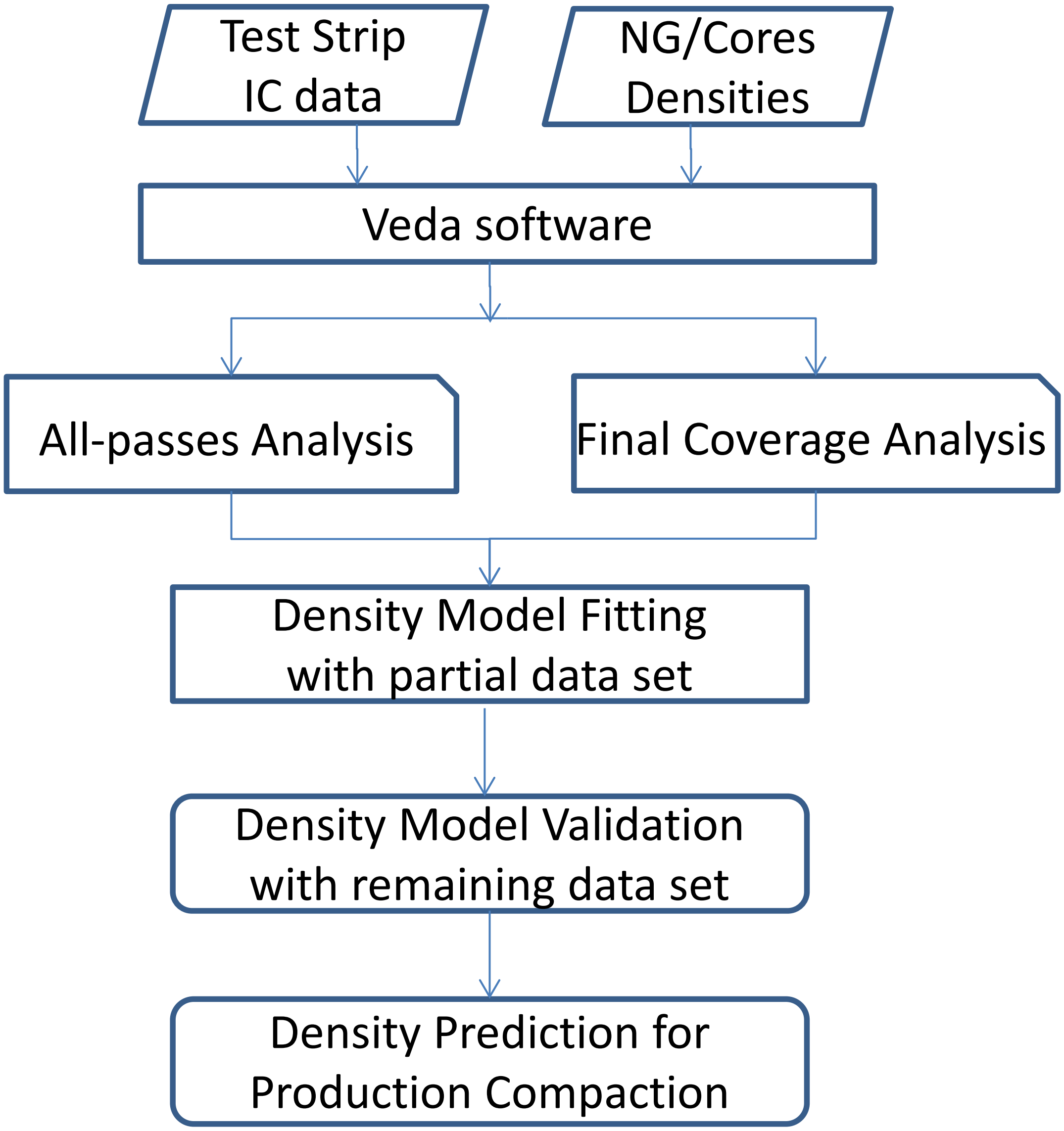


Figure 64. The process for IC-density model validation.

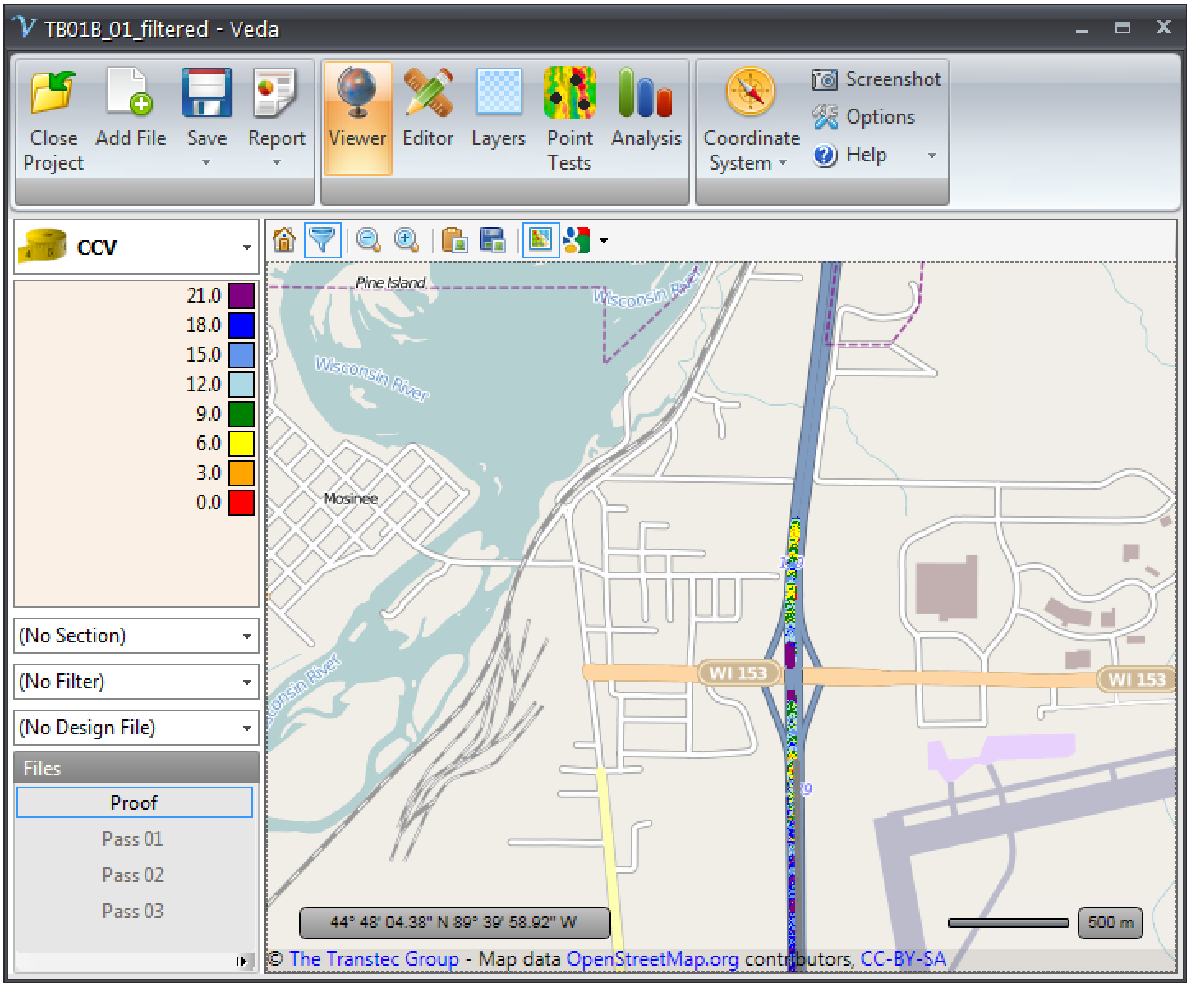


Figure 65. Veda software for IC data viewing and analysis (Veda 2014).

Linear Model Validation

The simple linear correlation between ICMV with NDG density for the local level of pass-by-pass data is presented in Figure 66. The R^2 ranges from 0.38 to 0.94 indicating poor to good correlation. It can be deduced that ICMV measurements during breakdown compaction do reflect the actual in-place asphalt density. The multivariate linear panel data model with fixed effect at the local level achieves fairly good correlation for the Maine site (Table 9). The R^2 is 0.95 and the adjusted R^2 is 0.87. The adjusted R^2 is to penalize the statistic when extra variables are included in the model.

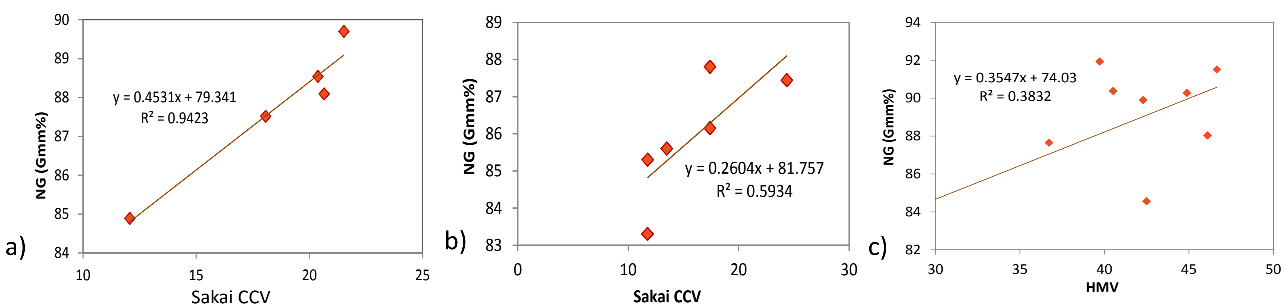


Figure 66. NDG density versus ICMV for projects in a) Florida; b) Ohio; and c) Maine.

Table 9. Multivariate linear density model at local level - Maine project, R^2=0.95 and adjusted R^2=0.87

Parameter	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept (%Gmm)	-58.57	177.38	-0.33	0.76	-623.08	505.94
HMV	0.27	0.33	0.79	0.49	-0.80	1.33
Frequency (Hz)	0.36	0.60	0.60	0.59	-1.55	2.28
Roller Speed (kph)	-6.18	12.15	-0.51	0.65	-44.84	32.48
Temperature (˚C)	1.07	1.43	0.75	0.51	-3.47	5.61
Pass count	3.56	3.40	1.05	0.37	-7.26	14.39

However, the density prediction at the project level using the homogeneous multivariate linear model with fixed effects yields a relatively poor correlation, as shown in Figure 67. The prediction values could exceed the max value of 100%G_{mm} (see the data points above the red dash line in Figure 67b). A significant portion of predictions are beyond the confidence level of $(\rho - \sigma, \rho + \sigma)$, where ρ is measured density and σ is its standard deviation. This indicates that the uncaptured nonlinearity for the density growth at the project level exists.

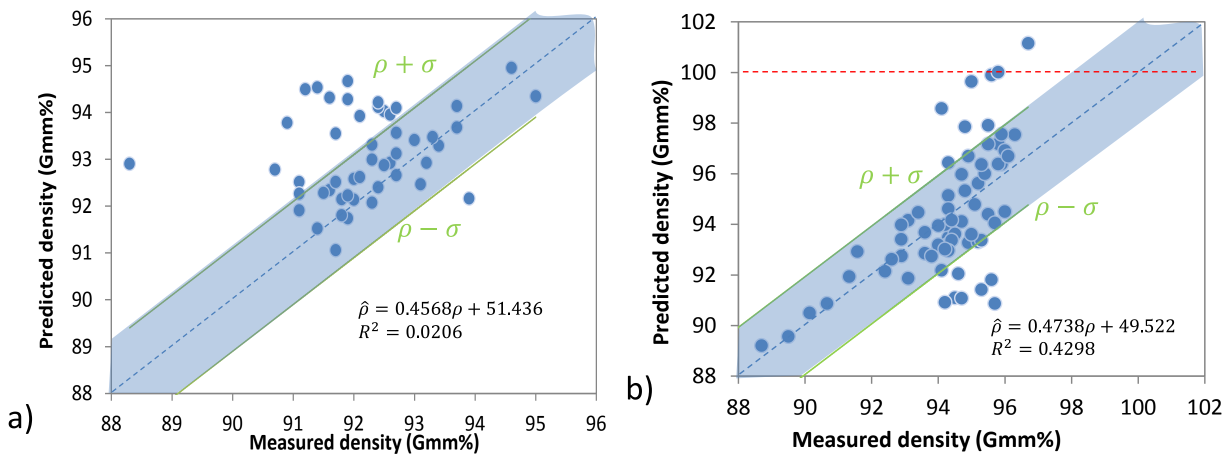


Figure 67. Multi-linear panel-data model predicting core density: a) Utah; b) Maine.

Nonlinear Model Validation

The multi-nonlinear model validation was conducted to explore the possibility of using such a model to overcome the limitation of the final coverage ICMV to correlate to in-place asphalt density at the project level. The pass-by-pass NDG measurements (converted to core density based on their linear relationship) were used along with the core-IC data picked up at five random locations for the IC-density model fitting. Then, the fitted model was used to correlate its density prediction with actual core density data measured at 60 coring locations after the finish roller and the pass-by-pass NDG measurements.

The IC-density model fitting and validation for these four demonstration projects are presented in Figure 68. These results indicate that the nonlinear panel data model has made significant improvements in correlation with in-place density compared to the multivariate linear panel data model. The Model I tends to perform better than the Model II of the nonlinear model. The R^2 values for the Model I correlation with measured densities are 0.34, 0.47, 0.70, 0.90, 0.30, and 0.56 for the projects in Ohio, Florida, Maine, Utah, Idaho, and Washington State respectively. The vast majority of predictions fall within the confidence level of $(\rho - \sigma, \rho + \sigma)$, and all values are controlled well within the bound limits $[\rho_0, \rho_{max}]$. It appears that the model works better when pass-by-pass measurements are present. The model tends not to perform well when core densities and NDG density measurements are not correlated to each other

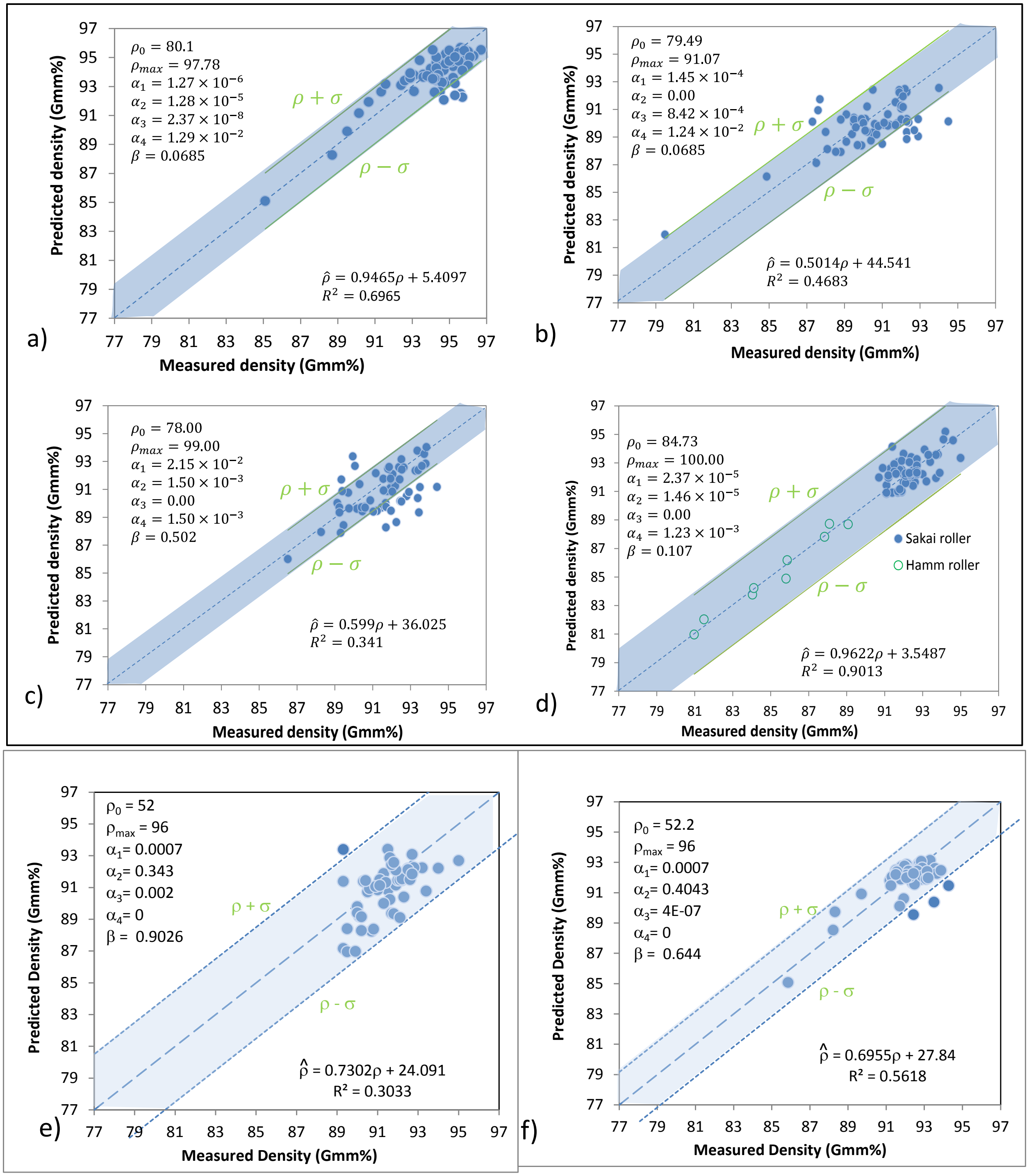


Figure 68. Multi-nonlinear panel-data model predicting core density at project level: a) Maine; b) Florida; c) Ohio, d) Utah, e) Idaho, f) Washington State.

However, not all projects achieve a high R^2 value for core density predictions with the density model. As observed from the above pass-by-pass IC data analysis, the compaction curves can vary from one location to another even with the same equipment, materials, and paving method. Therefore, a single IC-density model, no matter how well-calibrated, would face the challenge of matching a variety of compaction curves. Furthermore, idiosyncratic errors, due to the uncertainty of materials, locations, and supporting conditions, paving and compaction operations, etc., affect the final densities.

The idiosyncratic errors for the Ohio and Utah sites are presented in Figure 69. The idiosyncratic errors indicate the difference between predictions and measurements without using the Kriging model. These errors could follow normal distribution as proposed in the panel date models. The Kriging model was used to capture the influences of geospatial and linear factors of IC information, resulting in improved correlation. The R^2 values have improved 0.03, 0.14, 0.06, and 0.05 for the Maine, Florida, Ohio, and Utah sites. However, even using the above techniques cannot capture all uncertainties.

In addition, the narrow range of core density values would also pose challenges to the correlation between the IC-density model prediction and core/NDG measurements. Therefore, a technique to look beyond the least square (R^2) correlation is warranted by including the "band" of confidence levels. As observed in Figure 68, the vast majority of density prediction is covered within the confidence level of $(\rho - \sigma, \rho + \sigma)$.

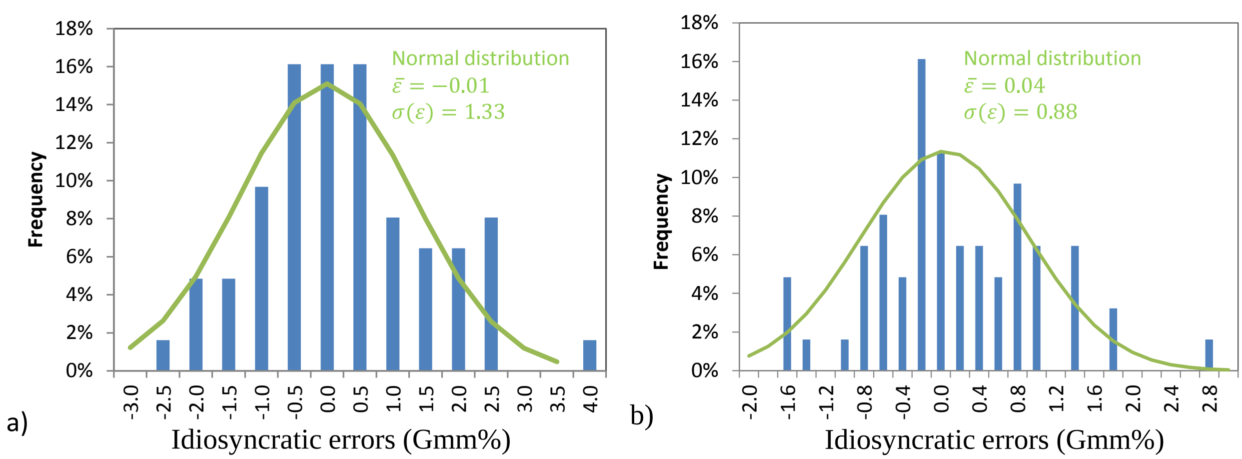


Figure 69. Density model idiosyncratic error: a) Ohio site; b) Utah site.

To sum up the development and validation of IC-based density models:

- The multivariate linear panel density model with fixed effects successfully modelled the density developments with time sequence or roller pass-by-pass at the local level, but failed in predicting material density at the project level.
- The multivariate nonlinear panel density model with fixed effects significantly improved the density predictions at the project level compared to the linear model, and the vast majority of predictions fall within the confidence level of $(\rho - \sigma, \rho + \sigma)$.
- The density model developed herein can potentially serve as a QC tool for the production rolling once validated with test strip in-place measurement data.

Chapter 6 Summary and Conclusions

There are many factors affecting in-place asphalt densities including materials/structure properties (Nominal Maximum Aggregate Size or NMAS to layer thickness ratio), use of paving and compaction equipment (material transfer vehicle, paver, screed in vibration/static, rollers sizes/amplitude/frequency/speed/rolling patterns), environmental conditions (ambient/support surface temperature), etc. Intelligent compaction (IC) provides the means to capture the "complete compaction history" – when/where and how compaction has been performed. Intelligent Compaction is defined as vibratory rollers equipped with accelerometers mounted on the axle of drums, survey-grade global positioning systems (GPS), infrared temperature sensors, and on-board computers that can display IC measurements as color-coded maps in real time. IC measurements include IC measurement values (ICMV), roller passes, asphalt surface temperatures, roller vibration frequencies/amplitudes, and speeds making it an ideal tool for quality control (QC). *The purpose of this study is to answer the question: Whether IC measurements can be more than a QC tool as identified in previous studies. Specifically, can ICMV values be used as a substitute for core data as acceptance tests?*

The Federal Highway Administration (FHWA) has been leading a national effort to advance the IC technology through several research projects including Transportation Pooled Fund (TPF) IC project TPF-5(128) Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material from 2007-2011. The TPF research was a partnership with twelve (12) participating states and had achieved three primary objectives: to develop IC specifications, to develop a knowledgebase that includes experience for participating states, and to identify and prioritize needed improvements of IC technologies. One of the major findings of the TPF study was that more extensive research on the relationship and possible correlation of ICMV and density was needed. If an adequate correlation could be established, it would then be feasible to use IC as an acceptance tool.

As a continuing effort of the above FHWA IC project, an extensive study was conducted to assess the correlation between the IC measurements and asphalt core densities between 2011 and 2014. The goal of this study is to evaluate whether IC can be both a quality control and acceptance tool for compaction. This study explored the relationship between in-place asphalt densities and IC measurements during the compaction process, including accelerometer-based ICMV, roller pass counts, and surface temperatures of asphalt layers, roller vibration frequencies/amplitudes and roller speeds. Extensive experiments were conducted on nine (9) field sites around the US to collect extensive amount of data (including 515 cores) to provide sufficient evidence to support the conclusions made in this report.

IC Rollers and Measurement Systems

The IC rollers used in this study include double drum IC rollers by BOMAG, Caterpillar, Hamm, and Sakai:

- The BOMAG double drum IC rollers are generally equipped with Trimble GPS and BOMAG AsphaltManager hardware and software. The ICMV of BOMAG IC system is called vibration modulus or Evib. Evib is backcalculated from the accelerometer signals using a mechanical lumped parameter model. Evib is correlated to layer stiffness from conversion plate load tests.
- The Caterpillar double drum IC rollers are factory-equipped with Caterpillar Compaction Control hardware and software and standard Satellite-based augmentation systems (SBAS) GPS accuracy that can be upgraded to Real-Time Kinematic(RTK) GPS accuracy with the purchase of additional software option keys. VisionLink software purchased through SITECH is required to view and analyze IC data. The ICMV of the Caterpillar IC system is Compaction Meter Value or CMV. CMV is calculated using a frequency analysis technique. CMV is correlated with layer stiffness.
- The Hamm double drum IC rollers are generally equipped with Trimble OmniSTAR GPS and Hamm Compaction Quality (HCQ) hardware and software. The OmniSTAR GPS makes use of virtual reference station via subscription without the need of an on-ground GPS base station. The ICMV of Hamm IC system is Hamm Measurement Value or HMV. HMV is similar to CMV that is calculated with a frequency analysis technique. HMV is also correlated to layer stiffness.

- The Sakai double drum IC rollers are generally equipped with TopCon GPS and TopCon SiteLink3D hardware and web software. The ICMV of Sakai IC system is Compaction Control Value or CCV. CCV is similar to CMV and HMV that is calculated with a frequency analysis technique. CCV is also correlated to layer stiffness.
- It should be noted that ICMV is influenced by the roller type/weight, vibration frequencies/amplitudes, and roller speeds. If the roller operation settings change, the ICMV values would change. Therefore, the operating settings should be kept constant during test strip in order to determine a rolling pattern to optimize the compaction. Any comparison between ICMV is only valid when the roller settings are the same.

Experimental Framework and Field Sites

The experimental framework of this study includes extensive data collection from nine (9) field sites to investigate the correlation between IC measurements and asphalt in-place density. The selection of field sites was based on the diversity of climate, traffic, and construction types (overlay and new construction) as well as availability of project windows. In 2012, field projects were conducted in Utah and Florida; in 2013, Ohio, Maine, and California; in 2014, Idaho, Maryland, Kentucky and Washington State. The route, location, urban/rural, type of construction, construction layer thickness, mixture, and IC rollers used are as follows:

- UT US-89, Lehi; urban; overlay; 2.5” base course; 19-mm Superpave HMA with RAP and PG 58-34 binder; Hamm, Sakai
- FL I-95, Brevard; rural; overlay; 1.5” base course; Hamm, Sakai
- OH I-71, Morrow; rural; overlay 1.75” base course, 19-mm Type A with RAP and PG 64-28 binder; Hamm, Sakai
- ME I-95, Island Falls; rural; new construction; 2” intermediate course; 12.5-mm course-graded with 20% RAP and PG 64-28 binder; Caterpillar, Hamm
- CA I-80, Solano; urban; overlay; 3” intermediate course; ¾” Type A with 15% RAP and PG 64-16; BOMAG, Caterpillar, Hamm
- ID US 95, Garwood; rural; new construction; 2” base course; Hamm, Sakai

- MD MD 170, BWI; urban; overlay; 2” base course; 19-mm base course mix with PG 64-22 binder; Caterpillar, Hamm
- KY I-65, Hart County; rural; new construction, 4” base course; 1.5D CL4 with PG 64-22 binder; Caterpillar, Hamm
- WA SR 539, Lynden-Aldergrove; rural; new construction; 4.5” base course; Caterpillar, Hamm

Prior to each field study, GPS measurements were validated a day prior to the construction to ensure all roller GPS measurements and hand-held GPS rover devices provide consistent measurements with reference to the same coordinate system. The IC rollers used in this study include double-drum IC rollers by BOMAG, Caterpillar, Hamm, and Sakai equipped with IC technology. For selected sites with availability of pre-test, pre-mapping using IC rollers were performed at the granular subbase in order to access the existing support condition. The roller settings for pre-mapping were at low frequency and low amplitude to avoid disturbing the existing support condition.

For each field site, at least two IC rollers were used. One was used as the breakdown and the other was used as the intermediate rollers to compact the asphalt mat and. The selection of which IC rollers was used at the breakdown or intermediate position were made jointly by the paving contractors and the IC research team in order to optimize the compaction efforts. Contractors normally made this decision for roller selection and rolling patterns based on their past experiences at similar projects. Nuclear density gauges were used to conduct extensive asphalt in-place density measurements right behind the paver, after each roller pass at breakdown/intermediate/finish compaction, GPS and surface temperature measurements were then made at each of the NDG locations. After the finish rolling, sixty (60) locations were marked for nuclear density gauge testing, coring (4 inches in diameter), GPS measurements, and other in situ tests (LWD-a and/or FWD). For some selected sites, Ground Penetrating Radar (GPR) testing were conducted on the pavement test section by either the. These cores were then tested in DOT asphalt laboratories to obtain bulk density values. A total of 515 asphalt cores were taken, tested, and analyzed.

From the experiences learned from the IC field projects, the following recommendations are provided to ensure the success of any IC projects:

- Planning: Thorough planning among all parties is crucial for the success of any IC field work. The state agency, contractors, and IC equipment suppliers need to plan ahead (at least 30 to 60 days) to schedule needed training (if any) and to address details of all field operations, especially the responsibility of each party, specific IC rollers and systems to be used, pre-construction briefing, and daily briefing, etc.GPS Recon: Well in advance of the project, surveyors need to recon the project site to identify whether there are any GPS “shadows” or locations that covered under overpasses/trees, and horizontal curves that block the transmission of GPS correction signals, etc. GPS repeaters may need to be installed at selected locations to relate the GPS correction to resolve the GPS shadows. In situations where GPS will not provide adequate positioning information, a laser-based technology (such as TotalStation) needs to be employed to overcome GPS issues such as tree coverage. Note that using laser-based equipment would add significant cost.
- IC Setup: IC roller setup and components mounting (i.e., retrofit systems) need to be completed at least one day prior to the field work. A trial run needs to be performed and IC data storage/transmission need to be checked. Then, the IC data need to be exported with the vendors’ software to the Veda-compatible format for quality checks.
- GPS Checks: To ensure all GPS records from all devices are compatible, GPS validation need to performed at least one day prior to the field work based on the recommended procedure in the FHWA Generic IC Specification (FHWA, 2014). All GPS devices need to use the same GPS datum and coordinate system (either UTM or State Plane). The tolerance from the GPS validation should be with ±12 inches. The tolerance may be adjusted when different correctional signals are used.
- Daily Data Submission and Checks: IC data need to be transferred from the IC rollers to other computing devices either via an USB flash drive or wireless infrastructure (such as: VisionLink, SiteLink3D, and etc.) at a daily basis. The raw native IC data need to be checked with IC vendors’ software and IC data need to be exported to Veda-compatible formats. Cautions need to be taken during the export procedures using vendors’ software to ensure correct data types (Veda-compatible final coverage and all-passes data), time

periods, coordinate system, and file naming with appropriate extension. The exported IC data need to be imported to Veda to check:

   a) if the GPS locations correctly displayed on the Veda map viewer with the aids of underlying street maps, imported plan file, or comparison maps automatically launched by Veda such as Google Maps or Google Earth;
   b) if the IC roller operation (speed, vibration frequency/amplitude) meet the requirements set by the QC managers;
   c) if the roller passes meet the required rolling patterns set by the QC manager;
   d) if the ICMV and temperature maps display any issues.

- Daily Briefing: Daily briefing prior to the start of the operation will identify the previous days' issues (if any) and make adjustment if necessary. Conducting daily briefings will maintain the proper communication if any unexpected issues occur.

IC Data and Spot Test Data Collection and Analysis

Within vendors' IC systems, IC data is stored at one point at the center of the vibratory drum (i.e., un-gridded data) at about 1 Hz by integrating the ICMV, surface temperature, roller speeds, roller vibration frequency and amplitude measurements. The un-gridded data is then processed to provide more refined, gridded data by the vendors' system, generally 1 ft by 1 ft grid or approximately 6 to 7 grids across a drum width of a full size roller. The gridded IC data were exported by using vendor-specific IC software to Veda-compatible forms, also vendor-specific. These exported are in two forms: all-passes data and final coverage data. The all-passes data includes all IC data through the entire compaction history while the final coverage is the last pass data (i.e., subset of the all-passes) indicating the final surface results.

In situ test data were gathered in various forms either in raw or reduced format. GPS data is obtained by exporting the measurements from GPS devices to text formats. Nuclear density gauge (NDG) data is recorded manually during the measurements onsite. Asphalt core data and analysis is provided by DOT laboratories in either PDF or Excel forms. LWD-a data and back-calculation results is provided by Kessler in either PDF or Excel forms. FWD data, if performed, were provided by DOT in raw data forms. The FWD data is analyzed to obtain normalized D0 reflection underneath the load platen with respect to 9,000 lb. load and back-calculated using a multi-layer analysis program to obtain layer moduli. All reduced in situ test data were organized in Excel spreadsheets for further analysis.

The IC data is imported to Veda for viewing and statistical analysis. Veda is a geospatial software for IC data management funded by MNDOT and can be downloaded from the IC website (www.IntelligentCompaction.com). Veda's Viewer features allow detailed inspection of IC data on top of geographical map (currently OpenStreetMap), including ICMV, surface temperature, roller speeds, roller vibration frequency and amplitude measurements. The Veda's display of IC data is in color coded map format with an option to customize color palette. Veda's Viewer also allows viewing of selected individual pass or final coverage with powerful filtering options to allow detailed examination of the IC data and rolling patterns.

The in situ test data were added to the Point Test feature of Veda for correlation analysis by copy-and-paste from Excel spreadsheets. The analysis of Veda produces basic statistics and histogram in overall analysis or fixed segment analysis. Veda extracts IC data within a radius of given spot test location, normally 3 ft, for the correlation analysis. The correlation analysis provide linear regression results with fitted linear equation and associated goodness-of-fit, R^2. The Veda results were extracted for further processing with Excel to perform additional charting. Further information regarding the usage of Veda can be found in the Veda Users' Manual (Chang et. al., 2013e). Training on the usage of Veda is available through workshops sponsored by FHWA (http://www.intelligentcompaction.com/learn/workshops/).

The data analysis focused on the following:

- Statistical Analysis of IC Data: The IC data were analyzed with Veda to produce basic statistics and histogram reports for ICMV, roller passes, roller speed, vibration frequency, amplitude, asphalt surface temperatures.

- Density Compaction Curves and Pass-by-Pass IC Data Analysis: Based on detailed observation of density growth curves based on NDG measurements, the influencing factors on in-place density can be better understood.
- Correlation Analysis between Core Density, Final Coverage IC Data, and In Situ Test data including NDG, LWD-a, and FWD Data: This is a one-to-one simple correlation analysis to evaluate the relationship between core densities and ICMV, even though each measures different properties.

From the above analysis, the following conclusions can be drawn:

- GPS validation prior to construction is critical to data quality assurance by ensuring all positioning system referencing and measurements are consistent.
- Usage of ground-based GPS stations or virtual GPS base station can successfully provide high precision positioning only when being setup and checked correctly. Lack of cellar coverage would not suitable for virtual GPS base station or internet-based GPS correction services. Being too close to a tree line or tree/foliage coverage would create GPS shadow and GPS will not work properly for both the above solutions. The MD site is the most challenging one for GPS signals due to one of the construction lane is adjacent to a tree line with foliage coverage. In this case, other laser-base technique (TotalStation) can supplement the positioning measurements. Consistently obtaining good GPS satellite coverage and correction signals are critical to maintain the real-time kinematic (RTK) GPS mode or equivalent.
- Universal Transverse Mercator (UTM) is recommended to be the choice of GPS coordinate system. Caution should be taken when using State Plane System with surface adjustment factors. All GPS devices for a given jobsite shall be using the same coordinate system and referencing to the same GPS base station. Other coordinates than the above are not recommended.
- Pre-mapping the existing granular bases prior to paving for new construction projects with IC rollers at low frequency and low amplitude are recommended to better understand the existing support condition and identify possible soft spots. The soft spots may potentially affect compaction of upper asphalt layers.

- IC data transfer should be performed a daily basis, either with a physical USB flash drive or download from the Cloud. Buffering data on local devices are recommended to create redundancy and maintain data security to prevent data loss.
- Daily IC data quality checks are essential to produce reliable and quality data. The data QA process would include exporting all-passes and final coverage IC data through vendors' software to Veda-compatible forms. Then, that data shall be imported to Veda for map-based viewing and statistical analysis/histogram. It is then easy to identify any issues with the positioning from GPS signals, signal issues from all sensors, gridding process with vendors' software, incorrect roller settings, and etc.
- All IC systems performed well during the field studies due to the following procedure: (a) Full IC system checkup/ trial runs and GPS validation tests were conducted a day prior to the construction. (b) The connection of the wiring harness for temperature sensors were checked at a daily basis. (c) The computer docking station and similar within roller cabinet were checked daily to ensure full connection with tablet PC or other IC display. (d) IC data QA were also performed at a daily basis.
- Extensive in-place density measurements with nuclear density gauge, temperatures measurements with infrared gun, and GPS measurements with hand-held GPS rover were conducted including after the paver (i.e., 0-pass), after each breakdown roller pass, after each intermediate roller pass, and after each finish roller pass. These measurements captured the complete compaction history from cradle to grave and provided detailed data regarding the complexity of field compaction due to materials, structure layer thickness, paver type/operation (esp. vibration screed), roller compaction (roller train sequence, roller size and operating weight, vibration frequency/amplitude), and temperature drops.
- LWD-a test were conducted and data were analyzed by Kessler Engineering at selected sites. The analysis results include back-calculated asphalt layer moduli (Elwd), back-calculated asphalt layer moduli that are normalized to 20°C (Elwd20), and asphalt surface temperatures during LWD-a testing. There are two generations of LWD-a that were used during the span of this project. The last version of LWD-a is lighter in weight and uses a larger metal stamp to facilitate the field operation and analysis results.
- FWD test were conducted by DOTs and data were analyzed by the research team at selected sites. The analysis with multi-layer linear elastic layer program results in

backcalculated asphalt layer moduli (Efwd), normalized FWD D0 deflection that are normalized to 9,000 lb. (Dfwd).

- A total of 515 asphalt cores were taken and tested for bulk density values by participating DOTs. 60 cores were taken on each project right after the finish rolling except that 35 were taken at the California project due to lack of operation time before the site was open to traffic. The number of cores taken was unprecedented and provided sufficient data for statistical significant analysis under this study.
- Pass-by-pass data show that density growth curves or patterns vary at a given project even with the same equipment, personnel, and materials. Many other factors may attribute to this variability: including the starting densities (or "zero-pass") right behind the paver, roller settings (amplitude/frequency/speed), timing and environmental conditions during roller passes, sequence of rolling train and rolling patterns. These observations illustrate the complex process of achieving the final in-place density.
- Asphalt density measurements with NDG correlate well with IC measurement values (ICMV) after each pass of breakdown rollers, but not intermediate rollers. The mean R^2 of linear correlation between the breakdown ICMV and nuclear density gauge measurements is 0.6. On the other hand, the mean R^2 of linear correlation between the intermediate ICMV and nuclear density measurements is only 0.3. This observation indicates the similar trend of increased ICMV and NDG measurements when the asphalt temperatures are high during breakdown compaction. The actual range of "elevated temperatures" is mix-dependent. It is postulated that the ICMV influence depth is shallow during the first several passes of the breakdown roller.
- The R^2 of linear correlations between the core densities and nuclear density gauge (NDG) measurements ranges from 0.5 to 0.8 for all test sites. However, significant bias was observed for 50% of the field data sets. NDG calibration against cores are highly recommended and stringent rules of operation (e.g. free of moisture and asphalt residue on the gauge contact surface) should be observed.
- Using conventional random sampling to select the data from one of the 60 core data, as in an example of the Utah site, would produce 50% probability for passing and 50% probability for failing. Conventional acceptance test with typical one core per 1,000 ton of asphalt paving would have similar limitation and uncertainty. Therefore, there is

always a risk for both agency and contractor when using random sampling of limited cores for acceptance.

- Asphalt core density does not correlate well to LWD-a data. The linear regression between core density and layer moduli (normalized to 20°C) back-calculated from LWD-a data exhibits no linear trend or occasionally reverse trend. The lack of linear relationship is expected due to the different nature of density and moduli.
- Asphalt core density does not correlate well to FWD data. Similar to the core density-LWD moduli correlation, the linear regression between core density and layer moduli back-calculated from FWD data exhibits no linear trend or occasionally reverse trend. Similar observation was obtained between core density and FWD D0 deflections (i.e., underneath the load platen) that were normalized to 9,000 lb. Again, this is not a surprise result either due to the difference of density and moduli.
- The correlation between final coverage ICMV and asphalt layer moduli backcalculated from LWD-a data is poor. These results reflect the limitations regarding differences in measurement depths and foot prints. However, it is anticipated improvement of correlation between ICMV and LWD-a once ICMV is de-coupled or broken down to layer responses.
- Asphalt core density does not correlate well to final coverage ICMV. Recall the final coverage data is the last pass data. The probable causes of the lack of correlation include:
  1) The asphalt mat temperatures corresponding to the final coverage (last pass) ICMV are generally in the lower temperature range where the asphalt binder viscosity is increasing which will influence the rebound behavior of the roller drum;
  2) The influence depths of ICMV may vary after each roller pass due to the complex vehicle-surface interactions while the mix is compacted;
  3) Therefore, ICMV influence depth at the final coverage may be deeper than the asphalt layer as materials density and stiffness increases, in turn changing the rebound behavior of the roller drum;

  4) The ICMV were only measured during the breakdown and intermediate compaction while the gains/losses of in-place densities by the finish rollers, even

though changes in density are likely small, may affect the correlation between final coverage ICMV and core densities;

5) The uncertainties of IC data gridding and GPS precision may affect the accuracy of data extraction. Therefore, ICMV alone cannot be used for asphalt density-related acceptance.

IC-Based Density Model Development and Validation

Due to the lack of linear relationship between core density and ICMV, a different approach was taken to improve the linear relationship between core density and all IC-related measurements via a modeling technique. Firstly, the complex behaviors of field compaction need to be studied. . Different densification curves were observed at various locations throughout typical field projects even though the same equipment and materials were used by the same crew for the construction process. Therefore, the densification characteristics in the field are very complex. Although the correlation between NDG density measurement and ICMV from the breakdown rollers is satisfactory, there is a need for an IC-based density model to predict the in-place asphalt densities. This model development effort considers multiple factors during compaction process and to fill the gap between breakdown/intermediate and finish compaction. The ultimate goal of this IC-based model is to provide a practical quality assurance tool for real-time in-place asphalt density prediction during production compaction. The model would have to be calibrated to project specific applications on each project.

Two types of density model were developed and tested to select the best model form for reliable density prediction: Multivariate Linear Panel Density Model and Multivariate Nonlinear Panel Density Model. The latter was also derived to different form as Model I and Model II. Basically, those density models are used to capture the “family of compaction curves” observed in the field.

The multivariate linear panel density model is a heterogeneous panel data model with fixed effects at the geospatial local level. It is developed as follows. Panel data refers to multi-dimensional data frequently involving measurements over time. The model parameters, such as constants and slope coefficients, vary across different geospatial locations. The multivariate nonlinear panel density model is a heterogeneous panel-data multivariate nonlinear model based on IC measurements. It is developed from multiple trials using different mathematical formulations. Though appearing complex, the above models simply make use of IC measurements during compaction to predict the density growth curves of the compacted materials. However, these models are superior to conventional statistical regression models by using the "panel technique" that can handle variable data in both spatial domain and time domain.

The above density models were implemented in an Excel spreadsheet with the Solver function. The Excel Solver function uses an iterative computing technique to minimize the differences between the model prediction and actual measured data in order to produce fitted model parameters. For model validation for a given test site, IC data and intensive in-place asphalt density measurements using the NDG and cores were collected in a test strip for a given site. The IC data and in-place density data were analyzed using the Veda software. IC data with respect to asphalt density measurements were extracted for both all-passes and final coverage data. Pass-by-pass data and a subset of the final coverage data set were used to fit the IC-density model using the Excel Solver function. During the solving process, all unconstrained variables were made positive and the evolutionary method was used to find a good solution to a reasonably well-scaled model. The fitted model was then validated using the remaining data set. The following summarize the validation and usage of the density models.

- Multivariate Linear Panel Density Model: The simple linear correlation between ICMV with NDG density for the local level of pass-by-pass data were performed. The R^2 ranges from 0.38 to 0.94 indicating poor to good correlation. The above values may be improved if outliers are removed. It can be deduced that ICMV measurements during breakdown compaction do reflect the actual in-place asphalt density. The multivariate linear panel data model with fixed effect at the local level achieves fairly good correlation for the Maine site. The R^2 is 0.95 and the adjusted R^2 is 0.87. The adjusted R^2 is to penalize the statistic when extra variables are included in the model. However, the density prediction at the project level using the homogeneous multivariate linear model with fixed effects yields a relatively poor correlation. The prediction values could exceed the max value of 100%G_{mm}. A significant portion of predictions are beyond the confidence level of (ρ-σ, ρ+σ), where ρ is measured density and σ is its standard deviation. This indicates that the uncaptured nonlinearity for the density growth at the project level exists.

- Multivariate Nonlinear Panel Density Model : The calibration of the density model require only limited in-place NDG and core test data (e.g., 5 data points) before being validated with the remaining data set of a given site (e.g., 60 data points). The nonlinear panel data model has made significant improvements in correlation with in-place density compared to the multivariate linear panel data model. The Model I tends to perform better than the Model II of the nonlinear model. The R^2 values for the Model I correlation with measured densities are 0.34, 0.47, 0.70, 0.90, 0.30, and 0.56 for the projects in Ohio, Florida, Maine, Utah, Idaho, and Washington State respectively. The vast majority of predictions fall within the confidence level of $(\rho - \sigma, \rho + \sigma)$, and all values are controlled well within the bound limits $[\rho_0, \rho_{max}]$. It appears that the model works better when pass-by-pass measurements are present. The model tends not to perform well when core densities and NDG density measurements are not correlated to each other. Overall, the level of correlation between the predicted densities and actual core densities is comparable to that between nuclear density gauge measurements and core densities. With IC covering 100% of the compacted area, the multivariate nonlinear panel density model is recommended to be used as an enhanced QC tool for the production rolling.

Final Conclusions

In a nutshell, the conclusions can be drawn from the above findings as follows:

- *Compaction curves and temperature drop curves based on pass-by-pass NDG and temperature data varied significantly for a typical project even when the same materials, the same pavement equipment and the work force were used. This indicates the complexity and challenges to achieve desired in-place asphalt density at a daily basis.*
- *Based on the pass-by-pass NDG, temperature and ICMV data, compaction is most effective at high temperature range and large gains in density are seen during the breakdown rolling. However, the specific high temperature range is dependent on the mixture type/thickness and asphalt binder grades. There were much lower gains in density during the intermediate and finish rolling phases. Therefore, these findings reaffirm the best practices to focus on breakdown compaction within the higher temperature range to obtain optimum in-place asphalt density.*
- *Since the pass-by-pass ICMV data correlate well with NDG measurements during breakdown compaction, IC can be used as an enhanced tool for QC by monitoring the ICMV in real time during construction in order to maximize the window of opportunity for compaction.*
- *As the final ICMV does not correlate well with core densities, <u>the final ICMV data is not recommended to replace cores for acceptance.</u> There are many likely causes of this, including differences in measurement depths and foot prints as well as the change in drum rebounds when asphalt temperatures drop below certain threshold (e.g., glassy temperature) which in turn extend of the measurement depth of ICMV beyond the compacted layer. There is also a gap between the final ICMV (during breakdown) and core densities that may produce minor density variation which in turn affects the above correlation.*
- *The IC-based density model prediction do correlate reasonably well with core densities by considering the ICMV, roller passes, roller vibration frequency/amplitude, and roller speeds. It makes use of panel model to capture family of compaction curves in spatial and temporal domains. It also includes a term to consider the gap between breakdown IC*

measurements and eventual core densities. With this IC-based density model calibrated with pass-by-pass NDG measurements and core density data from a test strip of a specific project, this model can produce predicted density values along with other existing IC measurements for enhanced QC during production compaction.

- *The current IC technology can be readily used for method-based acceptance such as roller pass counts and coverage. It is recommended to require at least 70% of compacted areas with target passes or more.*

Recommended Future Efforts on IC Research and Implementation

- The IC Road Map described in the TPF IC final report needs to be updated in order to provide industry guidance for future IC research and implementation:
    - *Track 1 – Equipment and Technologies (Standardization of IC roller measurement systems, Practical use of GPS in IC, Valid In-situ point tests to correlate with IC measurements).* Currently, there is still a lack of IC equipment specification and field checks to ensure IC systems meet the requirements of IC projects. GPS setup is still challenging at IC projects around the US. LWD-a, still evolving, is the only candidate spot test device for asphalt IC compaction. Therefore, there is a lot of work and needed activities under this Track.
    - *Track 2 – Data Management and Integration (National IC database and data collection guidelines, Standardization of IC data storage and exchange, A software tool for IC data viewing and reporting).* A national IC database and data collection guidelines are still lacking to provide resources for in-depth studies such as long term performance of IC field projects. It is expected that TFHRC may establish a cloud database where IC database can be accessible to provide academic and industry rich resource of IC data. It is still lacking standards for IC data format, gridding algorithm, and reporting. Veda software tool is now available for basic IC data viewing and analysis. However, upgrades and improvements for Veda are needed to be guided and funded through a TPF pooled fund study in order to continuously provide agencies and industry up-to-date tools to effectively process the massive amount of collected IC data on a typical project.

- *Track 3 – Specification (National guidelines for IC QC/QA specifications, Expert Task Group - ETG for AASHTO IC specification development, Technical support for States spec customization).* The FHWA generic IC specifications and AASHTO PP81-14 IC specifications are now published. The AASHTO IC specification is currently a provisional standard and will likely evolve and be updated base on future research findings in the next few years before turning into a full standard. Currently, there are more than 18 State DOT IC specifications with different forms and levels of requirements for implementation. However, there is lack of an ETG that is geared toward IC improvement and standardization. Therefore, major efforts are needed under this Track.
- *Track 4 – Technology Transfer and Training (IC workshops/certification, IC field demonstration, IC website and knowledge base).* Between 2012 and 2014, FHWA EDC 2 has supported numerous IC Overview workshops, ICDM workshops, and IC equipment demonstration to provide IC training to agencies, industry, and IC equipment suppliers. As increasing IC projects occur around the country, project-specific IC training (a.k.a. just-in-time training) are in high demand. Currently, IC certification is still lacking but it will be needed once IC data are used for acceptance (e.g., method-based acceptance based on roller passes and coverage). IC certification may include technician's certification for installing IC components on rollers and equipment certification to ensure IC measurements can meet certain thresholds and accuracies. The IC website (www.IntelligentCompaction.com) is now providing one-stop shop for IC. Due to the demands for supporting ever increasing IC projects, more IC technology transfer and training are needed under this Track.

- Since IC data management with Veda is one of the critical path for IC implementation, the followings are recommended to overcome data management-related issues:
  - *Upgrades and Improvements*: It is anticipated that a TPF IC data management project will be established from the *Solicitation No. 1381 "Enhancement to the Intelligent Construction Data Management System (Veda) and Implementation*" in order to fund and guide future improvements on Veda software. With FHWA as the liaison for this TPF project, it is recommended for the State DOTs which

are implementing IC or will be implementing in the near future to join this pooled fund project in order to pool resources, share experiences, and prioritize upgrades and improvements on Veda to facilitate IC data management.

  - *Training and Implementation*: It is recommended that FHWA continue the IC data management training program and technical support center to meet the training needs around the country.
  - *Training the Trainers*: In order to reach out to all State DOT IC projects and provide timely support, it is recommended to conduct a "training the trainers" program at a yearly basis in order to produce DOT in-house IC experts for meeting the above needs. This program is recommended to cover all IC manufacturers' systems.
  - *Industry Partnership with FHWA and DOTs*: It is also recommended for the industry to form partnership with FHWA and DOTs in order to develop IC data standards and improve IC data security, data sharing, and Veda-compatibility.

- Research on the influence depths of ICMV during asphalt compaction is recommended. This work can be accomplished by instrumenting geophones in the subgrade, subbase, and asphalt layers and monitoring vibration signals at these locations during each roller pass. The signals from geophones can then be compared with the accelerometer signals on the IC roller that produce ICMV by mapping each construction layers from the ground up. The intent is to understand better the rebound behavior of the roller drums when asphalt mix is being compacted and mix temperatures are dropping.
- Simplification and strengthening of the GPS setup and validation process is needed to ensure consistency of GPS records among different devices.
- Standardization of the color palette for IC data maps are recommended to facilitate consistent data interpretation. This would include color palettes for roller passes and temperatures. Simplified color palettes can also be standardized provide roller operators simple color zones to signifying under the desired level, at the desired level, and over the desired level, e.g., red, green, and blue for under, proper, over compaction.
- Standardization of the IC data recording and gridding process is needed to ensure consistency of IC data among different IC vendors. A standard for binary IC data format is also recommended. This would help integrating IC data collected with different IC

systems during different stages of construction, e.g., from grading, subbase compaction, and asphalt compaction.

- Since FHWA will not dictate any new standardized ICMV, the current ICMVs from all manufacturers are expected to evolve to meet the industry demands.
- Since standards for IC component/system checks are needed to ensure IC systems meet the IC requirements and function properly, the followings are recommended:
    - Individual accelerometer component needs to be checked with off-the-shelf "standard-traceable" test devices;
    - System check is needed once accelerometer is connected to an IC system by following a standard field procedure with independent "standard-traceable" devices and the range of measurements needs to be assigned correctly in the IC settings;
    - Individual temperature sensor needs to be checked with off-the-shelf "standard-traceable" test devices;
    - System check is needed once temperature is connected to an IC system by following a standard field procedure with independent "standard-traceable" devices and the range of measurements needs to be assigned correctly in the IC settings to avoid incidence such as timing-out;
    - Suggested certification for the above with programs at a given period similar to those for certifying inertial profilers. A Type-Test may be conducted with new models of OEM that cover all machines of the same models.
- National guide specifications (e.g., FHWA or AASHTO): Working with ETG and IC manufacturers, the above standardization entity may split the national guide specifications into separate standards in order to provide standards that are practical and implementable by agencies and industry:
    - A Specification on IC Equipment (including IC and GPS system),
    - A Specification on IC Operation and Checks (including GPS validation, data transmission, data QA, standard color palettes for ICMV, roller passes, and temperatures),
    - A Specification on Data Management (including standard data format, gridding algorithm, IC data maps, data analysis, and reporting).

- De-coupling ICMV are important to separate an ICMV to values that corresponding to layer properties which will satisfy the interest of specific work such as grading, subbase, and asphalt paving. Therefore, such research is warranted to develop such de-coupling methods and analysis by utilizing multi-sensors, multi-layer pavement analysis, and real time back-calculation techniques.
- IC data related issues need to be resolved in order to provide agencies and industry reliable data for future forensic analysis and acceptance:
  - IC data integration and security is important to prevent data loss and altering.
  - IC data standard should be in raw, ungridded, secured, binary form when submitted to agencies. Therefore, the data storage and transmission by contractors can be reduced and simplified. Also, the gridding process is recommended be performed by Veda to provide consistent process and results and avoid any issues such as contract disputes.
  - IC data are recommended to allow redundancy for storage on local display devices and cloud. Both wireless and local (USB) methods are allowed.
  - Simplification of data management and standard IC data format are recommended to speed up IC storage, transmission, and inspection.
- To maximize the potential benefits of the IC-based density models, the following efforts are recommended:
  - Improving the IC-based density models by considering multi-machine data of the entire rolling train is recommended to improve the correlation with core density.
  - Implementing IC-based density models as a re-usable computing component is recommended so that it can be used as a plug-in of vendors' real time IC monitoring system to improve quality control. It is expected IC data and spot measurements with core and nuclear density gauge measurements (such as pass-by-pass density/temperature measurements) from a test strip can be used to calibrate the density model for a given project condition. Then, the calibrated density model can be used to produce density prediction as another map on an IC onboard display during production compaction.
- Based on the experiences of utilizing original engineering manufacturers (OEM) IC system for this study, it should be emphasized that IC system setup and checks are critical

for IC system to function as expected, especially regarding correct installation of accelerometers, temperature sensors, and GPS components by certified technicians. Therefore, cautions should be taken when using non-OEM systems or IC retrofits. Certification of technician to perform IC retrofit installation is recommended. Field certification tests are recommended for both OEM and retrofitted IC rollers to ensure the IC measurements meet certain thresholds (such as differentiating soft and hard materials at a test site) and accuracy if IC is allowed to be used as an acceptance tool in the future either on method-based or end-results-based specifications.

- To leverage benefits of geospatial IC data, the followings are recommended:
    - Quantification of uniformity is recommended with the combination of coefficient of variation (COV) and semivariogram.
    - Study on the relationship between uniformity indictors and long-term pavement performance are recommended by using a combination of numerical modeling and accelerated loading tests.

As of the writing of this report, IC technologies are still evolving. It is anticipated that further IC research as well as many enhanced IC-related products and services from the IC vendors will occur in the near future. With such momentum, the asphalt paving industry is anticipated to continue using the IC technologies to improve quality of road construction. The public will then benefit from longer lasting roads.

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Appendix A IC Data Analysis

The following IC data analysis was focused on the “Day 2” tests where coring took place.

Utah Site

The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 70 and Figure 71.

Comments on Hamm data:

- ICMV: The Hamm HMV values are in the range of 4 to 140 with a mean value of 30.
- Pass counts: The pass counts are between 1 and 49 with a mean value at 13. These passes were drum passes and shall be divided by two to account for machine passes. Based on the on-site observation, the maximum roller passes are around 10-11. Therefore, the pass count statistics indicate that the pavements are not compacted uniformly with the target roller passes. Most of the passes are concentrated at the middle of the compacted lane with only 1 or 2 passes at the edges. Therefore, the pass count statistics of TB01 and TB02A&2B for the Hamm data are similar. Comparing the statistics with those from Sakai in later sections, it is suspected that the Hamm pass counts may be double of the actual values.
- Speed: The roller speeds average at 3 mph (4.8 kph).
- Temperature: The first-pass temperature or the maximum value is 280°F (138°C). The mean value of the asphalt surface temperatures during compaction is 199°F (92.8°C) with a standard deviation of 22°F (12.2°C).
- Compaction curve: Focusing on the first 10 passes, the compaction curve reaches the optimum around 7 passes.

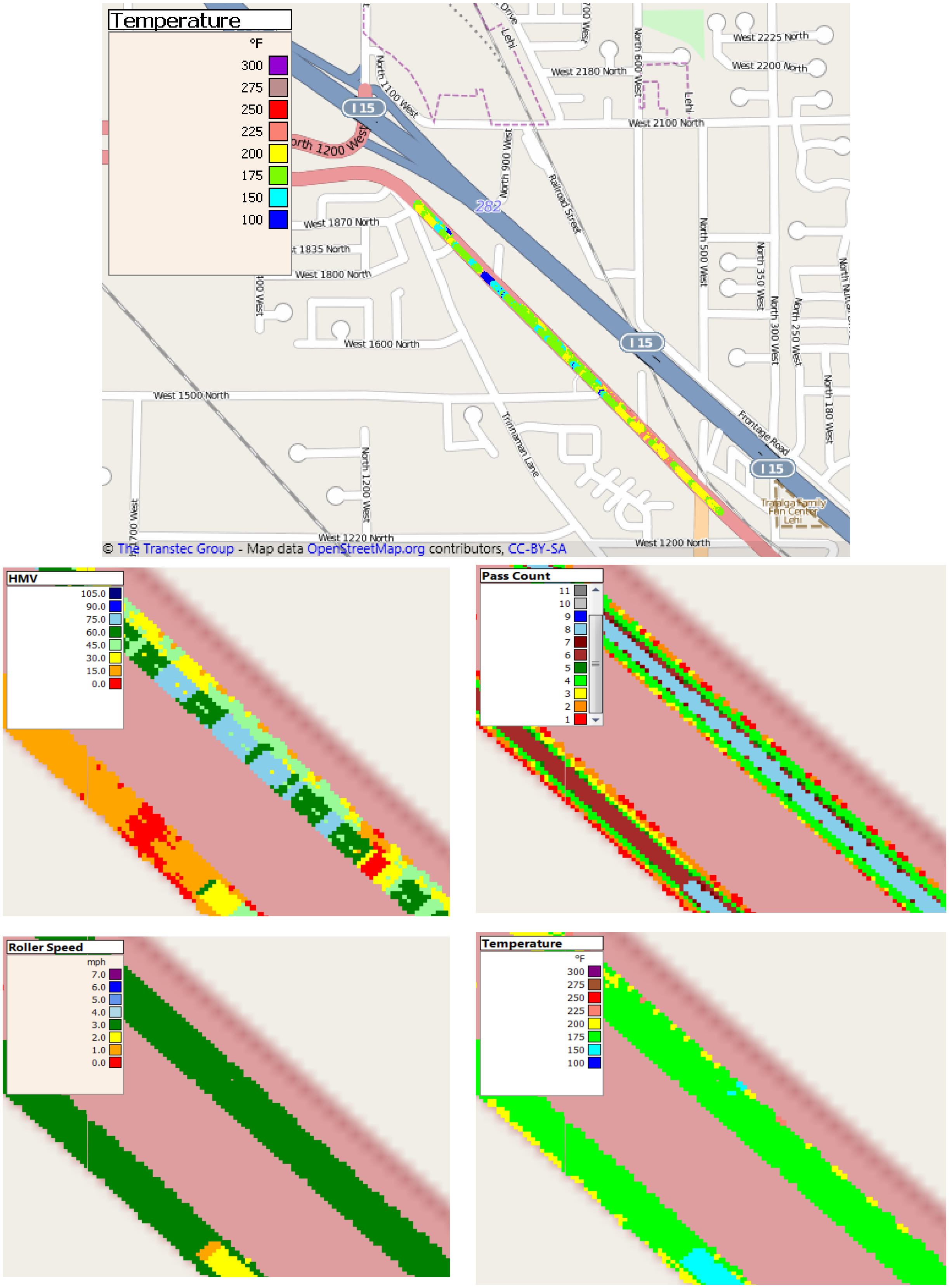

Figure 70. Hamm IC maps (breakdown), TB02A and TB02B, UT site.

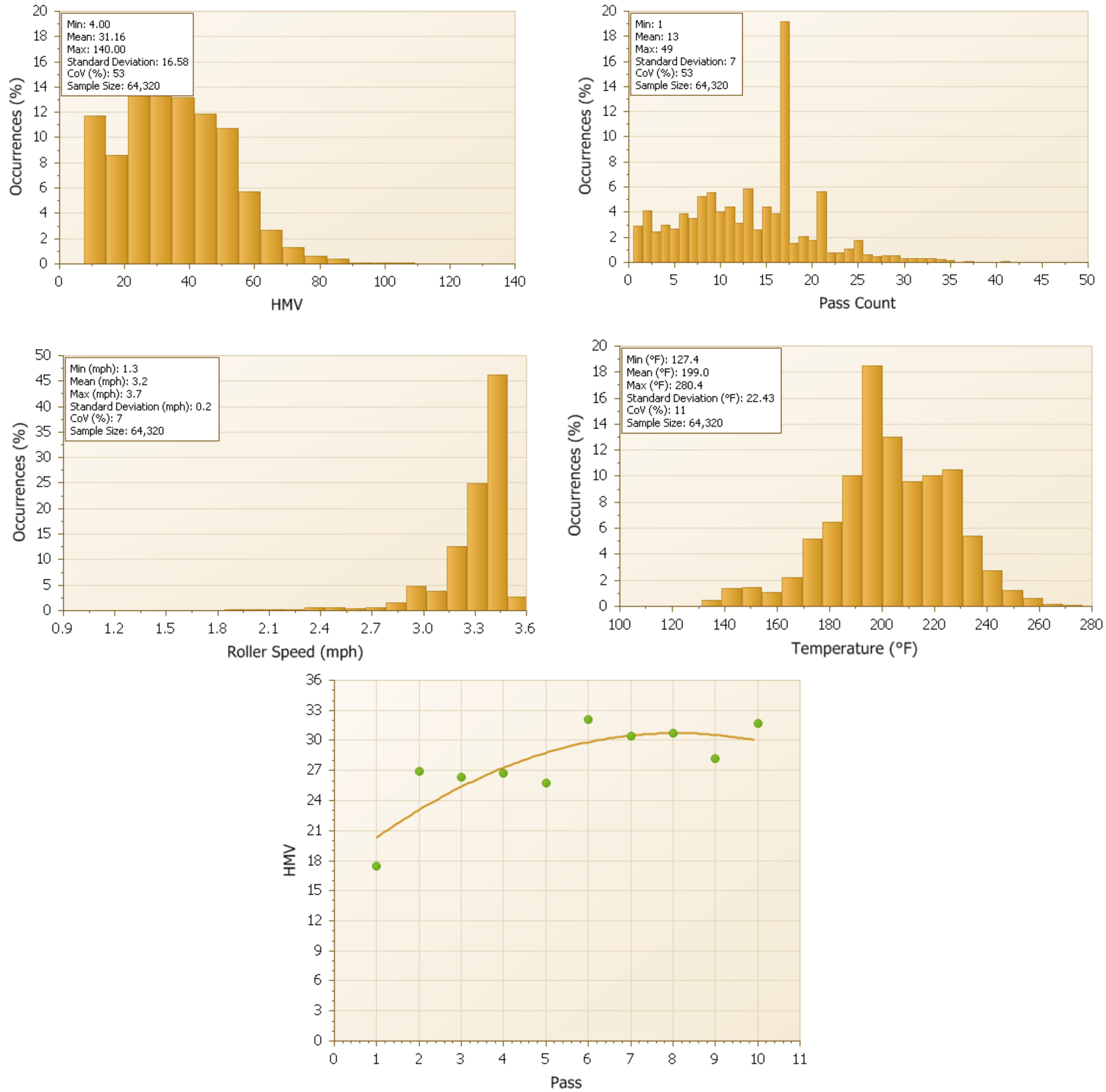

Figure 71. Hamm IC data statistics (breakdown), TB02A and TB02B, UT site.

The IC maps and statistics for the Sakai IC data (intermediate position) are presented in Figure 72 and Figure 73.

Comments on Sakai data (TB02A):

- ICMV: The CCV values are in the range of 0 to 100 with a mean value of 16.
- Pass counts: The pass counts are between 1 and 17 with a mean value at 6. The pass count statistics indicate that the pavements are not compacted uniformly with the target roller passes. Most of the passes are concentrated at the middle of the compacted lane with only 1 or 2 passes at the edges.
- Speed: The roller speeds average at 5.1 mph (7.5 kph).
- Temperature: The first-pass temperature or the maximum value is 244°F (118°C). The mean value of the asphalt surface temperatures during compaction is 177°F (81°C) with a standard deviation of 19°F (10.6°C).
- Compaction curve: Focusing on the first 10 passes, the compaction curve trends in a curve without a noticeable optimum.

Comments on Sakai data (TB02B):

- ICMV: The CCV values are in the range of 0 to 100 with a mean value of 16.
- Pass counts: The pass counts are between 1 and 23 with a mean value at 7. The pass count statistics indicate that the pavements are not compacted uniformly with the target roller passes. Most of the passes are concentrated at the middle of the compacted lane with only 1 or 2 passes at the edges.
- Speed: The roller speeds average at 5.1 mph (8.2 kph).
- Temperature: The first-pass temperature or the maximum value is 243°F (117°C). The mean value of the asphalt surface temperatures during compaction is 172°F (77.8°C) with a standard deviation of 21°F (11.7°C).
- Compaction curve: Focusing on the first 10 passes, the compaction curve trends in a curve without a noticeable optimum.

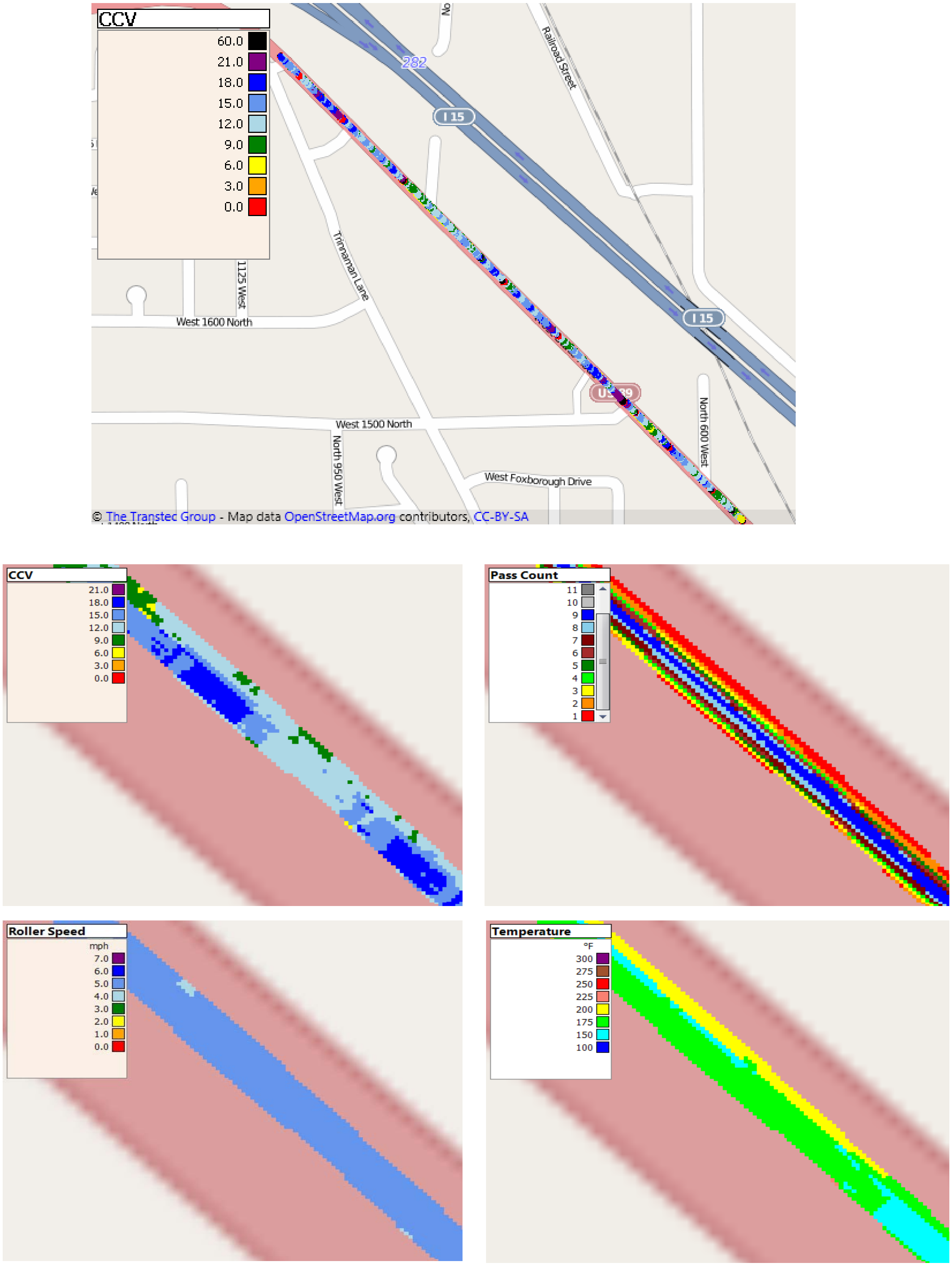

Figure 72. Sakai IC maps (intermediate), TB02A and TB02B, UT site.

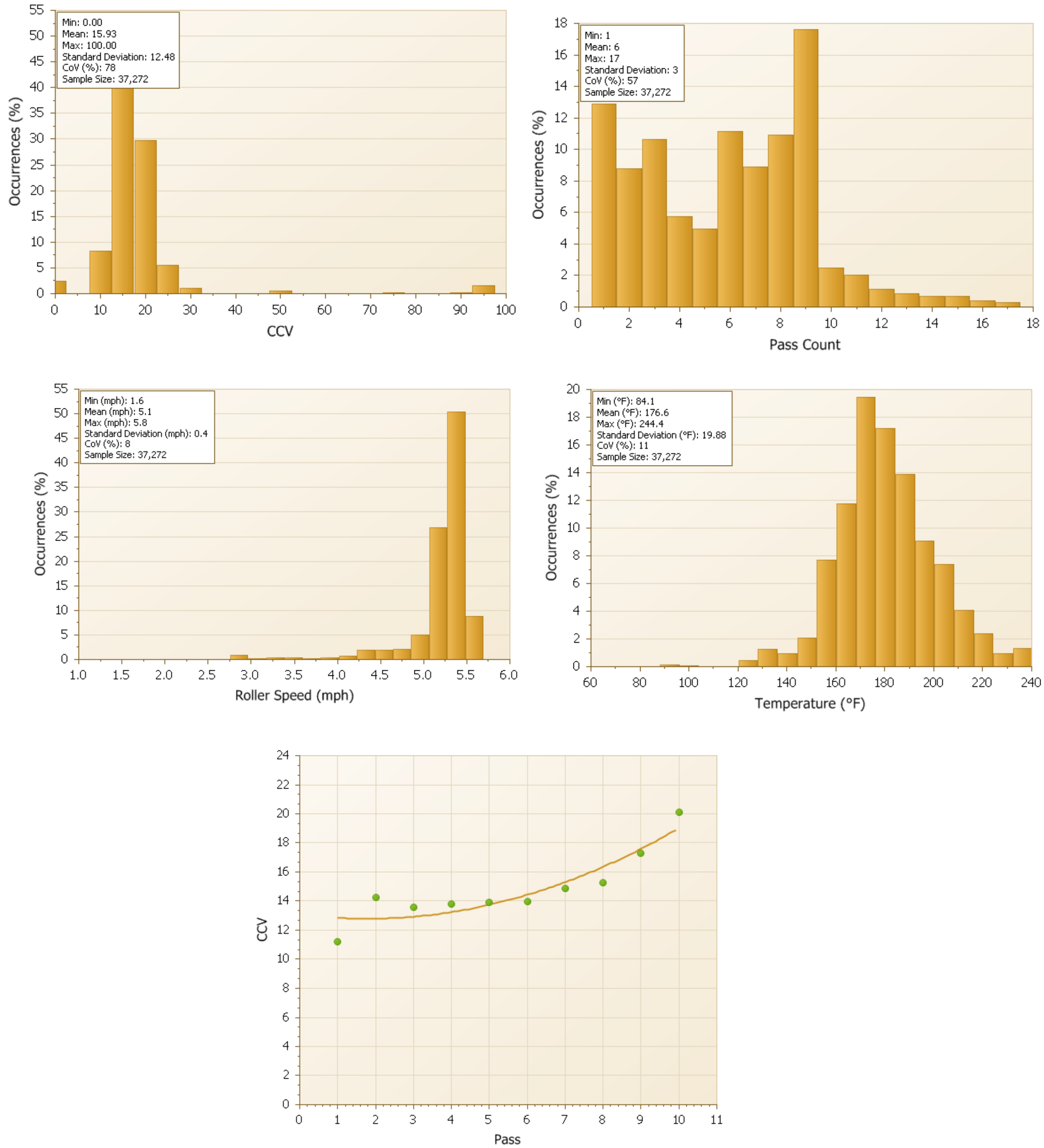

Figure 73. Sakai IC data statistics (intermediate), TB02A and TB02B, UT site.

Florida Site

The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 74 and Figure 75.

Comments on Hamm IC data:

- ICMV: The Hamm HMV values are in the range of 0 to 113 with a mean value of 43.1. The zero HMV data were from the IC roller at the static compaction mode.
- Pass counts: The pass counts are between 1 and 15 with a mean value at 5 and coefficient of variation of 51%. Based on the pass count map and statistics, the asphalt was not compacted uniformly with the center of the lane being compacted more than that of the edge areas.
- Speed: The roller speeds average at 3 mph (5.3 kph).
- Temperature: The first-pass temperature or the maximum value is 273°F (134°C). The mean value of the asphalt surface temperatures during compaction is 172°F (77.6°C) with a standard deviation of 25.7°F (14.3°C).
- Compaction curve: Analyzing the first 9 passes, the compaction curve reaches the optimum at around 5 passes.

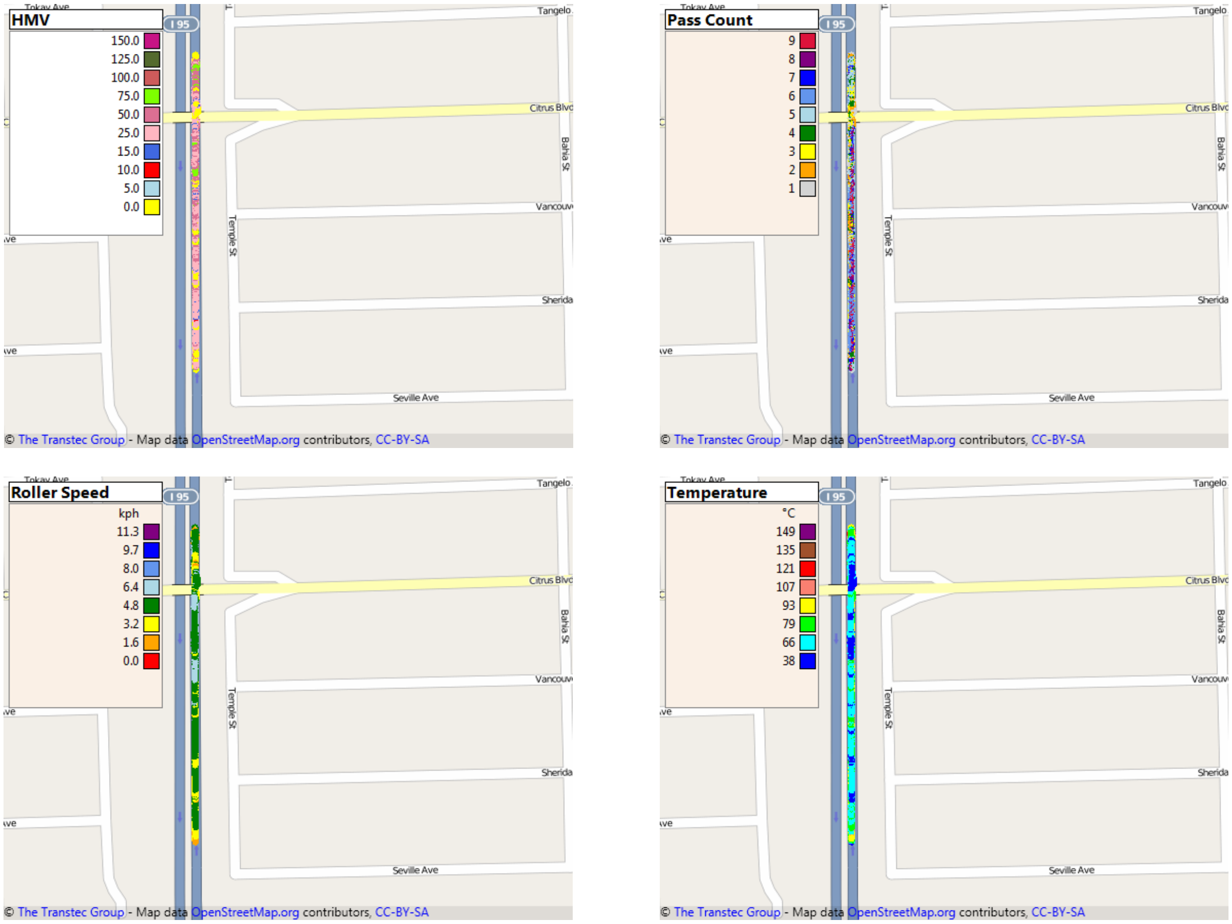

Figure 74. Hamm IC maps (breakdown), TB02, FL site.

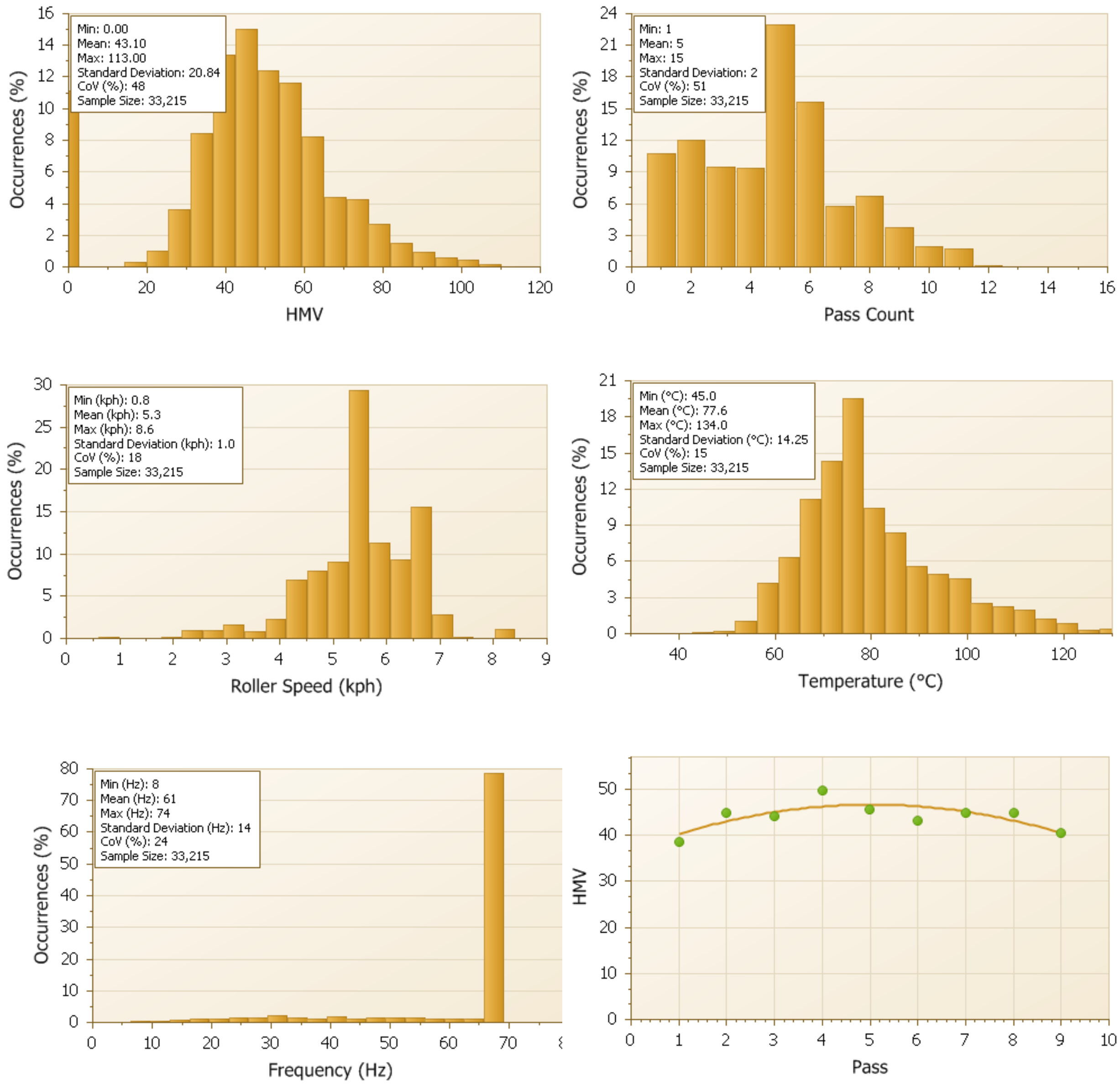

Figure 75. Hamm IC data statistics (breakdown), TB02, FL site.

The IC maps and statistics for the Sakai IC data (intermediate position) are presented in Figure 76 and Figure 77.

Comments on Sakai Data:

- ICMV: The CCV values are in the range of 0 to 100 with a mean value of 24.3.
- Pass counts: The pass counts are between 1 and 30 with a mean value at 7 and coefficient of variation of 56%. Based on the pass count map and statistics, the pavements were not compacted uniformly. The IC data is dispersed at the overpass location due to the loss of GPS signals under the overpass.
- Speed: The roller speeds average at 5.1 mph (7.1 kph).
- Temperature: The first-pass temperature or the maximum value is 189°F (87.4°C). The mean value of the asphalt surface temperatures during compaction is 126°F (52.4°C) with a standard deviation of 11.7°F (6.48°C). The temperature is lower than that of Hamm compaction since the Sakai roller was used as an intermediate/finish roller.

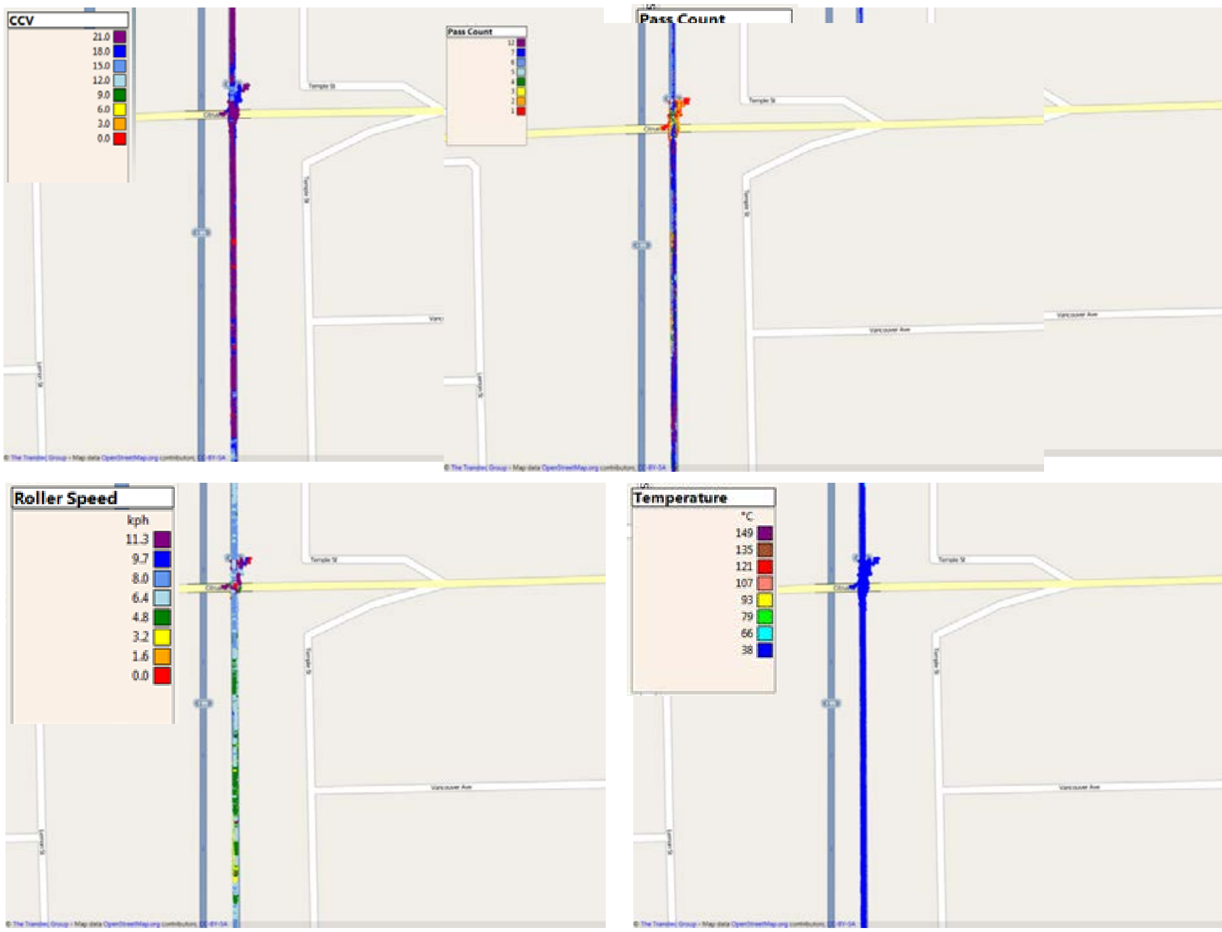

Figure 76. Sakai IC maps (intermediate), TB02, FL site.

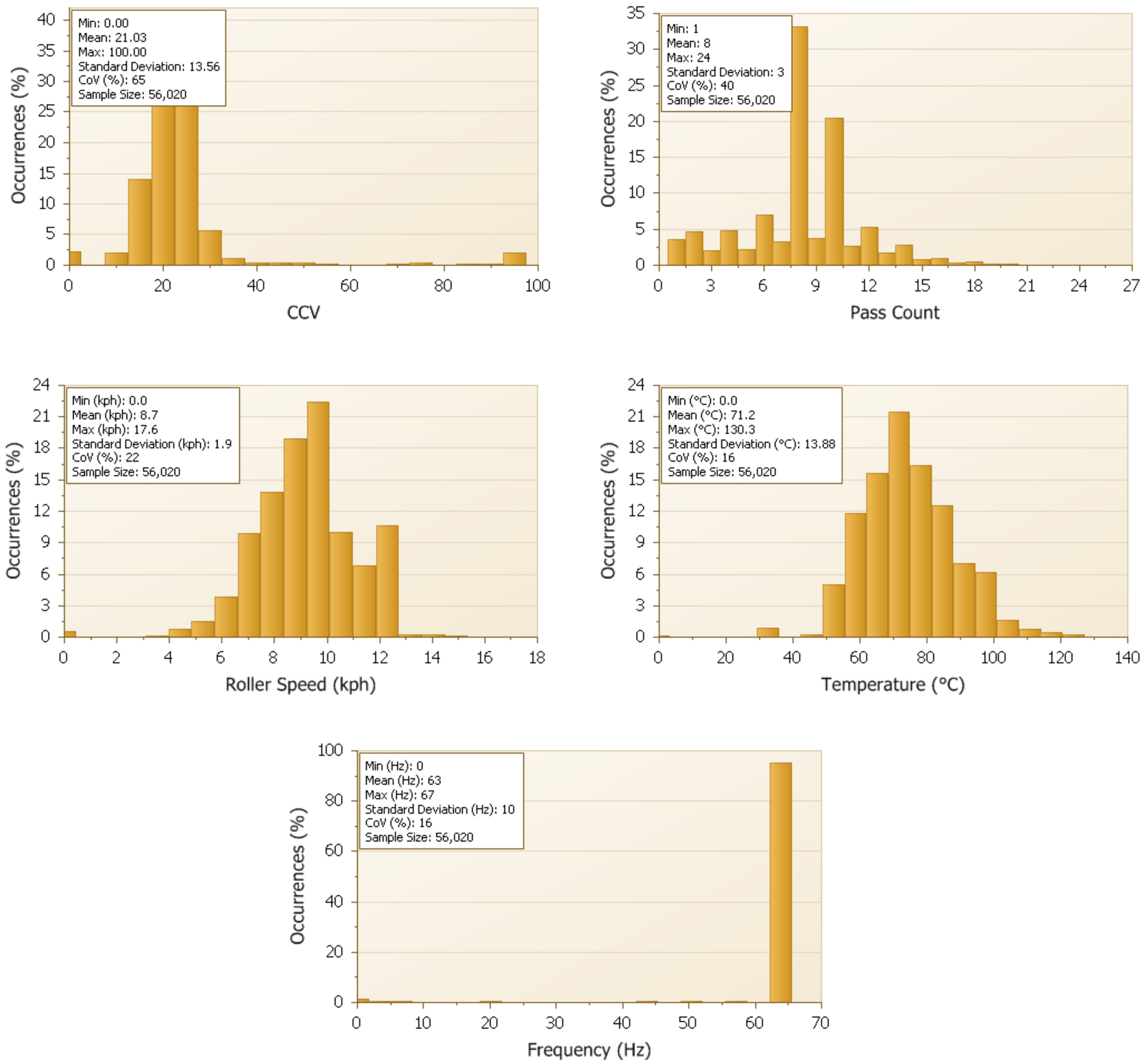

Figure 77. Sakai IC data statistics (intermediate), TB02, FL site.

Ohio Site

The IC maps and statistics for the Sakai IC data (breakdown position) are presented in Figure 78 and Figure 79.

Comments on Sakai Data:

- ICMV: The mean CCV value is 18 with standard deviation of 12. The high CCV values (greater than 60) may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 189°F (87.4°C) with standard deviation of 14.7°F (8.2°C). The majority of the areas were above 176°F (80°C) during the breakdown compaction.
- Pass counts: The roller pattern set by the contractor is 2 vibratory passes. However, 48 percent of compacted areas are with 2 passes, 9 percent of compacted areas are with 1 pass, and 33 percent of compacted areas are with 3 to 4 passes.
- Speed: The mean roller speed is 5.9 mph (9.5 kph).
- Frequency: The mean frequency is 3,720 vpm (62Hz).
- Compaction curve: Based on the CCV compaction curve, there is no evident optimum rolling pass.

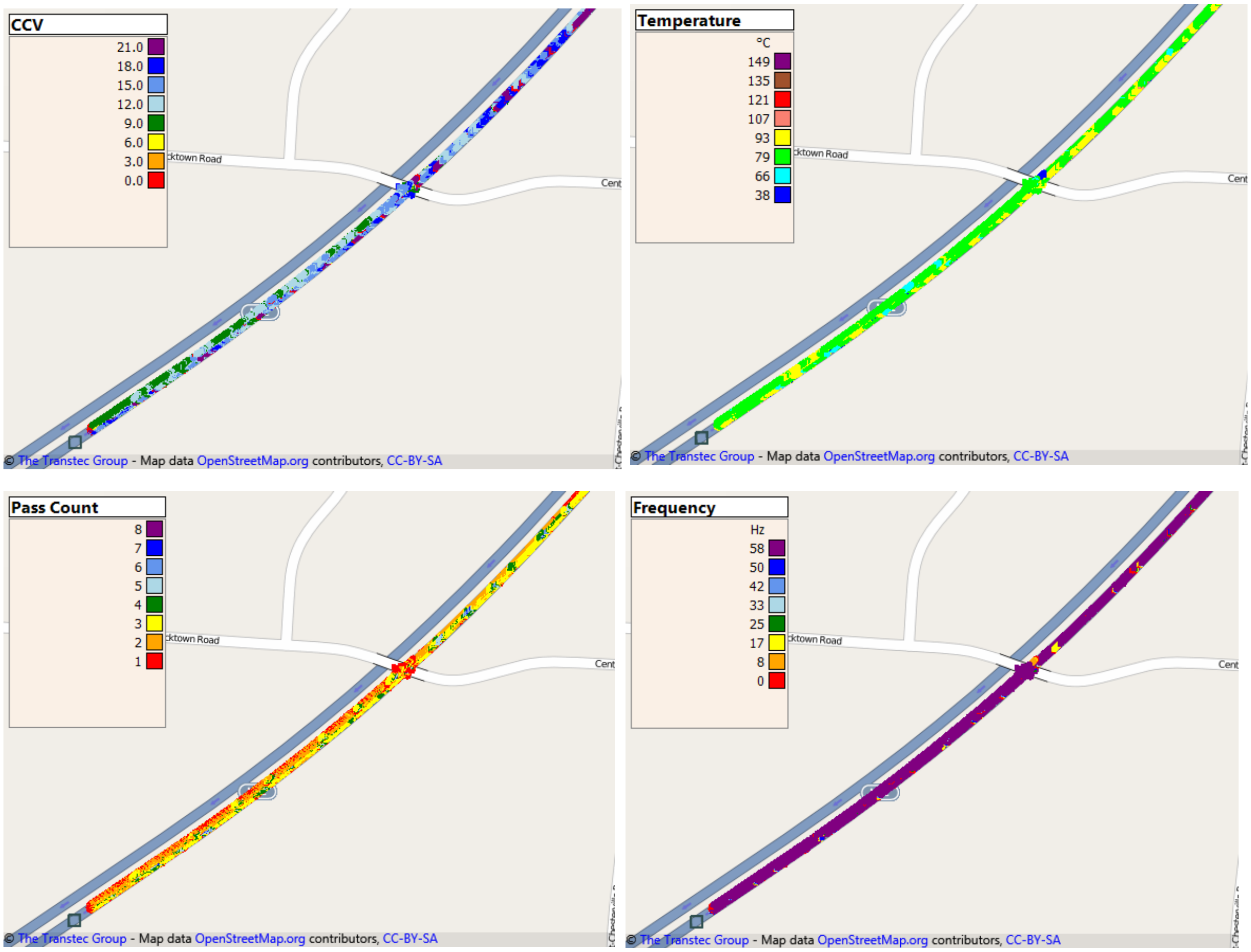

Figure 78. Sakai IC maps (breakdown), TB02, OH site.

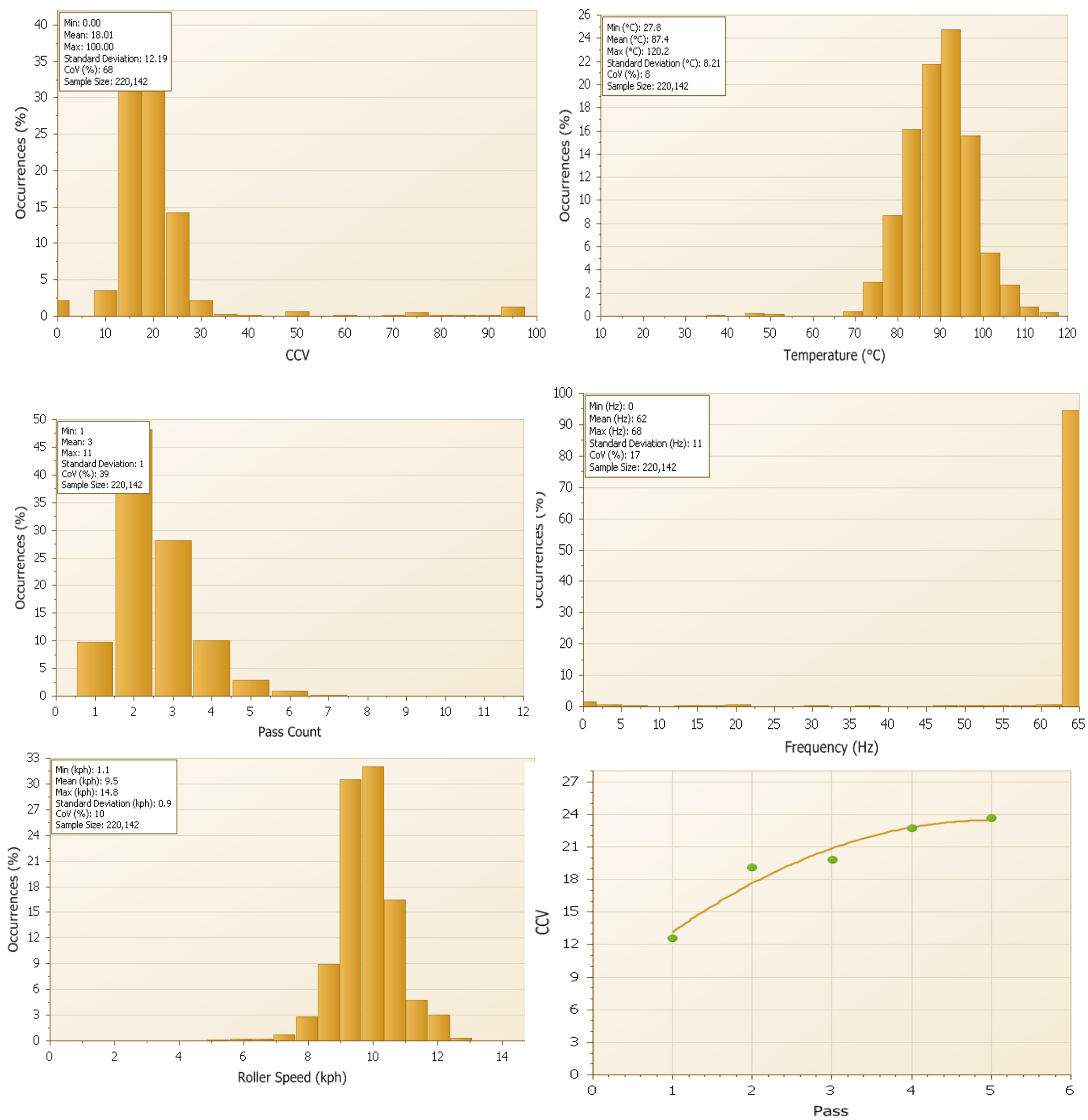

Figure 79. Sakai IC data statistics (breakdown), TB02, OH site.

The IC maps and statistics for the Hamm IC data (intermediate position) are presented in Figure 80 and Figure 81.

Comments on Hamm IC data:

- ICMV: The mean HMV value is 73 with standard deviation of 30. The zero HMV values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 167°F (75°C) with standard deviation of 14.4°F (8°C). More than 50% of the areas were below 176°F (80°C) during the intermediate/finish compaction.
- Pass counts: The roller pattern set by the contractor is 2 vibratory passes. 66 percent of compacted areas are with 2 passes, 7 percent of compacted areas are with 1 pass, and 25 percent of compacted areas are with 3 to 4 passes.
- Speed: The mean roller speed is 3.7 mph (6 kph).
- Frequency: The mean frequency is 3,780 vpm (63Hz).
- Compaction curve: Based on the HMV compaction curve, the optimum roller passes is 2.

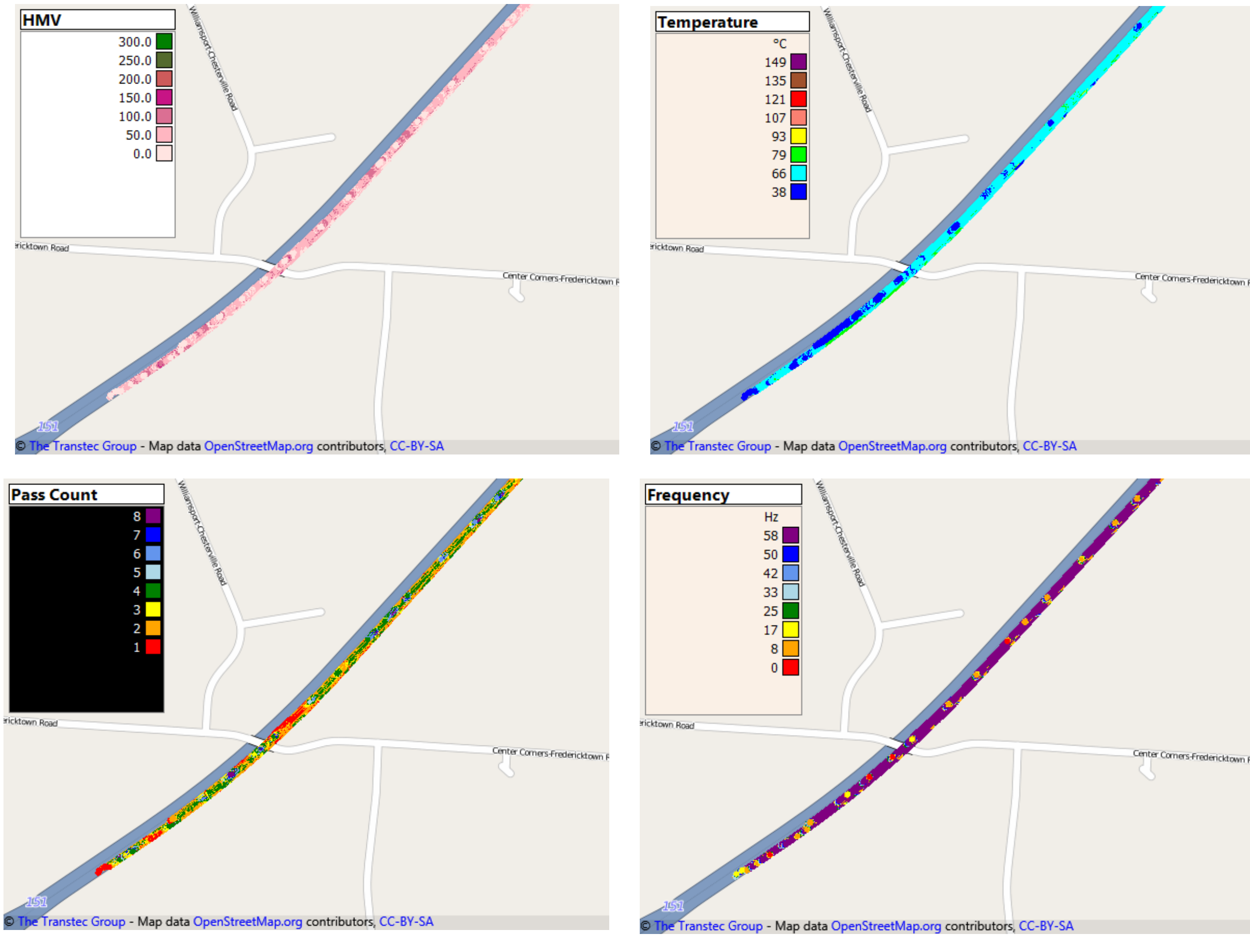

Figure 80. Hamm IC maps (intermediate), TB02, OH site.

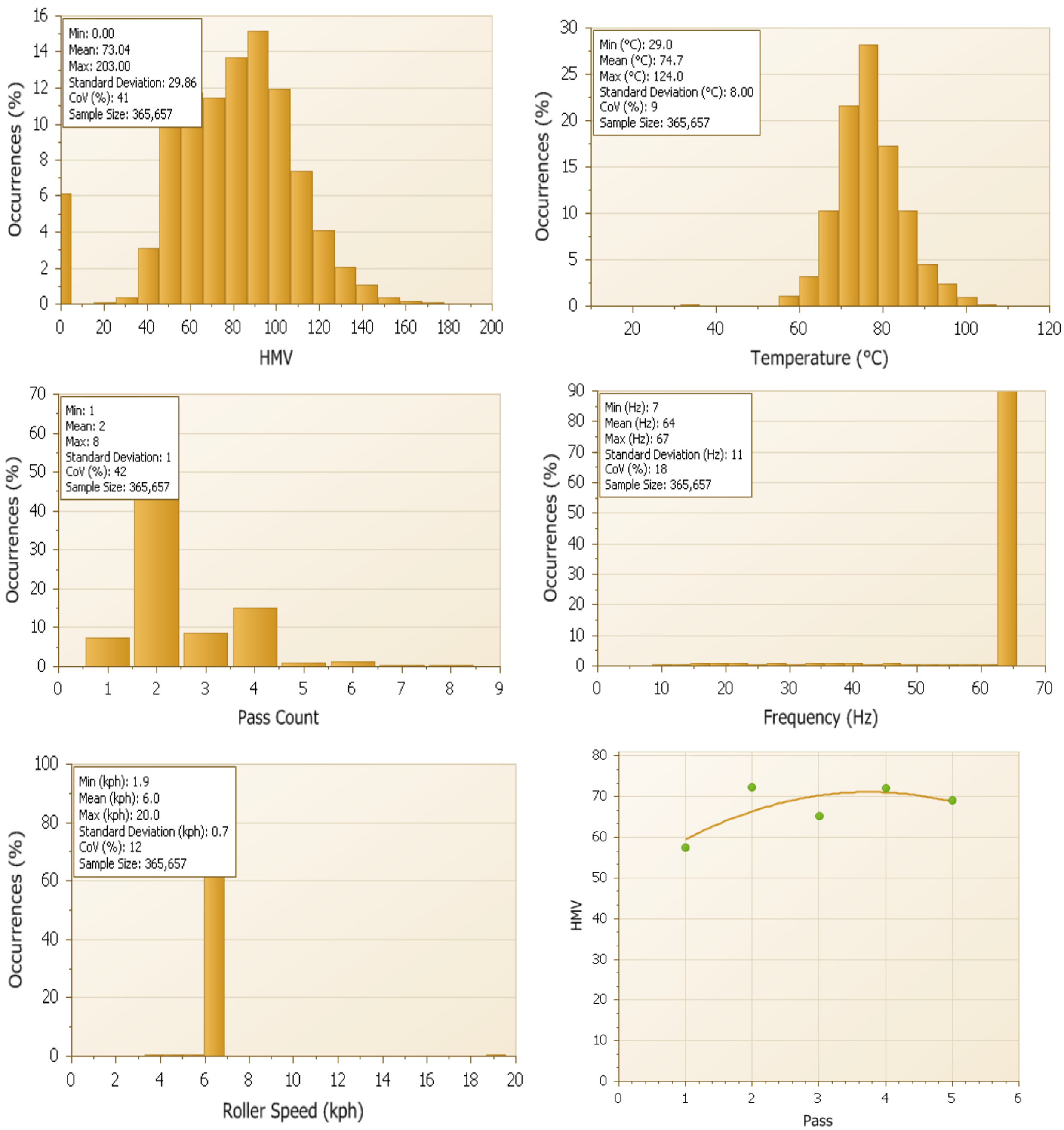

Figure 81. Hamm IC data statistics (intermediate), TB02, OH site.

Maine Site

The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 82 and Figure 83.

Comments on Hamm IC data:

- ICMV: The mean HMV value is 34 with standard deviation of 16. The zero HMV values may be due to sudden acceleration or stops of the roller.
- Temperature: The mean surface temperature is 190°F (88°C) with standard deviation of 36°F (20°C).
- Pass counts: The roller pattern set by the contractor is 10 vibratory passes. The recorded mean roller passes is 8.
- Speed: The mean roller speed is 1.9 mph (3 kph).
- Frequency: The mean frequency is 3,360 vpm (61Hz).
- Compaction curve: The curve grows monotonically with a very narrow range (6 HMV) without an apparent optimal value.

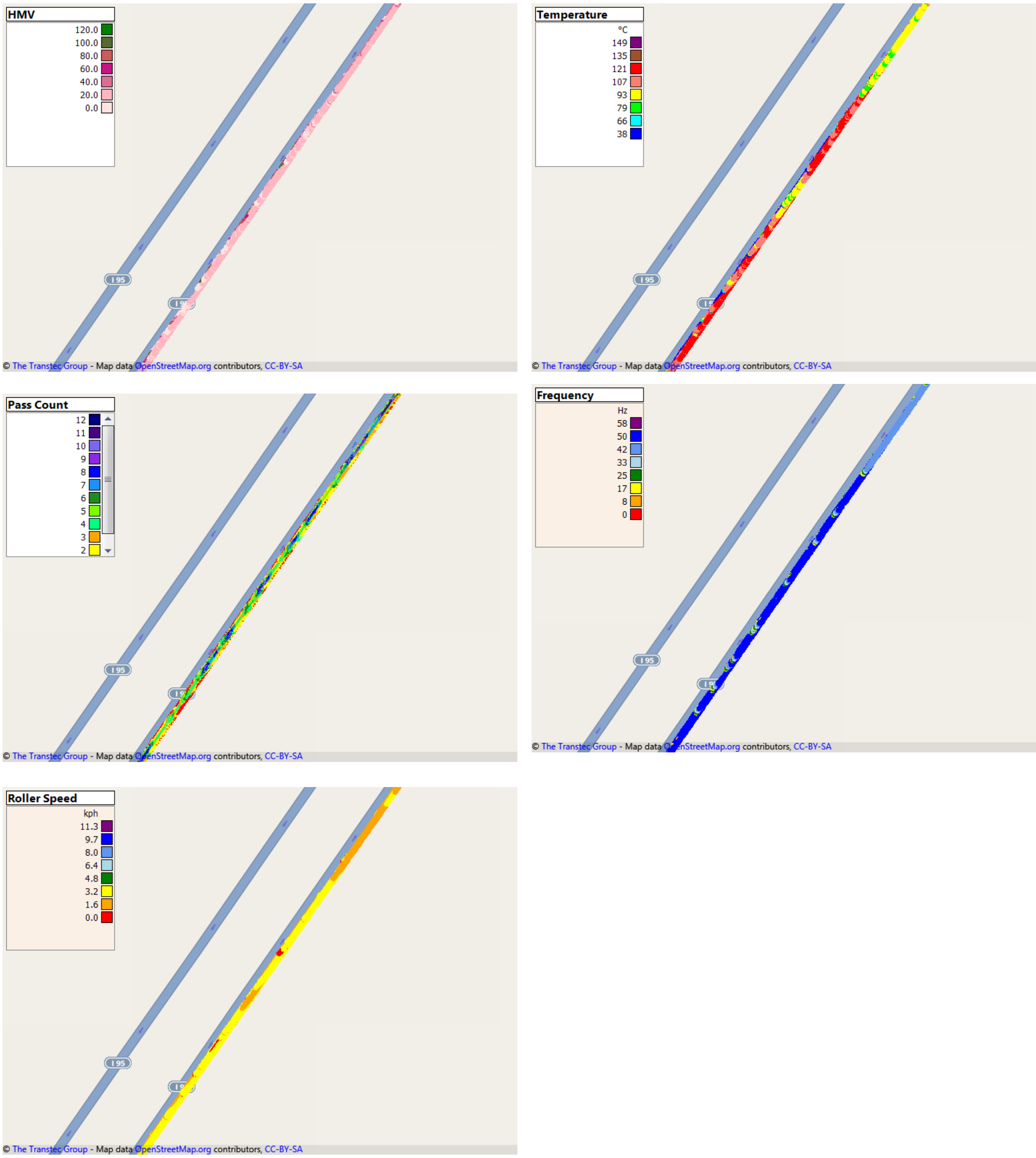

Figure 82. Hamm IC maps (breakdown), TB03, ME site.

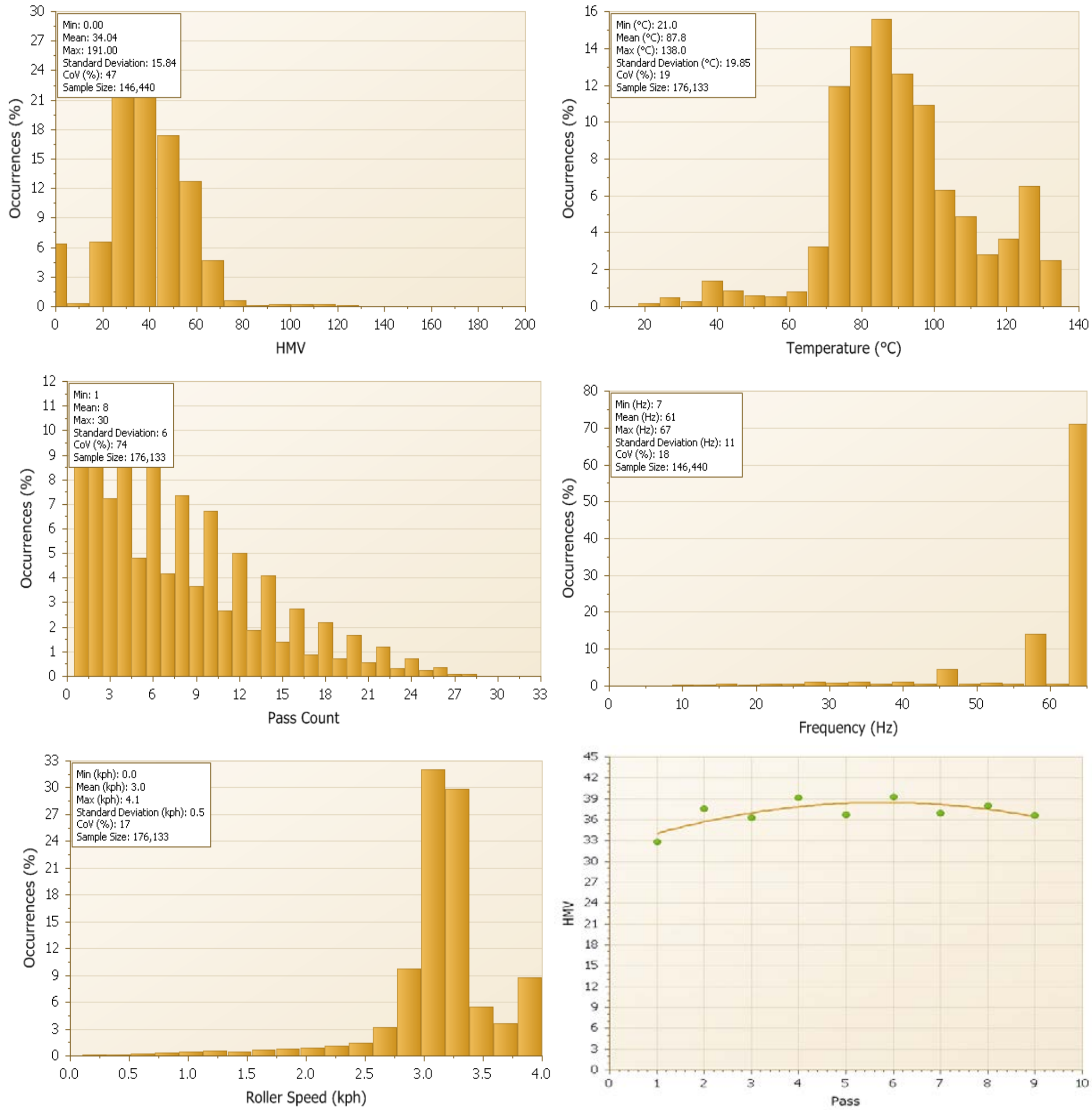

Figure 83. Hamm IC data statistics (breakdown), TB03, ME site.

The IC maps and statistics for the Caterpillar IC data (intermediate position) are presented in Figure 84 and Figure 85.

Comments on Caterpillar Data:

- ICMV: The mean CMV value is 42 with standard deviation of 9.
- Temperature: The mean surface temperature is 145°F (63°C) with standard deviation of 21.6°F (12°C).
- Pass counts: The roller pattern set by the contractor is 4 vibratory passes. The recorded mean roller passes is also 4.
- Speed: The mean roller speed is 3.4 mph (5.4 kph).
- Frequency: The mean frequency is 3,180 vpm (53Hz).
- Compaction curve: The curve is with a very narrow range (around 42 CMV) without an apparent optimal value.

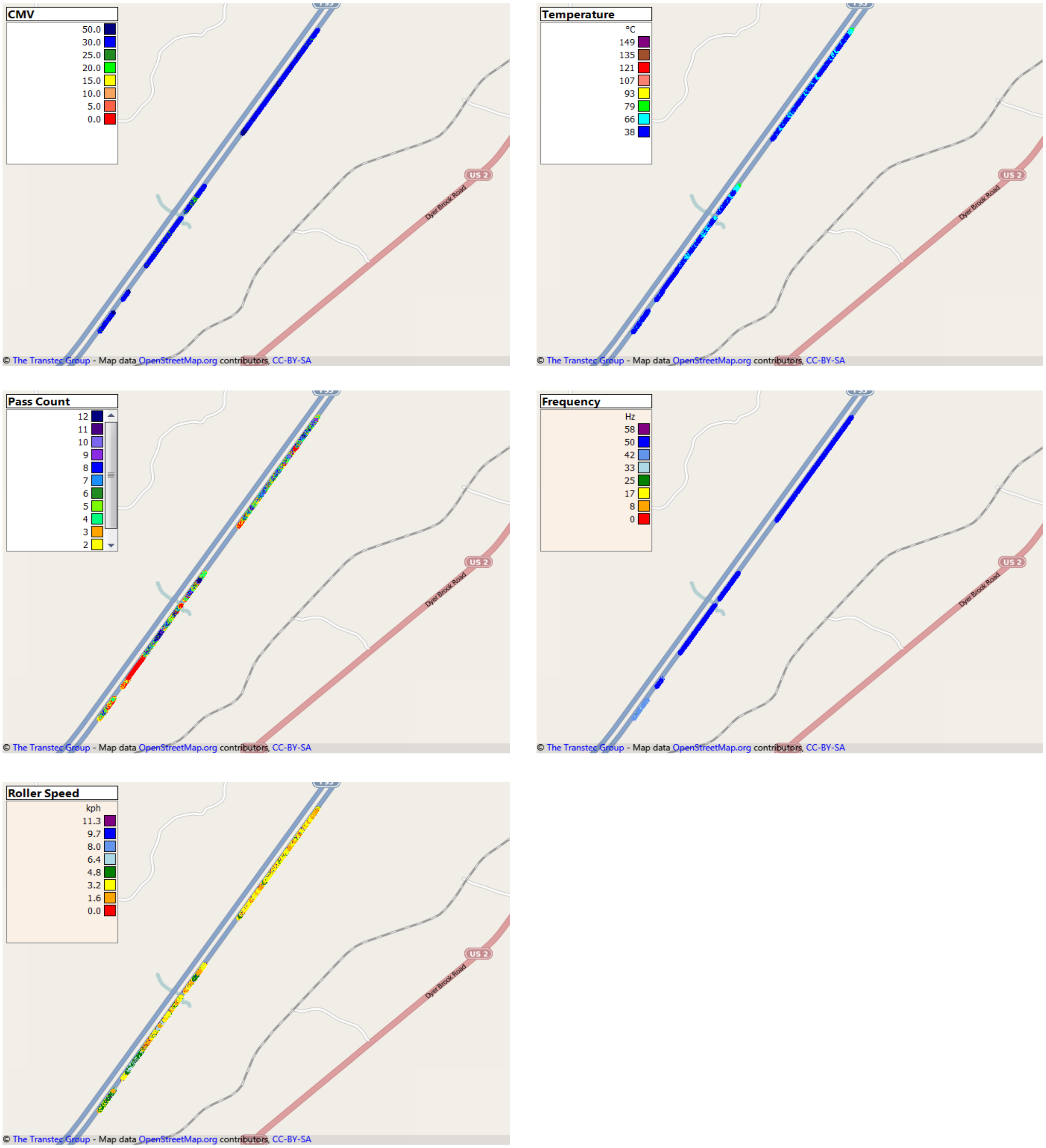

Figure 84. Caterpillar IC maps (intermediate), TB03, ME site.

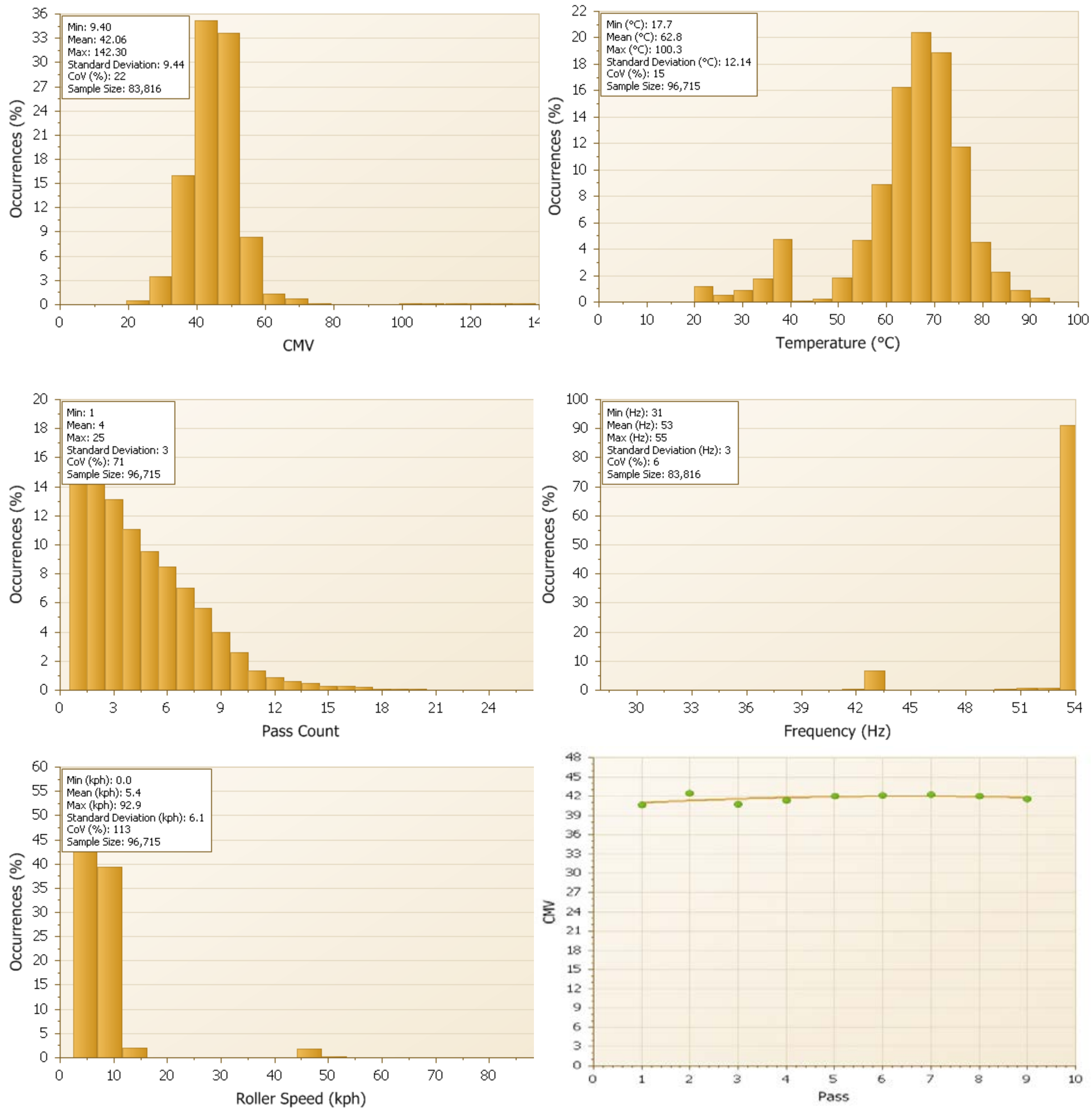

Figure 85. Caterpillar IC data statistics (intermediate), TB03, ME site.

California Site

The IC maps and statistics for the Caterpillar IC data (breakdown position) are presented in Figure 86 and Figure 87. Note that the Hamm IC roller and the Caterpillar IC roller operated in echelon but without much overlap. The Hamm IC data were not recorded due to lack of GPS services. The BOMAG roller was used in intermediate compaction.

Comments on Caterpillar Data:

- ICMV: The mean CMV value is 63 with standard deviation of 17.
- Temperature: The mean surface temperature is 170°F (77°C) with standard deviation of 94°F (52°C). The high deviation is due to the inclusion of a lower temperature groups, likely during transit between paving sections.
- Pass counts: The roller pattern set by the contractor is 2 vibratory passes. The recorded mean roller passes is also 2.
- Speed: The mean roller speed is 3.7 mph (6 kph). However, there are erratic speed records due to unknown reasons.
- Frequency: The mean frequency is 2,560 vpm (43 Hz).
- Compaction curve: The curve grows monotonically without an apparent optimal value.

Figure 86. Caterpillar IC maps (breakdown), TB02, CA site.

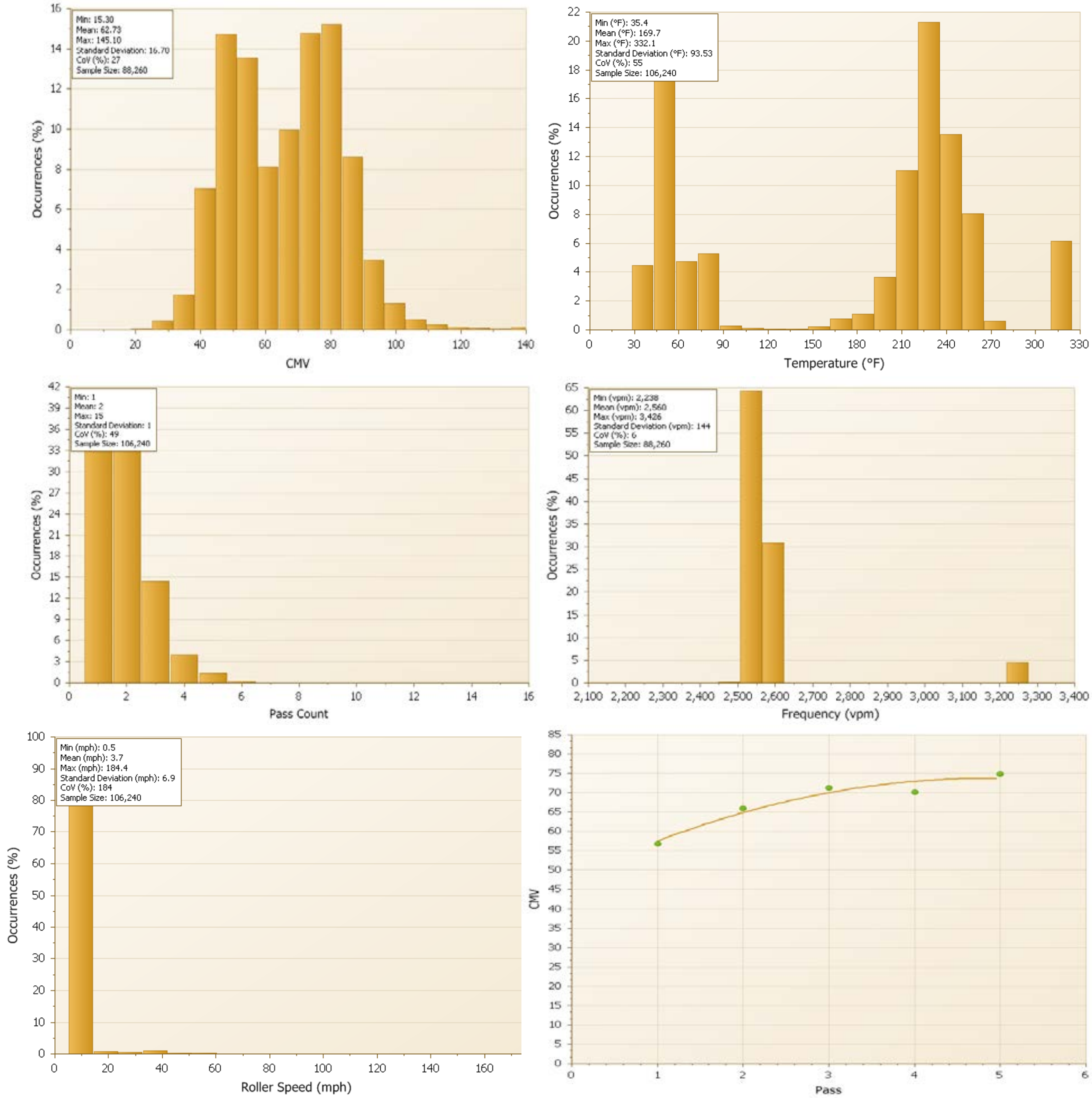

Figure 87. Caterpillar IC data statistics (breakdown), TB02, CA site.

The IC maps and statistics for the BOMAG IC data (intermediate position) are presented in Figure 88 and Figure 89.

Comments on BOMAG Data:

- ICMV: The mean Evib value is 51 with standard deviation of 8.
- Temperature: The mean surface temperature is 176°F (80°C) with standard deviation of 42°F (23°C). The distribution includes lower temperatures likely due to mobilization.
- Pass counts: The roller pattern set by the contractor is 3 vibratory passes. The recorded mean roller passes is also 3.
- Speed: The mean roller speed is 7 mph (11.3 kph).
- Frequency: The mean frequency is 2,873 vpm (48 Hz).
- Compaction curve: The curve is within a very narrow range (Evib values between 26 and 30) without an apparent optimal value.

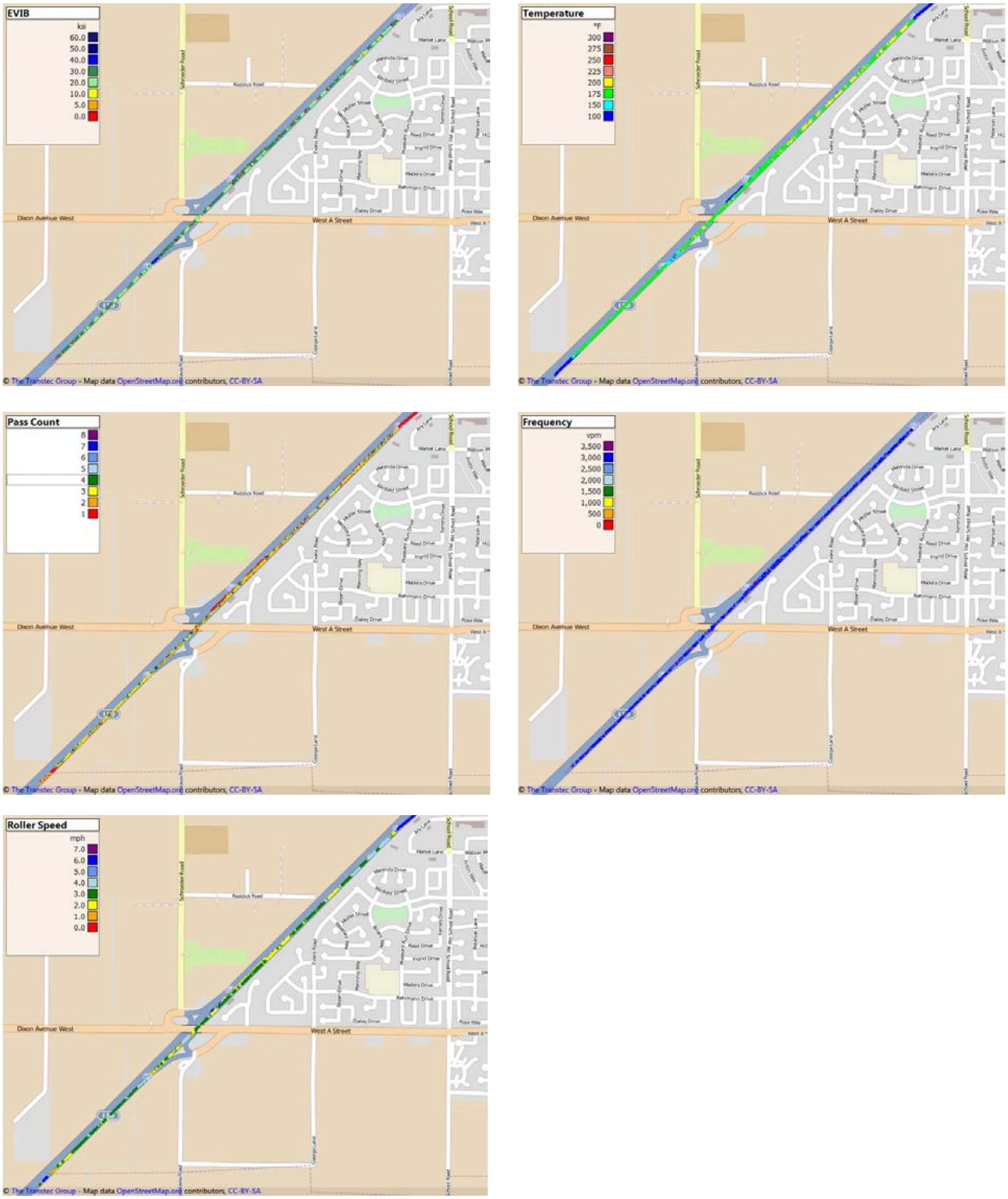

Figure 88. BOMAG IC maps (intermediate), TB02, CA site.

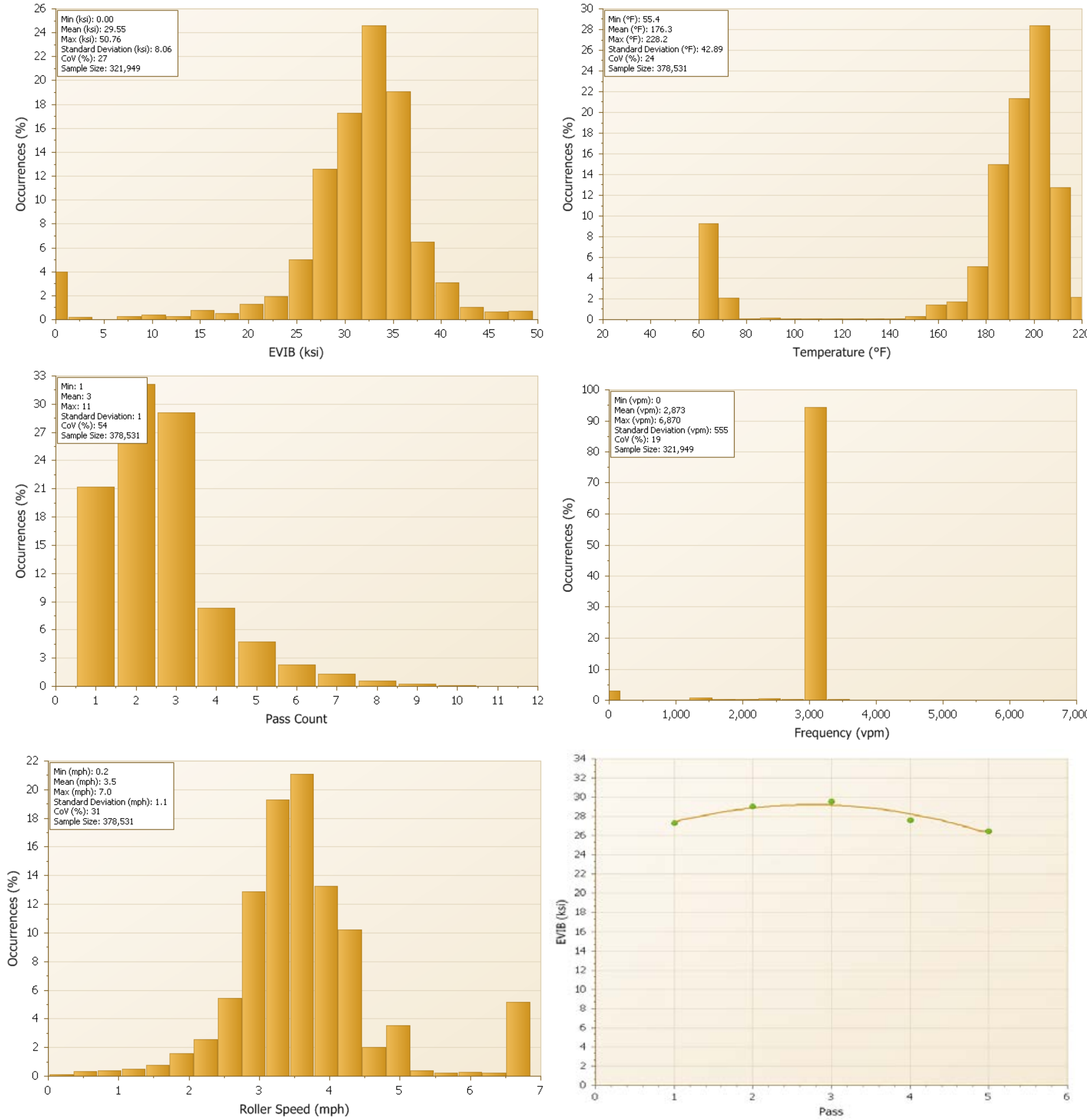

Figure 89. BOMAG IC data statistics (intermediate), TB02, CA site.

Idaho Site

The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 90 and Figure 91.

Comments on Hamm Data:

- ICMV: The mean HMV value is 36 with standard deviation of 7.9.
- Temperature: The mean surface temperature is 222°F (106°C) with standard deviation of 35°F (19°C).
- Pass counts: The recorded mean roller passes is 3.
- Frequency: The mean frequency is 3,016 vpm (50 Hz).
- Compaction curve: The ICMV curve grows parabolic with an asymptote at 38 for HMV and pass count of 4.
- Speeds: The mean roller speed is 2.8 mph (4.5 kph).

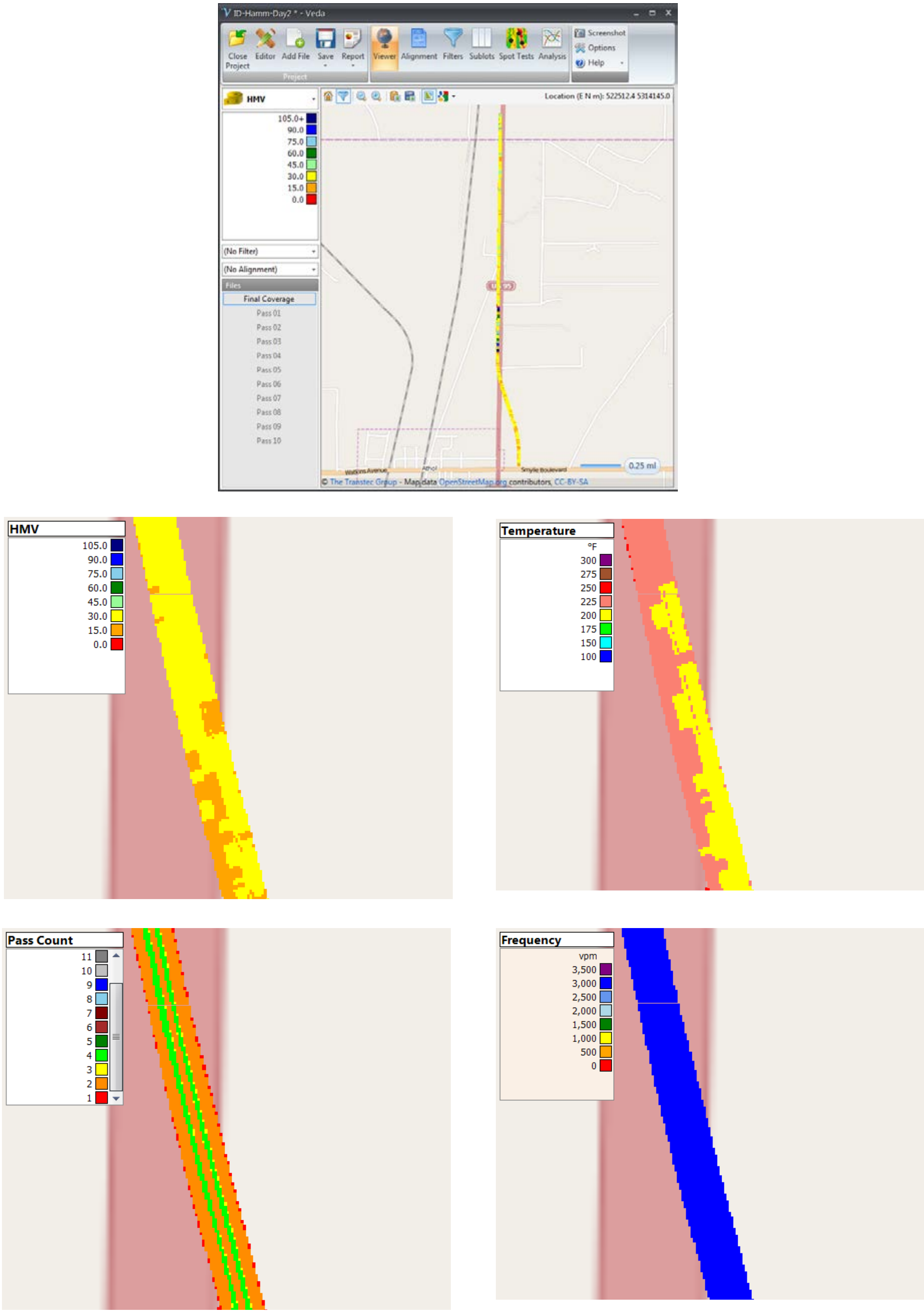

Figure 90. Hamm IC maps (breakdown), TB02, ID site.

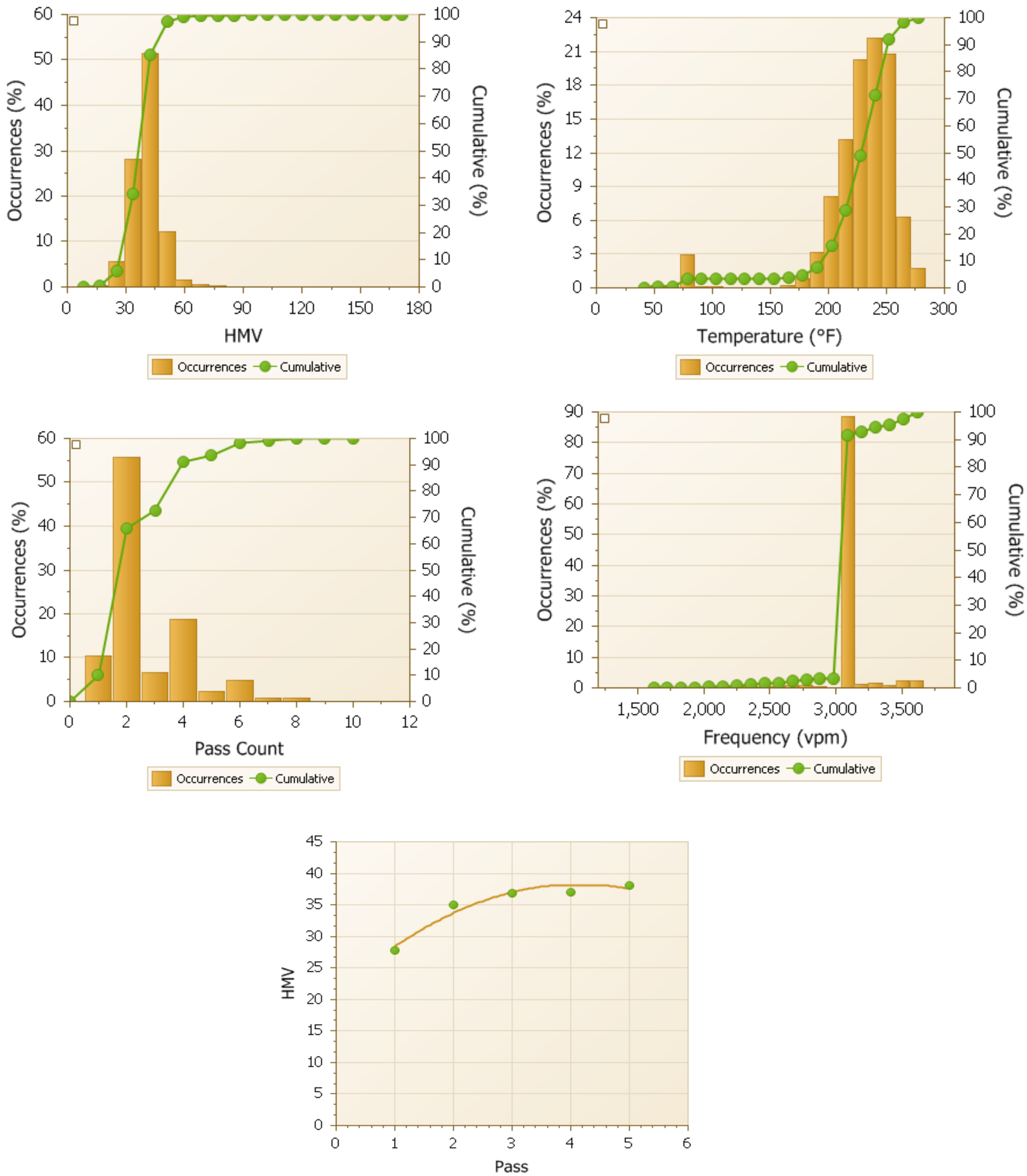

Figure 91. Hamm IC statistics (breakdown), TB02, ID site.

The IC maps and statistics for the Sakai IC data (intermediate position) are presented in Figure 92 and Figure 93.

Comments on Sakai Data:

- ICMV: The mean CCV value is 10.7 with standard deviation of 14.7. The high CCV values may be due to acceleration and deceleration at start and stop locations.
- Temperature: The mean surface temperature is 188°F (87°C) with standard deviation of 29.6°F (16.4°C). Some lower temperature values may be due to mobilization and sensor malfunctioning.
- Pass counts: The recorded mean roller passes is 3.
- Frequency: The mean frequency is 3,880 vpm (65 Hz).
- Compaction curve: The curve grows monotonically without an apparent optimal value.
- Speeds: The mean roller speed is 3.0 mph (4.8 kph).

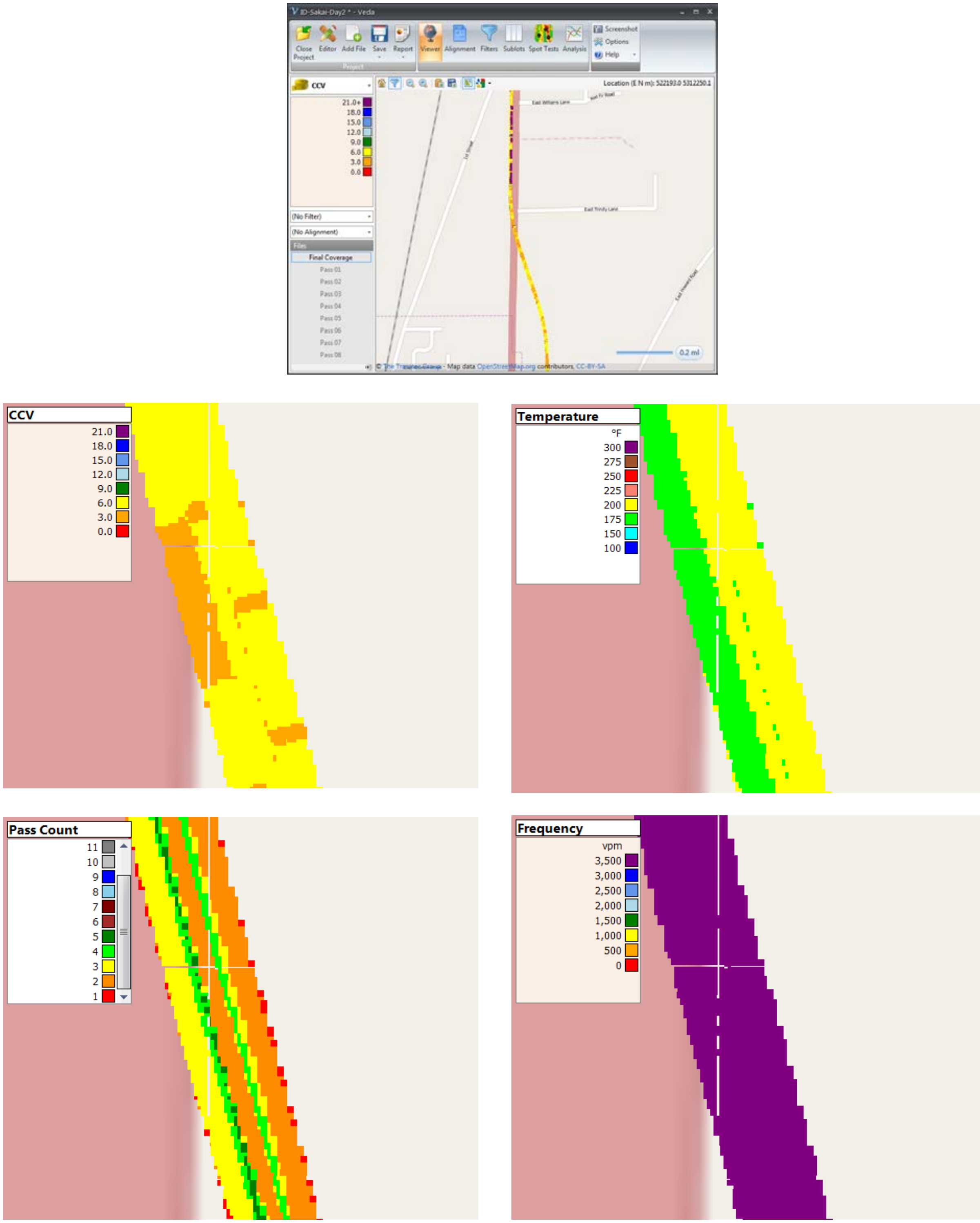

Figure 92. Sakai IC maps (intermediate), TB02, ID site.

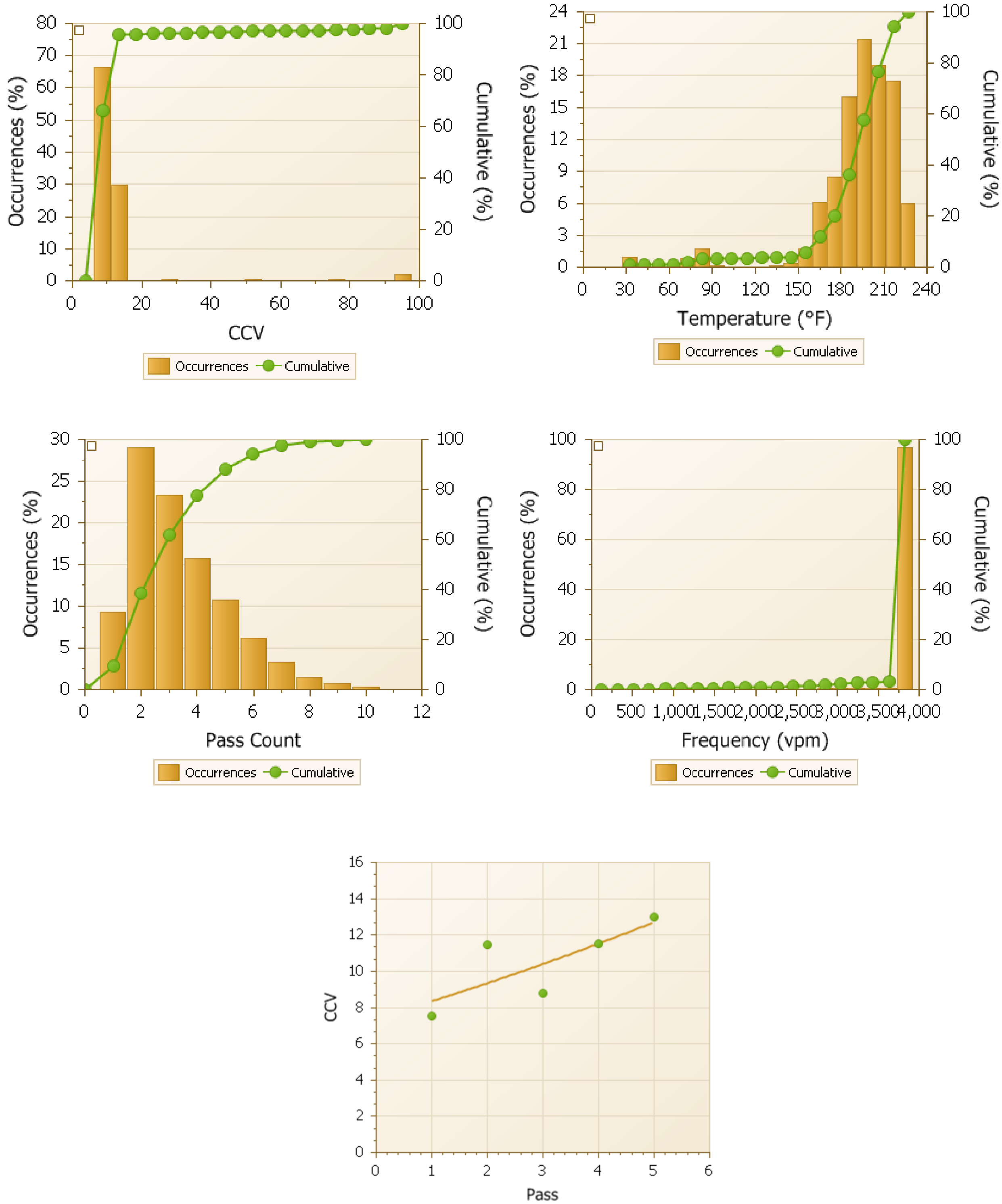

Figure 93. Sakai IC statistics (intermediate), TB02, ID site.

Maryland Site

The IC maps and statistics for the Caterpillar IC data (breakdown position) are presented in Figure 94 and Figure 95.

Comments on Caterpillar Data:

- ICMV: The mean CMV value is 67.6 with standard deviation of 23.5.
- Temperature: The mean surface temperature is 152°F (66.7°C) with standard deviation of 40°F (22°C). The temperature records appeared to be lower than manual measurements with infrared guns.
- Pass counts: The recorded mean roller passes is 2 but with 60% at pass number one. The records were not consistent with onsite manual counts of up to 7 passes.
- Frequency: The mean frequency is 2,500 vpm (45 Hz).
- Compaction curve: The curve grows monotonically without an apparent optimal value.
- The GPS reception was poor at this test bed due to tree coverage and the use of VRS. Based on the above observation, the Caterpillar data appeared to be questionable. Further investigation of the VisionLink export is warranted.

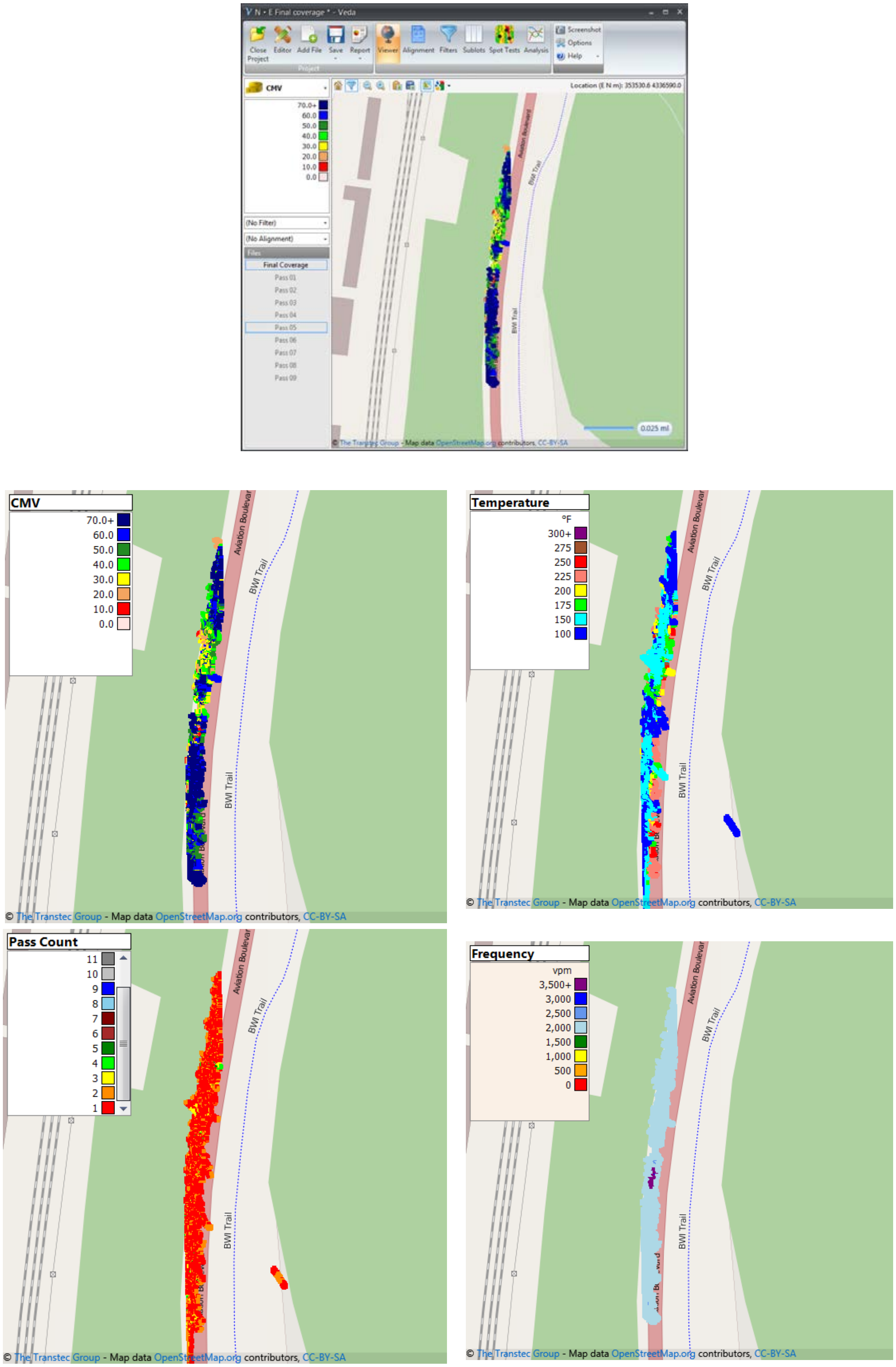

Figure 94. Caterpillar IC maps (breakdown), TB03, MD site.

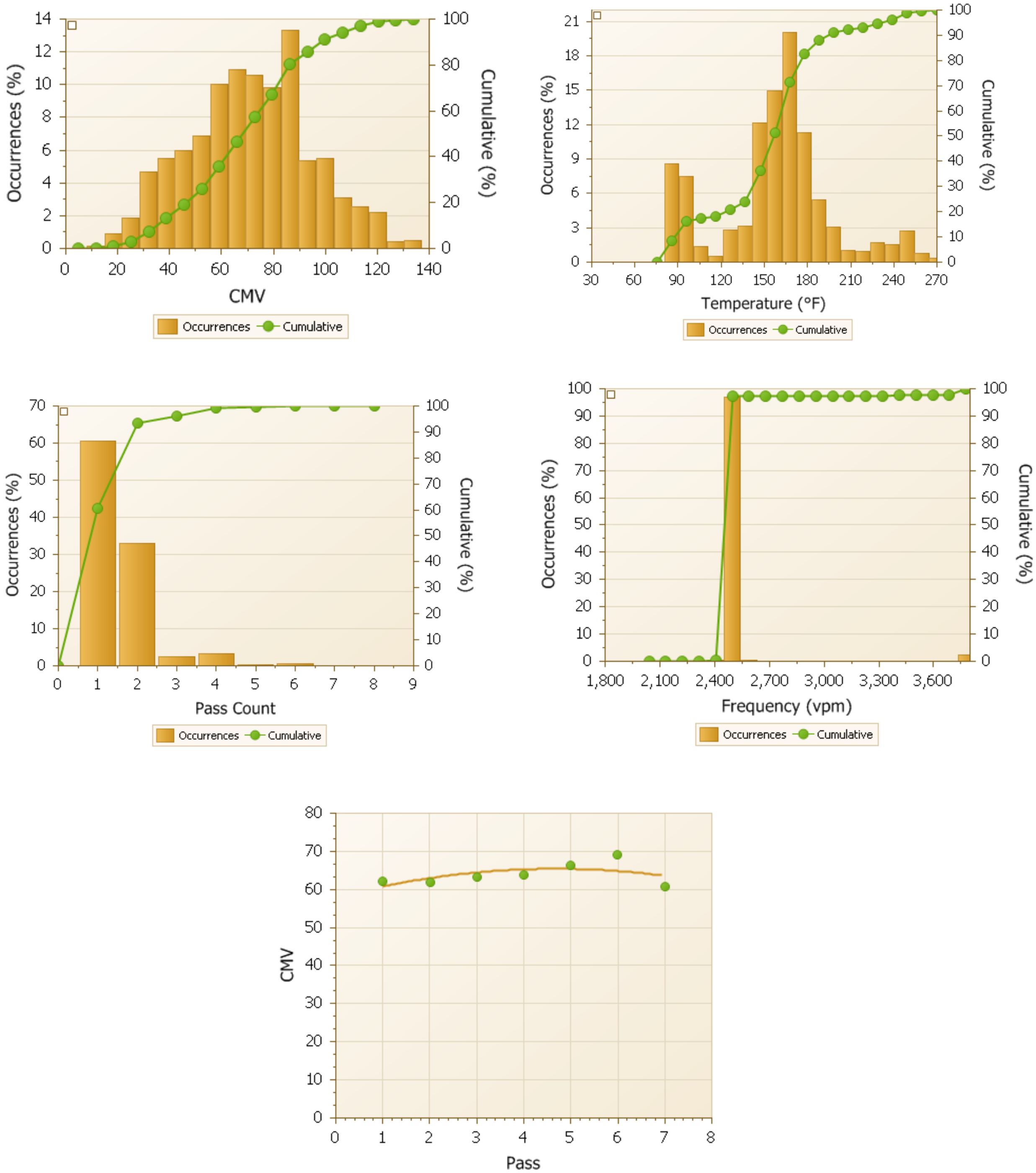

Figure 95. Caterpillar IC statistics (breakdown), TB03, MD site.

The IC maps and statistics for the Hamm IC data (intermediate position) are presented in Figure 96 and Figure 97.

Comments on Hamm Data:

- ICMV: The mean HMV value is 42 with standard deviation of 15.8.
- Temperature: The mean surface temperature is 202°F (94°C) with standard deviation of 31°F (17°C).
- Pass counts: The recorded mean roller passes is 4.
- Frequency: The mean frequency is 2,678 vpm (45 Hz).
- Compaction curve: The ICMV curve stays flat without a significant optimum.
- The GPS reception was poor at this test bed due to tree coverage. However, the OmniSTAR appeared to be less affected than VRS.

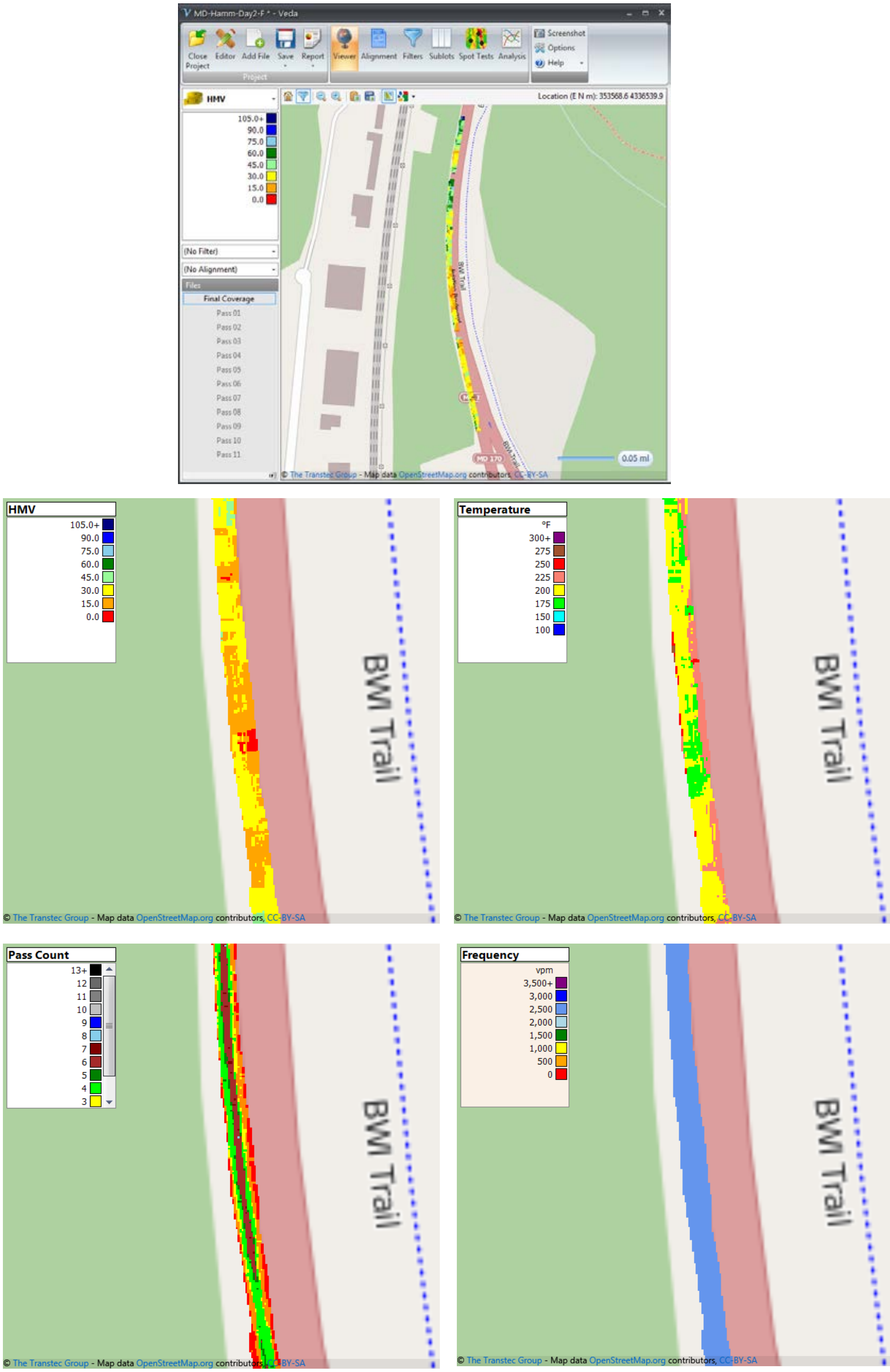

Figure 96. Hamm IC maps (intermediate), TB03, MD site.

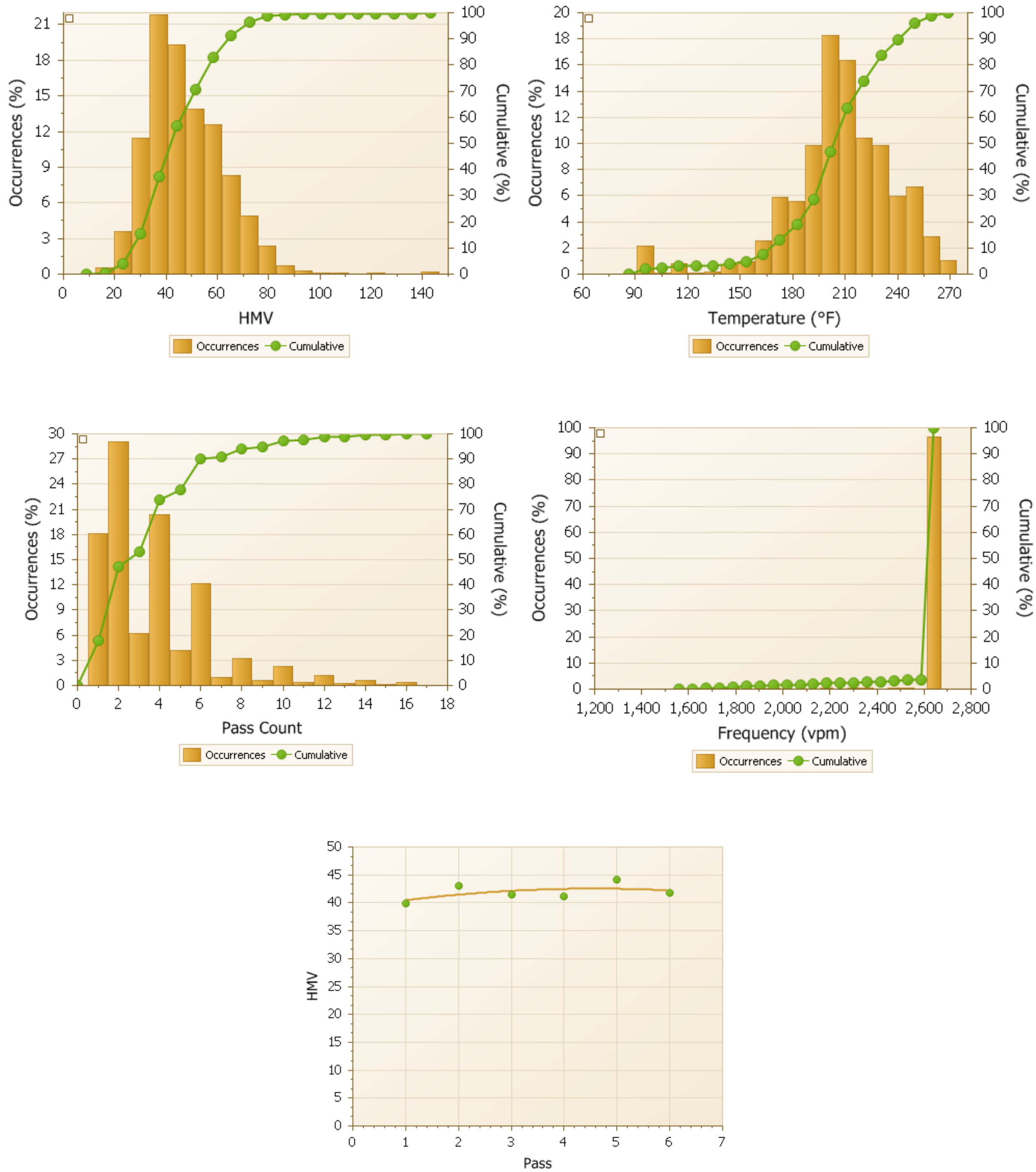

Figure 97. Hamm IC statistics (intermediate), TB03, MD site.

Kentucky Site

The IC maps and statistics for the Hamm IC data (breakdown position) are presented in Figure 98 and Figure 99.

Comments on Hamm Data:

- ICMV: The mean HMV value is 55.8 with standard deviation of 15.3.
- Temperature: The mean surface temperature is 207°F (97°C) with standard deviation of 55.6°F (31°C).
- Pass counts: The recorded mean roller passes is 5.
- Frequency: The mean frequency is 2,381 vpm (40 Hz).
- Compaction curve: The curve grows monotonically without an apparent optimal value.

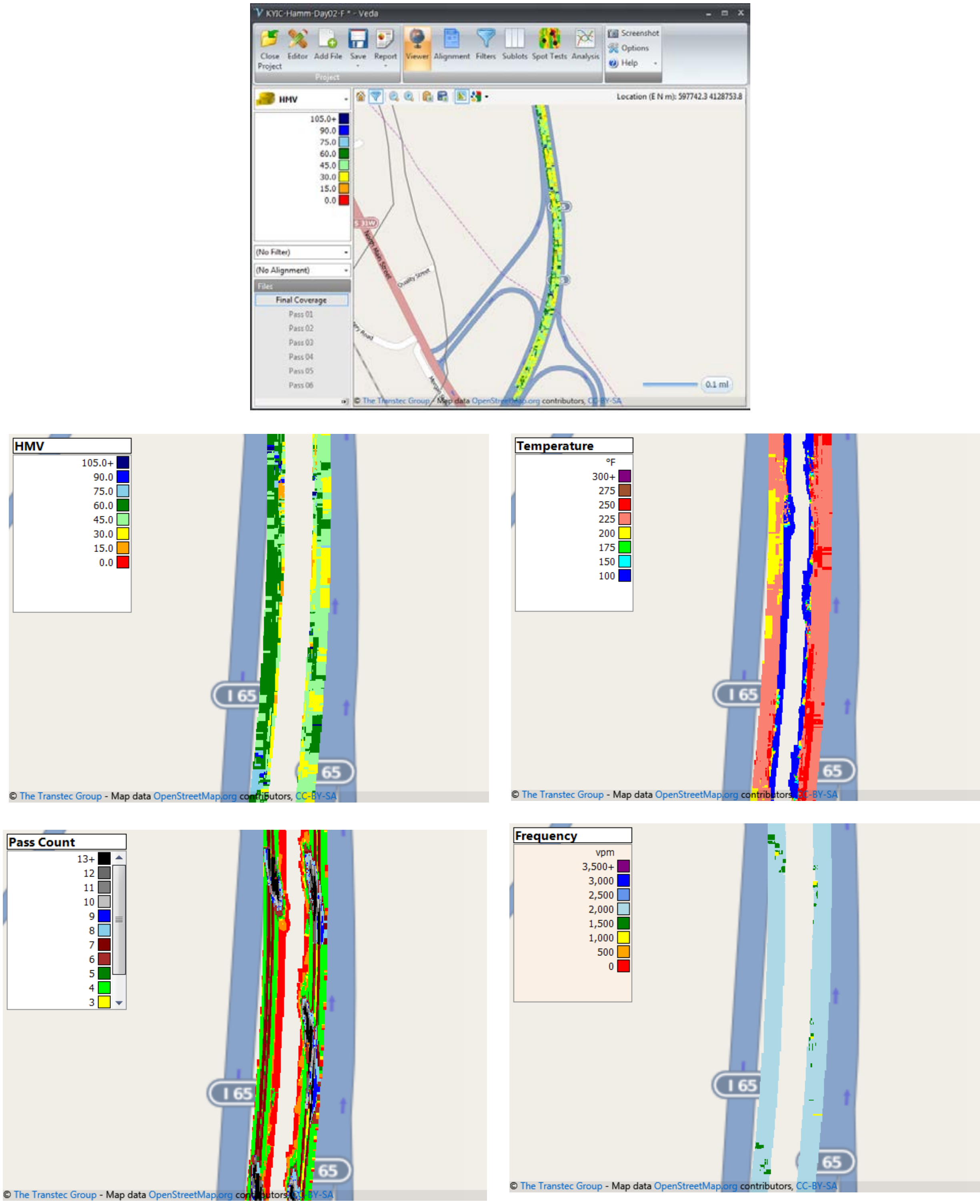

Figure 98. Hamm IC maps (breakdown), TB02A and TB02B, KY site.

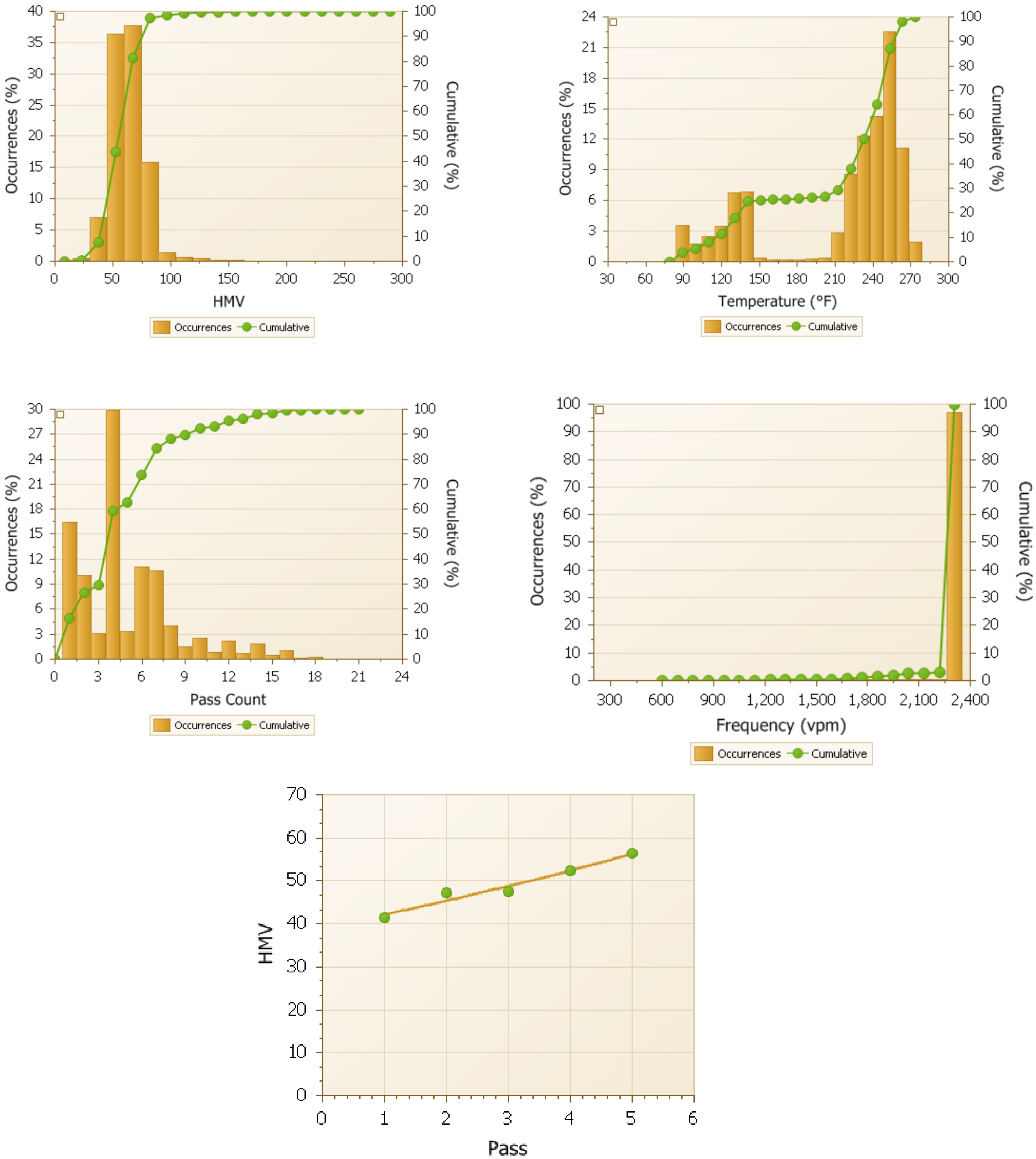

Figure 99. Hamm IC statistics (breakdown), TB02A and TB02B, KY site.

The IC maps and statistics for the Caterpillar IC data (intermediate position) are presented in Figure 100 and Figure 101.

Comments on Caterpillar Data:

- ICMV: The mean CMV value is 32 with standard deviation of 18.2. However, the CMV "pattern" appeared to be unusual.
- Temperature: The mean surface temperature is 157°F (69°C) with standard deviation of 34°F (19°C).
- Pass counts: The recorded mean roller passes is 11.
- Frequency: The mean frequency is 3,822 vpm (64 Hz).
- Compaction curve: The curve appeared to be in an unusual shape. Further investigation is warranted.

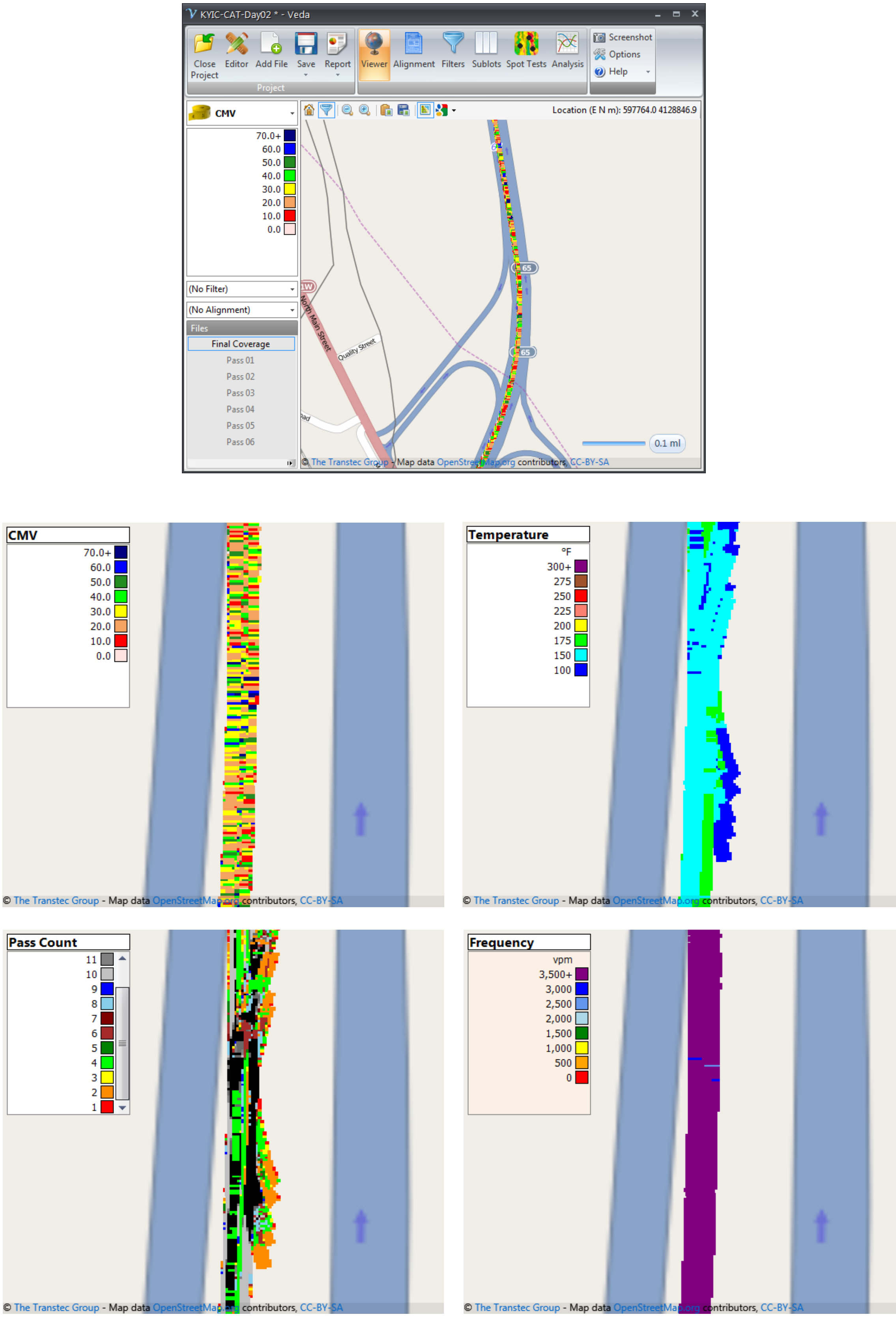

Figure 100. Caterpillar IC maps (intermediate), TB02A, KY site.

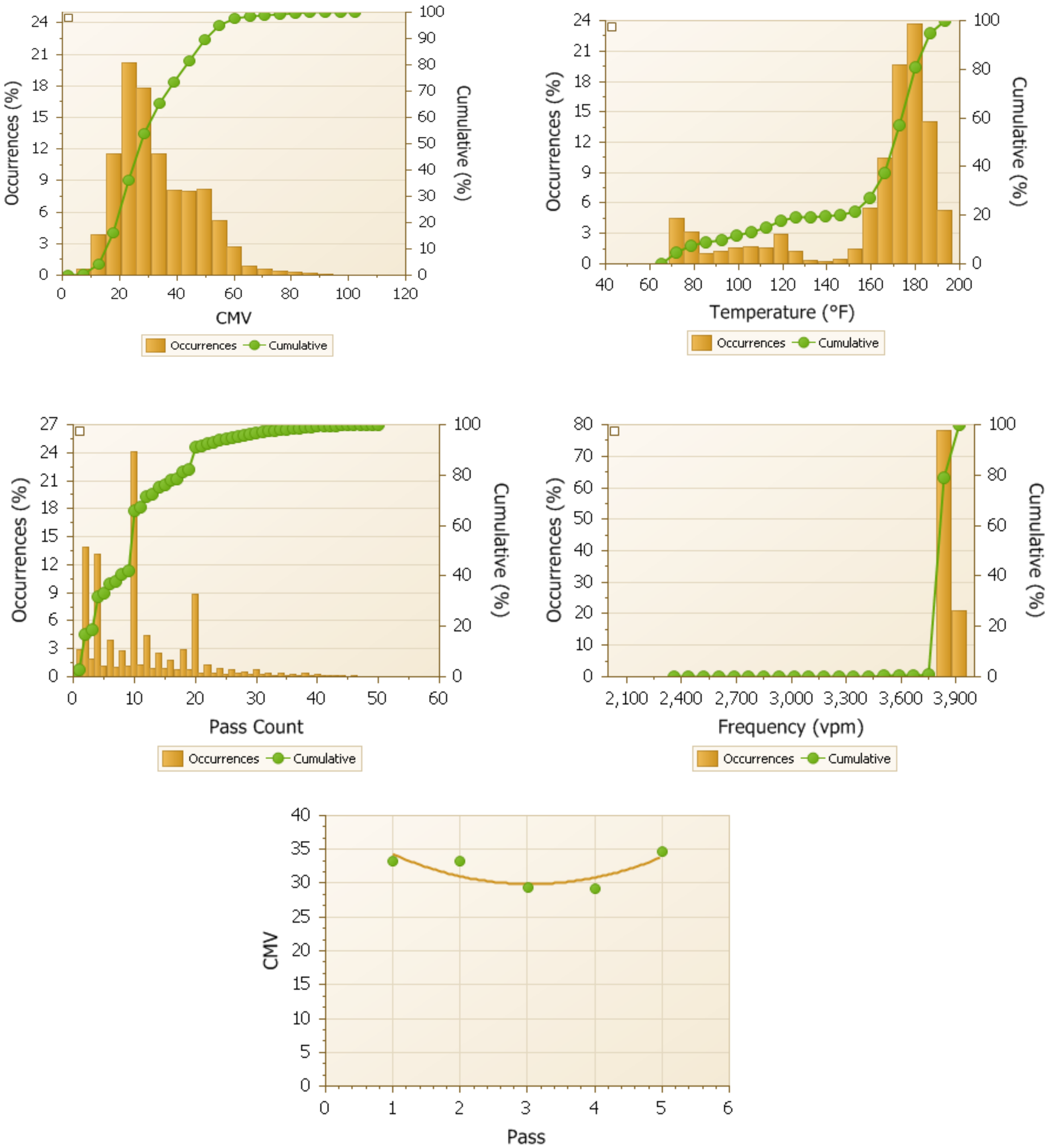

Figure 101. Caterpillar IC statistics (intermediate), TB02A, KY site.

Washington State Site

Pre-Mapping

The IC maps and statistics for the Hamm and Caterpillar IC pre-mapping data on the existing granular base are presented in Figure 102. The HMV map (5 mm, 3,800 vpm) indicates stiffer values on the eastern edge as compared with the western edge that is confined by the existing southbound asphalt pavements. The CMV map indicates a similar trend. HMV and CMV are based on frequency analysis methods.

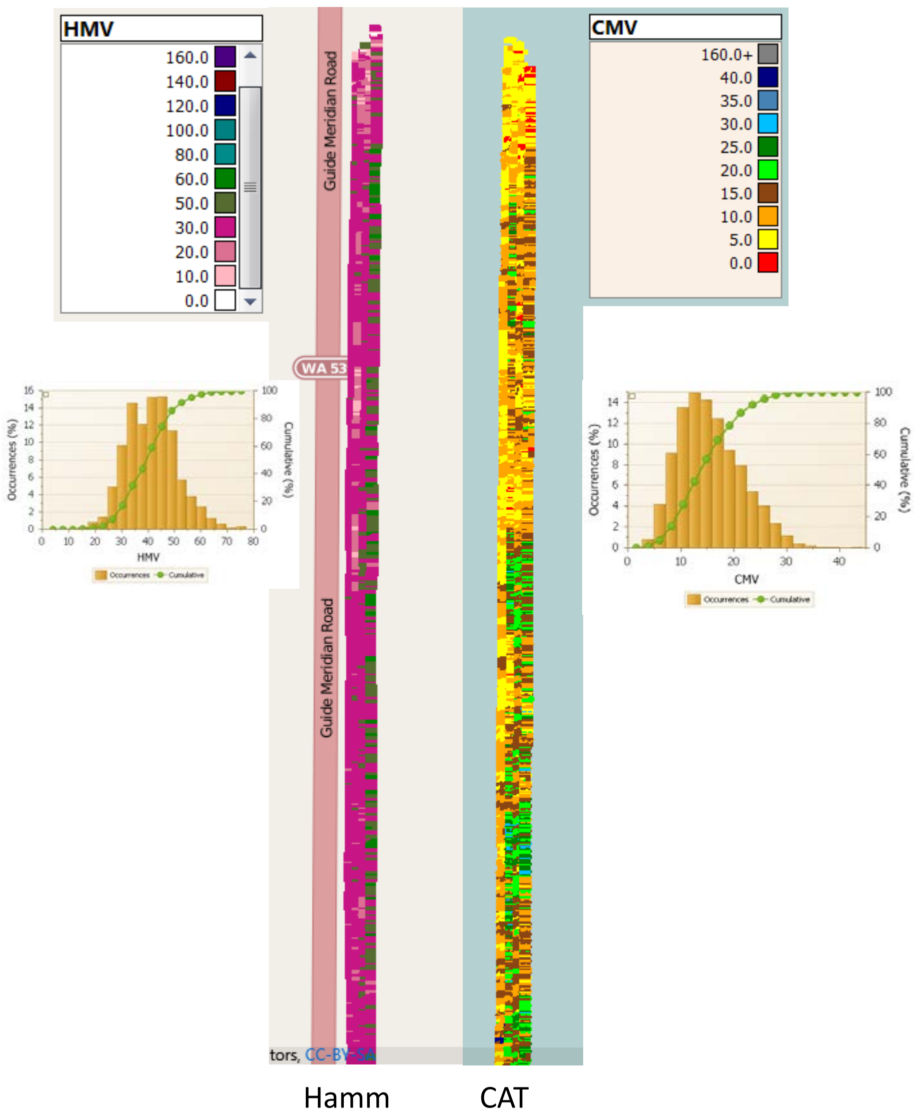

Figure 102. Hamm HMV map and Caterpillar CMV map for pre-mapping existing granular base, northern half, WA site.

TB02 IC Data

The IC maps and statistics for the Hamm IC data (breakdown position) for TB02 are presented in Figure 103 and Figure 104.

Comments on Hamm Data:

- ICMV: The mean HMV value is 56.2 with standard deviation of 16.22.
- Temperature: The mean surface temperature is 218°F (103°C) with standard deviation of 41.36°F (23.0°C).
- Pass counts: The recorded mean roller passes is 6, but the distribution is erratic.
- Frequency: The mean frequency is 3,943 vpm (66 Hz)
- Compaction curve: The curve grows and tapers off after 5 passes.

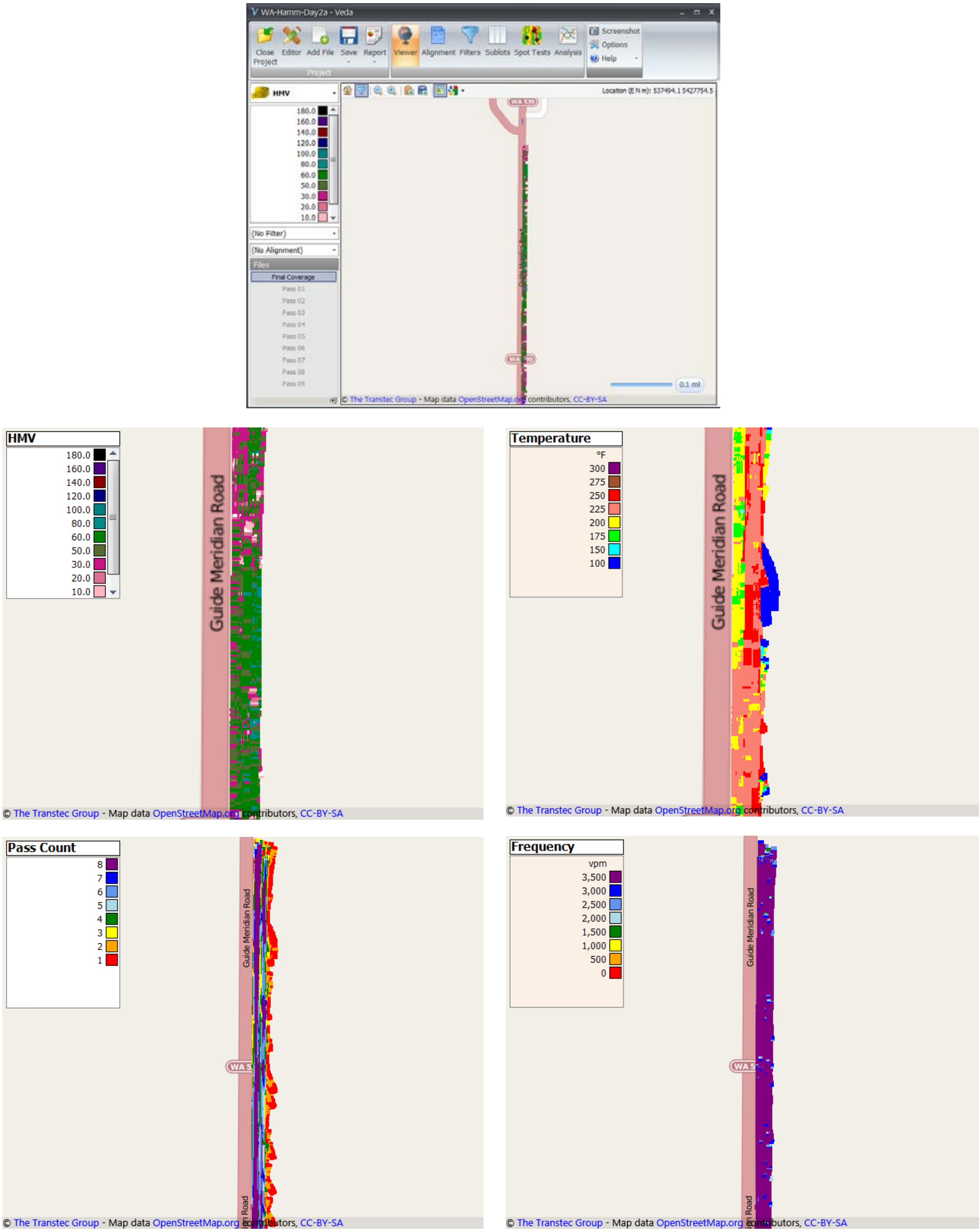

Figure 103. Hamm IC maps (breakdown), TB02A and TB02B, WA site.

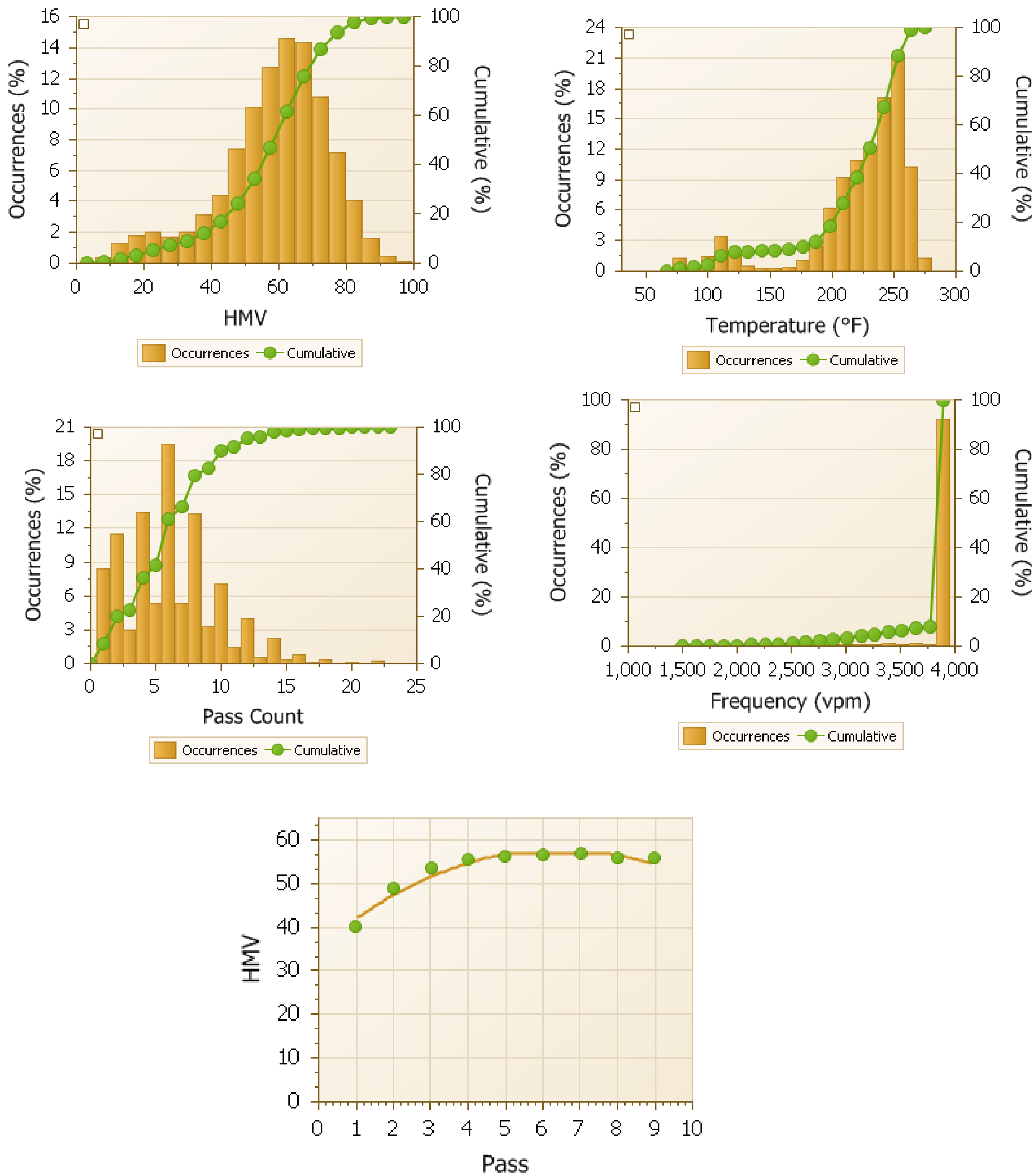

Figure 104. Hamm IC statistics (breakdown), TB02A and TB02B, WA site.

The IC maps and statistics for the Caterpillar IC data (intermediate position) for TB02 are presented in Figure 100 and Figure 101.

Comments on Caterpillar Data:

- ICMV: The mean CMV value is 6.96 with standard deviation of 2.68. The value is relative low compared with the CMV values from the other field sites (e.g., KY) with the same roller. It is suspected that the differences may be due to the changes of the mounting of the accelerometer.
- Temperature: The mean surface temperature is 193°F (89°C) with standard deviation of 19.4°F (10.8°C). The mat temperatures stay at elevated temperatures except for several discrete areas.
- Pass counts: The recorded mean roller passes is 13. It is higher than the 5 passes recorded manually during pass-by-pass NDG measurements. Further investigation is warranted regarding the gridding and pass counting procedure in VisionLink.
- Frequency: The mean frequency is 3,824 vpm (64 Hz).
- Compaction curve: The curve appeared to be in an unusual shape without an apparent plateau that indicate optimal passes. Further investigation is warranted.

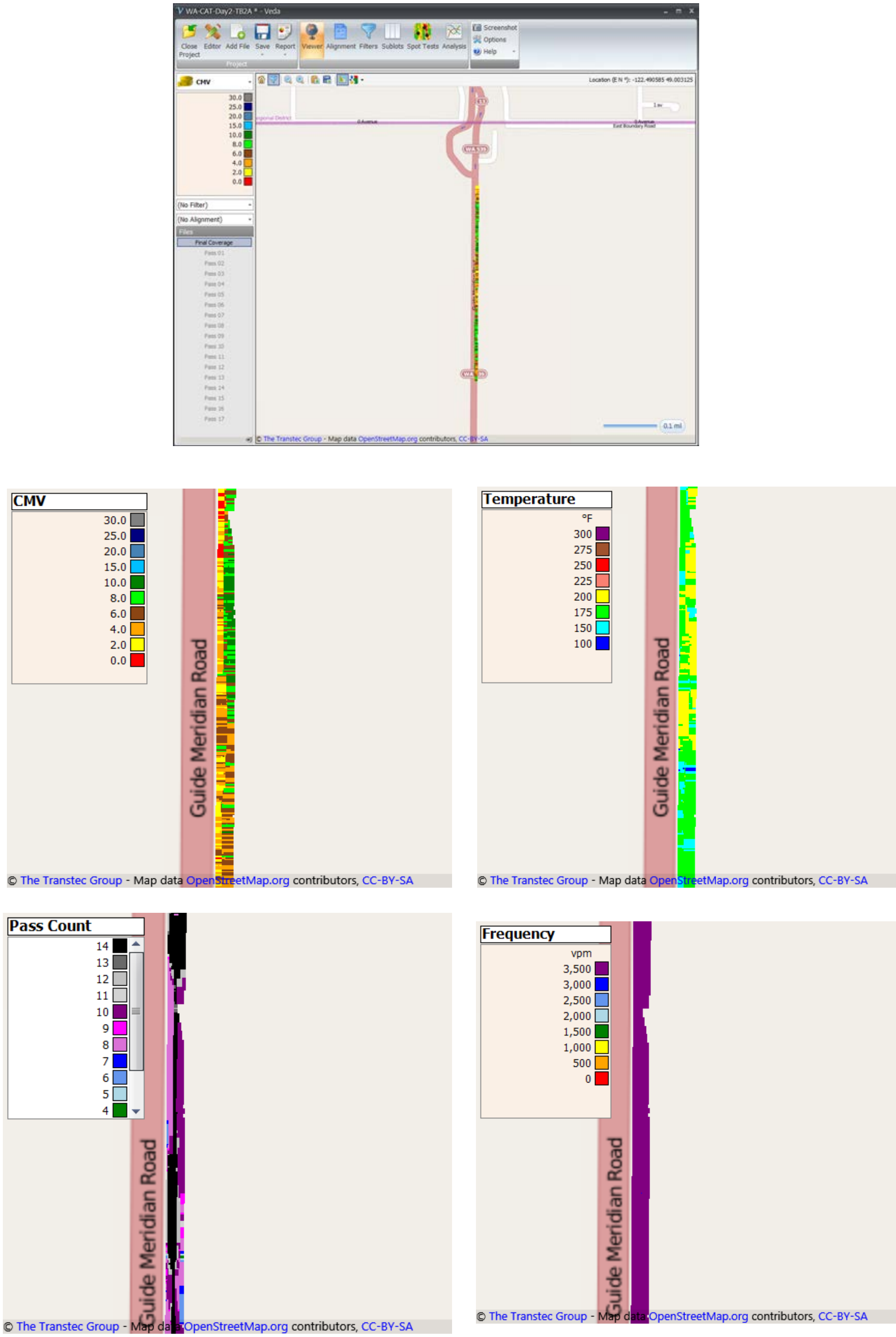

Figure 105. Caterpillar IC maps (intermediate), TB02A, WA site.

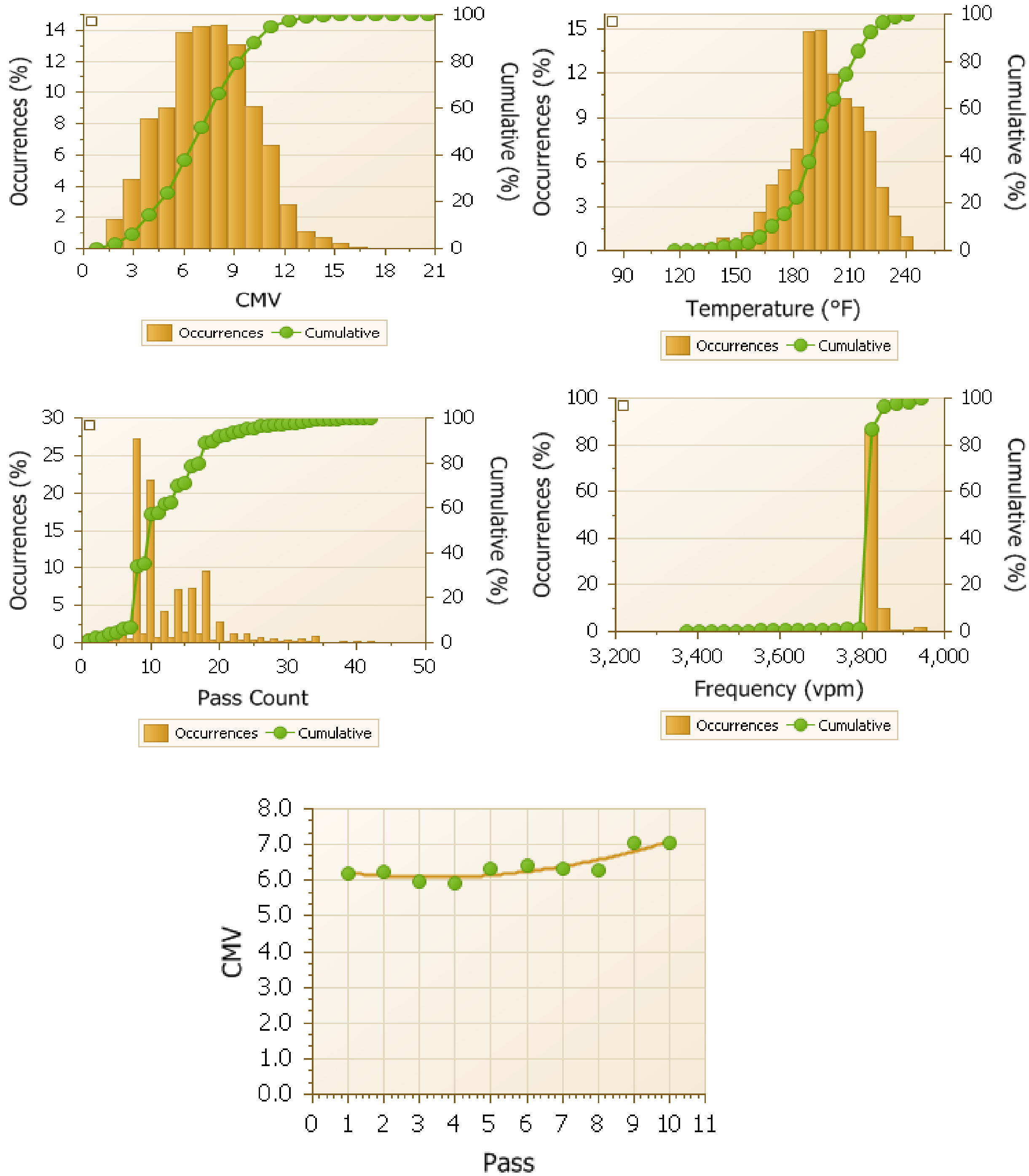

Figure 106. Caterpillar IC statistics (intermediate), TB02A, WA site.

Appendix B Core Density and In Situ Test Data

The followings are core density and reduced in situ test data for all test sites:

- Core densities were expressed in % Gmm.
- NDG is the nuclear density gauge density in % Gmm.
- Elwd20 is the asphalt layer moduli backcalculated from the LWD data and normalized to 20°C reference temperature.
- Dfwd is the FWD deflection at Sensor 0 and normalized to 9,000 lb reference load.
- Efwd is the asphalt layer moduli backcalculated from the FWD deflections.

Utah Site

Utah US 89, TB02 (Aug. 7, 2012)
UTM 12N Meters

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
1-1	4473229.741	426974.602	94.6	89.7
1-2	4473228.308	426972.941	94.2	90.9
2-1	4473241.293	426963.470	90.6	87.6
2-2	4473240.143	426961.872	91.4	87.2
3-1	4473252.015	426952.551	92.4	87.9
3-2	4473250.250	426950.591	92.0	88.0
4-1	4473262.777	426941.785	91.7	87.5
4-2	4473261.759	426940.307	91.9	87.4
5-1	4473273.461	426931.146	91.6	89.3
5-2	4473272.170	426929.640	92.5	90.6
6-1	4473284.329	426920.576	92.0	89.5
6-2	4473283.052	426918.935	93.0	90.8
7-1	4473295.278	426909.914	92.4	89.2
7-2	4473293.891	426908.314	93.7	90.1
8-1	4473306.107	426899.073	91.1	89.2
8-2	4473304.799	426897.524	92.6	90.8
9-1	4473316.902	426888.613	93.2	89.8
9-2	4473315.427	426887.080	93.9	92.4
10-1	4473327.847	426877.849	92.5	90.5
10-2	4473326.541	426876.207	95.0	93.1
11-1	4473338.321	426867.140	91.9	88.5
11-2	4473337.020	426865.676	93.8	93.3
12-1	4473349.302	426856.691	91.3	89.9
12-2	4473347.876	426855.192	92.6	89.5

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
13-1	4473360.115	426845.943	92.1	88.8
13-2	4473358.781	426844.513	90.9	88.6
14-1	4473370.855	426835.219	90.7	89.3
14-2	4473369.641	426833.765	92.7	90.1
15-1	4473381.925	426824.533	92.0	89.3
15-2	4473380.559	426823.111	92.7	91.4
16-1	4473392.800	426813.727	91.8	88.8
16-2	4473391.633	426812.171	93.7	90.6
17-1	4473403.929	426802.260	91.5	89.4
17-2	4473402.539	426800.787	93.1	92.5
18-1	4473414.879	426791.700	93.4	90.8
18-2	4473413.413	426790.193	94.1	92.0
19-1	4473425.985	426781.057	92.3	88.8
19-2	4473424.684	426779.568	93.3	90.2
20-1	4473436.903	426770.209	91.5	89.1
20-2	4473435.299	426768.971	92.7	89.9
21-1	4473447.593	426759.587	91.2	87.2
21-2	4473446.252	426758.199	92.7	87.8
22-1	4473458.472	426748.874	88.3	84.1
22-2	4473457.173	426747.435	91.2	88.1
23-1	4473469.580	426738.494	91.1	87.1
23-2	4473468.189	426736.893	92.1	89.8
24-1	4473480.344	426727.898	91.4	89.4
24-2	4473478.970	426726.400	92.4	90.3
25-1	4473491.150	426717.388	91.1	88.7
25-2	4473489.803	426716.009	91.6	86.9
26-1	4473502.131	426706.846	91.7	88.5
26-2	4473500.663	426705.270	92.3	88.4
27-1	4473513.059	426696.048	91.9	86.8
27-2	4473511.749	426694.847	92.7	88.0
28-1	4473523.938	426685.743	91.7	88.8
28-2	4473522.558	426684.261	92.1	87.6
29-1	4473534.574	426675.087	91.9	90.1
29-2	4473533.320	426673.640	92.3	86.7
30-1	4473545.585	426664.426	91.8	89.9
30-2	4473544.132	426662.833	92.7	90.5

Florida Site

Florida I-95 IC Project - TB01 (Oct. 15, 2012)
UTM 17N

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
NA	[m]	[m]	[%Gmm]	[%Gmm]
1-1	3143780.112	517610.320	92.3	95.0
1-2	3143780.060	517612.425	94.0	92.1
2-1	3143795.276	517610.399	91.7	91.9
2-2	3143795.355	517612.462	92.2	91.8
3-1	3143811.097	517610.177	90.2	90.5
3-2	3143811.093	517612.373	91.9	92.3
4-1	3143826.650	517610.105	91.1	92.4
4-2	3143826.703	517612.239	91.9	92.6
5-1	3143842.051	517610.230	92.9	94.0
5-2	3143842.132	517612.248	92.1	94.2
6-1	3143857.612	517610.141	91.3	90.2
6-2	3143857.606	517612.196	87.7	89.9
7-1	3143872.859	517610.159	89.5	90.2
7-2	3143872.868	517612.170	89.1	88.7
8-1	3143887.987	517610.088	92.4	93.1
8-2	3143888.053	517612.086	90.1	90.8
9-1	3143902.349	517610.014	92.3	93.1
9-2	3143902.325	517612.133	89.5	91.5
10-1	3143917.840	517610.023	92.9	93.5
10-2	3143917.856	517612.117	89.4	90.9
11-1	3143933.372	517609.945	92.3	94.2
11-2	3143933.386	517612.052	89.5	91.0
12-1	3143948.672	517609.998	90.4	91.2
12-2	3143948.723	517612.027	90.5	89.5
13-1	3143963.610	517609.943	89.9	89.9
13-2	3143963.594	517612.022	90.7	91.6
14-1	3143976.729	517609.946	91.0	92.1
14-2	3143976.797	517612.030	91.8	91.9
15-1	3143990.647	517609.905	89.1	90.2
15-2	3143990.682	517612.056	89.5	91.5

ID	Northing	Easting	Core Density	NDG Density
NA	[m]	[m]	[%Gmm]	[%Gmm]
16-1	3144003.443	517609.730	90.2	92.5
16-2	3144003.417	517611.906	92.3	92.3
17-1	3144016.696	517609.765	92.0	91.5
17-2	3144016.720	517611.868	94.5	92.1
18-1	3144030.755	517609.744	92.0	93.4
18-2	3144030.760	517611.768	92.3	92.2
19-1	3144045.078	517609.771	87.6	88.4
19-2	3144045.124	517611.863	88.4	88.8
20-1	3144059.110	517609.667	90.0	91.4
20-2	3144059.117	517611.722	90.1	90.4
21-1	3144073.466	517609.606	89.9	91.7
21-2	3144073.388	517611.556	90.6	91.3
22-1	3144088.451	517609.474	91.1	93.7
22-2	3144088.449	517611.451	91.4	92.7
23-1	3144103.111	517609.566	89.0	89.9
23-2	3144103.078	517611.516	87.3	88.7
24-1	3144117.473	517609.525	92.0	92.6
24-2	3144117.390	517611.517	91.3	91.6
25-1	3144131.742	517609.359	92.1	93.2
25-2	3144131.759	517611.345	92.7	93.2
26-1	3144145.790	517609.375	90.8	93.2
26-2	3144145.793	517611.208	91.7	93.1
27-1	3144161.002	517609.099	88.0	89.1
27-2	3144160.958	517611.054	88.8	90.7
28-1	3144175.495	517609.136	88.8	90.6
28-2	3144175.446	517611.104	90.0	90.7
29-1	3144190.095	517608.988	90.1	91.5
29-2	3144190.010	517611.020	89.6	89.4
30-1	3144204.178	517608.939	91.1	91.6
30-2	3144204.036	517611.064	90.5	90.4

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
NA	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
1-1	3143780.112	517610.320		642	44	111
1-2	3143780.060	517612.425				
2-1	3143795.276	517610.399		604	50	122
2-2	3143795.355	517612.462				
3-1	3143811.097	517610.177		682	44	111
3-2	3143811.093	517612.373				
4-1	3143826.650	517610.105		888	44	111
4-2	3143826.703	517612.239				
5-1	3143842.051	517610.230		873	42	108
5-2	3143842.132	517612.248				
6-1	3143857.612	517610.141		981	36	97
6-2	3143857.606	517612.196				
7-1	3143872.859	517610.159		814	41	106
7-2	3143872.868	517612.170				
8-1	3143887.987	517610.088		882	41	106
8-2	3143888.053	517612.086				
9-1	3143902.349	517610.014		876	40	104
9-2	3143902.325	517612.133				
10-1	3143917.840	517610.023		564	40	104
10-2	3143917.856	517612.117				
11-1	3143933.372	517609.945		1278	31	88
11-2	3143933.386	517612.052				
12-1	3143948.672	517609.998		817	43	109
12-2	3143948.723	517612.027				
13-1	3143963.610	517609.943		966	45	113
13-2	3143963.594	517612.022				
14-1	3143976.729	517609.946		682	42	108
14-2	3143976.797	517612.030				
15-1	3143990.647	517609.905		1125	34	93
15-2	3143990.682	517612.056				

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
NA	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
16-1	3144003.443	517609.730		762	42	108
16-2	3144003.417	517611.906				
17-1	3144016.696	517609.765		740	43	109
17-2	3144016.720	517611.868				
18-1	3144030.755	517609.744		934	48	118
18-2	3144030.760	517611.768				
19-1	3144045.078	517609.771		1008	38	100
19-2	3144045.124	517611.863				
20-1	3144059.110	517609.667		934	44	111
20-2	3144059.117	517611.722				
21-1	3144073.466	517609.606		888	45	113
21-2	3144073.388	517611.556				
22-1	3144088.451	517609.474		861	43	109
22-2	3144088.449	517611.451				
23-1	3144103.111	517609.566		901	32	90
23-2	3144103.078	517611.516				
24-1	3144117.473	517609.525		879	43	109
24-2	3144117.390	517611.517				
25-1	3144131.742	517609.359		948	44	111
25-2	3144131.759	517611.345				
26-1	3144145.790	517609.375		974	43	109
26-2	3144145.793	517611.208				
27-1	3144161.002	517609.099		977	41	106
27-2	3144160.958	517611.054				
28-1	3144175.495	517609.136		1021	40	104
28-2	3144175.446	517611.104				
29-1	3144190.095	517608.988		907	44	111
29-2	3144190.010	517611.020				
30-1	3144204.178	517608.939		833	44	111
30-2	3144204.036	517611.064				

Backcalculated FWD Data

ID	Northing	Easting	Dfwd	Efwd
NA	[m]	[m]	[mils]	[psi]
1-1	3143780.112	517610.320	15.96	133748
1-2	3143780.060	517612.425		
2-1	3143795.276	517610.399	18.02	102579
2-2	3143795.355	517612.462		
3-1	3143811.097	517610.177	17.91	123831
3-2	3143811.093	517612.373		
4-1	3143826.650	517610.105	14.43	166393
4-2	3143826.703	517612.239		
5-1	3143842.051	517610.230	14.35	166882
5-2	3143842.132	517612.248		
6-1	3143857.612	517610.141	14.26	263643
6-2	3143857.606	517612.196		
7-1	3143872.859	517610.159	15.39	196529
7-2	3143872.868	517612.170		
8-1	3143887.987	517610.088	15.76	185372
8-2	3143888.053	517612.086		
9-1	3143902.349	517610.014	14.84	179242
9-2	3143902.325	517612.133		
10-1	3143917.840	517610.023	13.70	205060
10-2	3143917.856	517612.117		
11-1	3143933.372	517609.945	13.22	241589
11-2	3143933.386	517612.052		
12-1	3143948.672	517609.998	13.32	164995
12-2	3143948.723	517612.027		
13-1	3143963.610	517609.943	15.43	167224
13-2	3143963.594	517612.022		
14-1	3143976.729	517609.946	13.91	214727
14-2	3143976.797	517612.030		
15-1	3143990.647	517609.905	11.84	229664
15-2	3143990.682	517612.056		

ID	Northing	Easting	Dfwd	Efwd
NA	[m]	[m]	[mils]	[psi]
16-1	3144003.443	517609.730	14.67	143827
16-2	3144003.417	517611.906		
17-1	3144016.696	517609.765	14.31	130305
17-2	3144016.720	517611.868		
18-1	3144030.755	517609.744	10.23	159878
18-2	3144030.760	517611.768		
19-1	3144045.078	517609.771	10.88	195163
19-2	3144045.124	517611.863		
20-1	3144059.110	517609.667	11.90	184436
20-2	3144059.117	517611.722		
21-1	3144073.466	517609.606	12.07	152574
21-2	3144073.388	517611.556		
22-1	3144088.451	517609.474	13.03	174999
22-2	3144088.449	517611.451		
23-1	3144103.111	517609.566	12.93	256713
23-2	3144103.078	517611.516		
24-1	3144117.473	517609.525	14.14	182054
24-2	3144117.390	517611.517		
25-1	3144131.742	517609.359	11.98	211620
25-2	3144131.759	517611.345		
26-1	3144145.790	517609.375	10.97	160583
26-2	3144145.793	517611.208		
27-1	3144161.002	517609.099	12.90	184823
27-2	3144160.958	517611.054		
28-1	3144175.495	517609.136	13.45	201814
28-2	3144175.446	517611.104		
29-1	3144190.095	517608.988	13.43	159174
29-2	3144190.010	517611.020		
30-1	3144204.178	517608.939	13.77	148473
30-2	3144204.036	517611.064		

Ohio Site

Ohio I-71 IC Project, TB02 (June 25, 2012)
UTM 17N (meters)

Core Density and NDG Density

ID	Northing	Easting	Core	NDG
	[m]	[m]	[%Gmm]	[%Gmm]
01L	4484790.233	355202.982	89.4	86.8
01R	4484788.234	355204.253	90.0	86.9
02L	4484798.387	355215.715	91.7	91.2
02R	4484796.424	355216.970	92.3	89.9
03L	4484807.191	355228.429	91.8	90.9
03R	4484804.789	355229.996	93.5	93.6
04L	4484815.456	355240.994	86.5	86.1
04R	4484812.901	355242.713	92.5	89.6
05L	4484824.016	355253.340	91.7	91.4
05R	4484821.724	355254.915	90.6	89.8
06L	4484832.946	355265.583	92.3	92.4
06R	4484830.361	355267.262	92.5	88.1
07L	4484841.867	355277.898	93.5	93.6
07R	4484838.897	355279.480	93.4	92.0
08L	4484850.791	355290.275	90.2	89.2
08R	4484847.369	355292.497	94.4	93.3
09L	4484859.679	355302.854	89.1	85.5
09R	4484857.369	355304.762	90.3	88.2
10L	4484868.816	355314.787	91.8	90.3
10R	4484865.123	355317.328	92.2	89.3
11L	4484877.463	355326.651	92.5	90.3
11R	4484874.326	355328.726	93.1	92.1
12L	4484885.942	355340.142	92.0	91.4
12R	4484883.565	355341.770	93.4	91.1
13L	4484895.345	355352.056	91.5	90.7
13R	4484892.909	355353.828	92.0	90.0
14L	4484904.587	355364.331	89.2	86.8
14R	4484903.060	355365.668	91.2	87.8
15L	4484913.568	355376.745	92.2	92.7
15R	4484912.240	355377.921	92.0	92.7

ID	Northing	Easting	Core	NDG
	[m]	[m]	[%Gmm]	[%Gmm]
16L	4484922.732	355389.132	89.2	88.0
16R	4484921.433	355390.125	91.0	89.8
17L	4484932.005	355401.415	90.5	85.4
17R	4484929.994	355402.994	90.9	88.5
18L	4484941.226	355413.204	91.7	91.6
18R	4484938.625	355415.417	91.6	89.6
19L	4484950.449	355425.358	92.8	91.4
19R	4484947.832	355427.755	92.9	92.3
20L	4484959.357	355437.739	89.7	90.0
20R	4484957.130	355439.278	94.0	93.0
21L	4484968.761	355449.807	89.4	88.5
21R	4484966.621	355451.916	92.0	90.3
22L	4484979.564	355462.533	91.9	90.6
22R	4484976.758	355464.606	92.4	92.5
23L	4484988.725	355474.366	91.9	89.1
23R	4484986.372	355476.077	92.1	90.0
24L	4484998.562	355485.841	92.4	91.0
24R	4484995.615	355488.521	93.5	92.3
25L	4485007.838	355498.126	90.1	88.7
25R	4485005.735	355500.031	92.6	91.3
26L	4485018.104	355509.873	91.2	87.7
26R	4485015.483	355512.528	91.8	86.0
27L	4485027.657	355521.590	91.6	87.4
27R	4485025.118	355523.650	91.9	90.9
28L	4485037.202	355533.231	93.3	93.9
28R	4485034.625	355535.824	93.8	92.5
29L	4485047.237	355545.280	93.4	89.2
29R	4485044.966	355547.600	93.7	90.4
30L	4485056.938	355557.111	92.5	89.9
30R	4485055.044	355559.180	93.6	91.2

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
01L	4484790.233	355202.982	4717	764	46	115
01R	4484788.234	355204.253				
02L	4484798.387	355215.715	7240	951	49	120
02R	4484796.424	355216.970				
03L	4484807.191	355228.429	7248	888	50	122
03R	4484804.789	355229.996				
04L	4484815.456	355240.994	5154	777	47	117
04R	4484812.901	355242.713				
05L	4484824.016	355253.340	5133	674	49	120
05R	4484821.724	355254.915				
06L	4484832.946	355265.583	5771	707	50	122
06R	4484830.361	355267.262				
07L	4484841.867	355277.898	5288	525	53	127
07R	4484838.897	355279.480				
08L	4484850.791	355290.275	6340	675	52	126
08R	4484847.369	355292.497				
09L	4484859.679	355302.854	7198	766	52	126
09R	4484857.369	355304.762				
10L	4484868.816	355314.787	5874	583	53	127
10R	4484865.123	355317.328				
11L	4484877.463	355326.651	5556	551	53	127
11R	4484874.326	355328.726				
12L	4484885.942	355340.142	7262	724	53	127
12R	4484883.565	355341.770				
13L	4484895.345	355352.056	7039	651	54	129
13R	4484892.909	355353.828				
14L	4484904.587	355364.331	5023	708	48	118
14R	4484903.060	355365.668				
15L	4484913.568	355376.745	5731	702	50	122
15R	4484912.240	355377.921				

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
16L	4484922.732	355389.132	5227	686	49	120
16R	4484921.433	355390.125				
17L	4484932.005	355401.415	6133	653	52	126
17R	4484929.994	355402.994				
18L	4484941.226	355413.204	7472	742	53	127
18R	4484938.625	355415.417				
19L	4484950.449	355425.358	6731	668	53	127
19R	4484947.832	355427.755				
20L	4484959.357	355437.739	5170	478	54	129
20R	4484957.130	355439.278				
21L	4484968.761	355449.807	6577	805	50	122
21R	4484966.621	355451.916				
22L	4484979.564	355462.533	4809	477	53	127
22R	4484976.758	355464.606				
23L	4484988.725	355474.366	5357	431	56	133
23R	4484986.372	355476.077				
24L	4484998.562	355485.841	6547	527	56	133
24R	4484995.615	355488.521				
25L	4485007.838	355498.126	4389	353	56	133
25R	4485005.735	355500.031				
26L	4485018.104	355509.873	7420	519	58	136
26R	4485015.483	355512.528				
27L	4485027.657	355521.590	5949	591	53	127
27R	4485025.118	355523.650				
28L	4485037.202	355533.231	6670	710	52	126
28R	4485034.625	355535.824				
29L	4485047.237	355545.280	7476	645	55	131
29R	4485044.966	355547.600				
30L	4485056.938	355557.111	5872	507	55	131
30R	4485055.044	355559.180				

Backcalculated FWD Data

ID	Northing	Easting	Dfwd
	[m]	[m]	[mils]
01L	4484790.233	355202.982	8.71
01R	4484788.234	355204.253	9.98
02L	4484798.387	355215.715	8.62
02R	4484796.424	355216.97	10.30
03L	4484807.191	355228.429	8.03
03R	4484804.789	355229.996	8.25
04L	4484815.456	355240.994	6.07
04R	4484812.901	355242.713	7.39
05L	4484824.016	355253.34	9.68
05R	4484821.724	355254.915	10.25
06L	4484832.946	355265.583	8.89
06R	4484830.361	355267.262	9.08
07L	4484841.867	355277.898	9.42
07R	4484838.897	355279.48	11.36
08L	4484850.791	355290.275	8.02
08R	4484847.369	355292.497	9.79
09L	4484859.679	355302.854	8.09
09R	4484857.369	355304.762	8.72
10L	4484868.816	355314.787	10.79
10R	4484865.123	355317.328	10.25
11L	4484877.463	355326.651	11.08
11R	4484874.326	355328.726	11.91
12L	4484885.942	355340.142	9.54
12R	4484883.565	355341.77	11.74
13L	4484895.345	355352.056	8.48
13R	4484892.909	355353.828	8.19
14L	4484904.587	355364.331	7.38
14R	4484903.06	355365.668	7.64
15L	4484913.568	355376.745	8.71
15R	4484912.24	355377.921	8.29

ID	Northing	Easting	Dfwd
	[m]	[m]	[mils]
16L	4484922.732	355389.132	8.34
16R	4484921.433	355390.125	8.39
17L	4484932.005	355401.415	9.54
17R	4484929.994	355402.994	9.56
18L	4484941.226	355413.204	8.53
18R	4484938.625	355415.417	8.57
19L	4484950.449	355425.358	8.52
19R	4484947.832	355427.755	9.46
20L	4484959.357	355437.739	9.14
20R	4484957.13	355439.278	8.80
21L	4484968.761	355449.807	7.67
21R	4484966.621	355451.916	8.23
22L	4484979.564	355462.533	7.72
22R	4484976.758	355464.606	9.21
23L	4484988.725	355474.366	10.52
23R	4484986.372	355476.077	12.70
24L	4484998.562	355485.841	11.67
24R	4484995.615	355488.521	10.33
25L	4485007.838	355498.126	10.34
25R	4485005.735	355500.031	9.15
26L	4485018.104	355509.873	9.34
26R	4485015.483	355512.528	10.54
27L	4485027.657	355521.59	10.82
27R	4485025.118	355523.65	10.50
28L	4485037.202	355533.231	8.64
28R	4485034.625	355535.824	10.87
29L	4485047.237	355545.28	9.62
29R	4485044.966	355547.6	10.49
30L	4485056.938	355557.111	11.40
30R	4485055.044	355559.18	10.51

Maine Site

Maine I-95 IC Project, TB03 (Aug. 21, 2013)
UTM 19N Meters

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
1L	5102410.802	560248.063	96.7	95.6
1R	5102409.890	560249.459	95.8	95.3
2L	5102423.595	560256.379	96.3	96.0
2R	5102422.497	560258.069	95.2	94.5
3L	5102436.060	560265.330	93.1	93.7
3R	5102435.396	560266.218	94.3	92.6
4L	5102448.572	560273.393	94.9	95.1
4R	5102447.924	560275.045	95.3	94.9
5L	5102461.003	560281.786	95.0	94.4
5R	5102460.098	560283.459	95.8	95.2
6L	5102472.913	560289.933	95.3	94.0
6R	5102472.107	560291.703	96.1	95.8
7L	5102485.355	560298.722	96.0	94.9
7R	5102484.580	560300.321	95.7	95.8
8L	5102498.166	560307.125	94.2	94.4
8R	5102496.909	560308.771	94.7	94.3
9L	5102508.225	560314.028	94.5	94.2
9R	5102507.433	560315.639	95.3	94.9
10L	5102520.847	560322.486	95.7	95.8
10R	5102519.800	560324.153	95.6	95.4
11L	5102533.486	560331.195	95.5	95.2
11R	5102532.393	560332.822	96.0	96.0
12L	5102546.063	560339.901	95.9	95.5
12R	5102545.394	560341.458	95.9	96.0
13L	5102558.788	560348.458	94.1	92.9
13R	5102557.607	560350.167	94.2	94.4
14L	5102571.416	560357.012	94.6	93.7
14R	5102570.314	560358.603	95.2	93.9
15L	5102583.528	560365.418	94.3	93.5
15R	5102582.443	560366.761	94.4	94.6

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
16L	5102597.020	560374.391	95.1	94.5
16R	5102595.773	560376.099	95.5	95.2
17L	5102609.337	560382.753	95.4	95.1
17R	5102608.282	560384.193	95.8	95.3
18L	5102621.986	560391.620	94.8	94.1
18R	5102620.809	560393.179	94.3	93.7
19L	5102634.242	560400.051	93.8	93.8
19R	5102633.176	560401.489	94.4	94.0
20L	5102646.750	560408.641	92.6	91.7
20R	5102645.684	560410.027	93.6	93.7
21L	5102659.457	560417.163	93.4	93.0
21R	5102658.310	560418.662	94.1	94.6
22L	5102672.028	560425.889	94.3	93.1
22R	5102670.882	560427.288	95.0	94.5
23L	5102684.619	560434.527	94.3	93.9
23R	5102683.549	560436.071	94.8	94.5
24L	5102697.215	560443.231	92.9	91.9
24R	5102696.155	560444.633	94.0	94.4
25L	5102709.943	560451.773	92.4	91.4
25R	5102709.152	560453.064	94.7	94.3
26L	5102722.621	560460.280	93.1	92.6
26R	5102721.480	560461.616	94.2	94.4
27L	5102734.963	560468.939	94.0	92.9
27R	5102733.951	560470.351	94.5	94.4
28L	5102747.759	560477.672	94.7	93.4
28R	5102746.771	560478.989	95.6	96.1
29L	5102760.448	560486.240	94.9	94.1
29R	5102759.346	560487.570	95.5	95.4
30L	5102773.091	560494.880	93.6	92.4
30R	5102772.050	560496.284	94.3	93.7

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
1L	5102410.802	560248.063	1796	413	41	106
1R	5102409.890	560249.459				
2L	5102423.595	560256.379	2567	416	46	115
2R	5102422.497	560258.069				
3L	5102436.060	560265.330	2878	378	49	120
3R	5102435.396	560266.218				
4L	5102448.572	560273.393	2879	405	48	118
4R	5102447.924	560275.045				
5L	5102461.003	560281.786	2942	360	50	122
5R	5102460.098	560283.459				
6L	5102472.913	560289.933	2903	381	49	120
6R	5102472.107	560291.703				
7L	5102485.355	560298.722	2792	422	47	117
7R	5102484.580	560300.321				
8L	5102498.166	560307.125	2281	345	47	117
8R	5102496.909	560308.771				
9L	5102508.225	560314.028	2745	387	48	118
9R	5102507.433	560315.639				
10L	5102520.847	560322.486	2636	371	48	118
10R	5102519.800	560324.153				
11L	5102533.486	560331.195	3160	445	48	118
11R	5102532.393	560332.822				
12L	5102546.063	560339.901	2778	391	48	118
12R	5102545.394	560341.458				
13L	5102558.788	560348.458	2121	279	49	120
13R	5102557.607	560350.167				
14L	5102571.416	560357.012	2705	355	49	120
14R	5102570.314	560358.603				
15L	5102583.528	560365.418	2627	345	49	120
15R	5102582.443	560366.761				

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
16L	5102597.020	560374.391	2811	344	50	122
16R	5102595.773	560376.099				
17L	5102609.337	560382.753	3062	350	51	124
17R	5102608.282	560384.193				
18L	5102621.986	560391.620	2974	317	52	126
18R	5102620.809	560393.179				
19L	5102634.242	560400.051	3073	327	52	126
19R	5102633.176	560401.489				
20L	5102646.750	560408.641	3037	323	52	126
20R	5102645.684	560410.027				
21L	5102659.457	560417.163	3198	365	51	124
21R	5102658.310	560418.662				
22L	5102672.028	560425.889	3150	335	52	126
22R	5102670.882	560427.288				
23L	5102684.619	560434.527	3371	359	52	126
23R	5102683.549	560436.071				
24L	5102697.215	560443.231	3093	379	50	122
24R	5102696.155	560444.633				
25L	5102709.943	560451.773	2918	333	51	124
25R	5102709.152	560453.064				
26L	5102722.621	560460.280	2599	366	48	118
26R	5102721.480	560461.616				
27L	5102734.963	560468.939	2976	340	51	124
27R	5102733.951	560470.351				
28L	5102747.759	560477.672	2889	308	52	126
28R	5102746.771	560478.989				
29L	5102760.448	560486.240	3236	321	53	127
29R	5102759.346	560487.570				
30L	5102773.091	560494.880	2656	283	52	126
30R	5102772.050	560496.284				

Backcalculated FWD Data

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[psi]
1L	5102410.802	560248.063	16.75	81760
1R	5102409.890	560249.459		
2L	5102423.595	560256.379	16.17	68890
2R	5102422.497	560258.069		
3L	5102436.060	560265.330	17.28	56263
3R	5102435.396	560266.218		
4L	5102448.572	560273.393	16.70	58392
4R	5102447.924	560275.045		
5L	5102461.003	560281.786	18.32	51628
5R	5102460.098	560283.459		
6L	5102472.913	560289.933	17.37	51079
6R	5102472.107	560291.703		
7L	5102485.355	560298.722	17.35	55607
7R	5102484.580	560300.321		
8L	5102498.166	560307.125	18.51	57822
8R	5102496.909	560308.771		
9L	5102508.225	560314.028	16.78	63763
9R	5102507.433	560315.639		
10L	5102520.847	560322.486	18.15	57215
10R	5102519.800	560324.153		
11L	5102533.486	560331.195	17.50	60988
11R	5102532.393	560332.822		
12L	5102546.063	560339.901	16.84	63091
12R	5102545.394	560341.458		
13L	5102558.788	560348.458	17.03	68898
13R	5102557.607	560350.167		
14L	5102571.416	560357.012	17.66	59366
14R	5102570.314	560358.603		
15L	5102583.528	560365.418	17.31	60646
15R	5102582.443	560366.761		

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[psi]
16L	5102597.020	560374.391	16.72	67779
16R	5102595.773	560376.099		
17L	5102609.337	560382.753	16.85	64136
17R	5102608.282	560384.193		
18L	5102621.986	560391.620	17.57	56737
18R	5102620.809	560393.179		
19L	5102634.242	560400.051	17.65	59867
19R	5102633.176	560401.489		
20L	5102646.750	560408.641	17.88	56628
20R	5102645.684	560410.027		
21L	5102659.457	560417.163	16.81	67913
21R	5102658.310	560418.662		
22L	5102672.028	560425.889	16.77	68142
22R	5102670.882	560427.288		
23L	5102684.619	560434.527	17.82	58487
23R	5102683.549	560436.071		
24L	5102697.215	560443.231	17.51	61307
24R	5102696.155	560444.633		
25L	5102709.943	560451.773	17.78	59751
25R	5102709.152	560453.064		
26L	5102722.621	560460.280	17.44	63184
26R	5102721.480	560461.616		
27L	5102734.963	560468.939	18.42	53094
27R	5102733.951	560470.351		
28L	5102747.759	560477.672	18.89	51312
28R	5102746.771	560478.989		
29L	5102760.448	560486.240	18.42	50601
29R	5102759.346	560487.570		
30L	5102773.091	560494.880	17.93	54905
30R	5102772.050	560496.284		

California Site

California I-80 IC Project - TB02 (Sept 6, 2013)
UTM 10N

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
01L	4255193.528	598916.268	95.7	94.5
01R	4255192.231	598917.312	95.9	93.3
02L	4255204.620	598927.029	94.1	93.3
02R	4255202.975	598928.358	95.4	93.4
03L	4255215.028	598939.907	93.1	89.1
03R	4255216.002	598938.302	94.9	93.7
04L	4255226.597	598948.956	94.7	92.9
04R	4255225.330	598950.039	95.5	91.8
05L	4255237.334	598959.388	93.6	88.9
05R	4255236.048	598960.696	95.5	92.9
06L	4255247.762	598969.858	94.9	92.9
06R	4255246.489	598971.230		94.1
07L	4255257.051	598981.506		93.5
07R	4255258.365	598980.132	95.2	92.2
08L	4255269.070	598990.646	94.2	89.6
08R	4255267.737	598991.965		92.4
09L	4255278.333	599002.584		93.3
09R	4255279.637	599001.176	96.0	93.4
10L	4255289.069	599013.102	94.9	93.6
10R	4255290.344	599011.665		93.9
11L	4255301.121	599022.300		93.3
11R	4255299.896	599023.721	95.8	92.1
12L	4255313.098	599033.954	94.3	93.1
12R	4255311.830	599035.256		91.7
13L	4255323.666	599044.493		92.8
13R	4255322.395	599045.834	94.8	92.5
14L	4255334.523	599055.100	93.9	93.4
14R	4255333.219	599056.466		91.2
15L	4255345.059	599065.726		92.6
15R	4255343.773	599067.071	95.7	92.8

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
16L	4255356.237	599076.600	94.1	92.5
16R	4255354.885	599077.983		91.8
17L	4255367.017	599087.102		93.4
17R	4255365.738	599088.436	95.7	92.3
18L	4255377.419	599097.393	94.9	93.7
18R	4255376.193	599098.660		93.4
19L	4255387.946	599107.933		92.6
19R	4255386.653	599109.309	95.6	92.4
20L	4255397.859	599117.628	94.5	91.5
20R	4255396.585	599119.019		91.9
21L	4255407.839	599127.406		92.7
21R	4255406.524	599128.693	94.7	91.5
22L	4255417.704	599137.082	93.4	91.3
22R	4255416.434	599138.473		90.7
23L	4255428.316	599147.614		92.8
23R	4255427.038	599148.951	95.7	90.4
24L	4255438.865	599158.197	93.5	93.1
24R	4255437.621	599159.469		91.2
25L	4255449.115	599168.206		92.5
25R	4255447.703	599169.413	96.2	91.3
26L	4255460.113	599178.775	95.0	93.7
26R	4255458.693	599180.064		90.9
27L	4255470.617	599189.429		93.5
27R	4255469.457	599190.740	95.9	92.7
28L	4255480.966	599199.492	94.1	93.6
28R	4255479.546	599200.874		91.9
29L	4255491.765	599210.131		93.4
29R	4255490.524	599211.307	95.9	92.8
30L	4255502.490	599220.620	95.2	93.4
30R	4255501.060	599221.979		93.9

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
01L	4255193.528	598916.268	1741	654	93	200
01R	4255192.231	598917.312				
02L	4255204.620	598927.029	2335	1081	88	190
02R	4255202.975	598928.358				
03L	4255215.028	598939.907	1716	795	88	190
03R	4255216.002	598938.302				
04L	4255226.597	598948.956	2379	893	93	200
04R	4255225.330	598950.039				
05L	4255237.334	598959.388	1894	762	91	197
05R	4255236.048	598960.696				
06L	4255247.762	598969.858	1613	649	91	197
06R	4255246.489	598971.230				
07L	4255257.051	598981.506	1493	691	88	190
07R	4255258.365	598980.132				
08L	4255269.070	598990.646	2441	743	99	209
08R	4255267.737	598991.965				
09L	4255278.333	599002.584	1912	718	93	200
09R	4255279.637	599001.176				
10L	4255289.069	599013.102	3122	1172	93	200
10R	4255290.344	599011.665				
11L	4255301.121	599022.300	2290	747	97	206
11R	4255299.896	599023.721				
12L	4255313.098	599033.954	2032	711	95	203
12R	4255311.830	599035.256				
13L	4255323.666	599044.493	3306	661	109	229
13R	4255322.395	599045.834				
14L	4255334.523	599055.100	2345	665	100	213
14R	4255333.219	599056.466				
15L	4255345.059	599065.726	2244	683	99	209
15R	4255343.773	599067.071				

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°C]	[°F]
16L	4255356.237	599076.600	2568	781	99	209
16R	4255354.885	599077.983				
17L	4255367.017	599087.102	3903	1107	100	213
17R	4255365.738	599088.436				
18L	4255377.419	599097.393	2829	748	102	216
18R	4255376.193	599098.660				
19L	4255387.946	599107.933	4539	1288	100	213
19R	4255386.653	599109.309				
20L	4255397.859	599117.628	4163	1101	102	216
20R	4255396.585	599119.019				
21L	4255407.839	599127.406	3304	1005	99	209
21R	4255406.524	599128.693				
22L	4255417.704	599137.082	3728	1134	99	209
22R	4255416.434	599138.473				
23L	4255428.316	599147.614	2320	812	95	203
23R	4255427.038	599148.951				
24L	4255438.865	599158.197	3056	1070	95	203
24R	4255437.621	599159.469				
25L	4255449.115	599168.206	3464	1212	95	203
25R	4255447.703	599169.413				
26L	4255460.113	599178.775	2506	762	99	209
26R	4255458.693	599180.064				
27L	4255470.617	599189.429				
27R	4255469.457	599190.740				
28L	4255480.966	599199.492	3910	1109	100	213
28R	4255479.546	599200.874				
29L	4255491.765	599210.131	4799	1460	99	209
29R	4255490.524	599211.307				
30L	4255502.490	599220.620	4908	1392	100	213
30R	4255501.060	599221.979				

Backcalculated FWD Data

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[ksi]
01L	4255193.528	598916.268	8.34	496
01R	4255192.231	598917.312		
02L	4255204.620	598927.029	9.60	157
02R	4255202.975	598928.358		
03L	4255215.028	598939.907	7.75	213
03R	4255216.002	598938.302		
04L	4255226.597	598948.956	8.82	256
04R	4255225.330	598950.039		
05L	4255237.334	598959.388	9.29	184
05R	4255236.048	598960.696		
06L	4255247.762	598969.858	8.95	325
06R	4255246.489	598971.230		
07L	4255257.051	598981.506	8.72	343
07R	4255258.365	598980.132		
08L	4255269.070	598990.646	9.70	279
08R	4255267.737	598991.965		
09L	4255278.333	599002.584	10.57	240
09R	4255279.637	599001.176		
10L	4255289.069	599013.102	8.78	475
10R	4255290.344	599011.665		
11L	4255301.121	599022.300	10.74	228
11R	4255299.896	599023.721		
12L	4255313.098	599033.954	10.66	273
12R	4255311.830	599035.256		
13L	4255323.666	599044.493	10.83	310
13R	4255322.395	599045.834		
14L	4255334.523	599055.100	10.27	261
14R	4255333.219	599056.466		
15L	4255345.059	599065.726	9.87	198
15R	4255343.773	599067.071		

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[ksi]
16L	4255356.237	599076.600	8.97	366
16R	4255354.885	599077.983		
17L	4255367.017	599087.102	8.13	244
17R	4255365.738	599088.436		
18L	4255377.419	599097.393	9.73	183
18R	4255376.193	599098.660		
19L	4255387.946	599107.933	9.47	281
19R	4255386.653	599109.309		
20L	4255397.859	599117.628	10.09	211
20R	4255396.585	599119.019		
21L	4255407.839	599127.406	10.47	397
21R	4255406.524	599128.693		
22L	4255417.704	599137.082	9.72	413
22R	4255416.434	599138.473		
23L	4255428.316	599147.614	10.64	324
23R	4255427.038	599148.951		
24L	4255438.865	599158.197	10.65	342
24R	4255437.621	599159.469		
25L	4255449.115	599168.206	10.93	175
25R	4255447.703	599169.413		
26L	4255460.113	599178.775	10.15	211
26R	4255458.693	599180.064		
27L	4255470.617	599189.429	10.40	214
27R	4255469.457	599190.740		
28L	4255480.966	599199.492	11.57	148
28R	4255479.546	599200.874		
29L	4255491.765	599210.131	11.37	201
29R	4255490.524	599211.307		
30L	4255502.490	599220.620	9.06	171
30R	4255501.060	599221.979		

Idaho Site

Idaho US-95 IC Project - TB02 (May 6, 2014)
UTM 11N Meters

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
01L	5310831.771	522681.653	90.1	87.4
01R	5310832.140	522685.379	90.5	90.2
02L	5310847.648	522679.586	91.5	91.0
02R	5310848.250	522683.101	90.1	89.8
03L	5310863.220	522676.701	89.3	86.5
03R	5310863.773	522680.682	90.0	88.9
04L	5310878.099	522674.453	92.2	91.4
04R	5310878.585	522678.012	91.0	89.6
05L	5310892.916	522671.577	90.2	89.7
05R	5310893.538	522675.222	91.3	91.5
06L	5310907.730	522668.766	91.1	91.3
06R	5310908.375	522672.227	93.4	90.1
07L	5310922.781	522665.331	91.8	90.4
07R	5310923.856	522669.251	89.5	88.4
08L	5310937.910	522661.989	91.7	91.5
08R	5310938.736	522665.622	89.9	89.0
09L	5310952.713	522659.210	90.3	90.0
09R	5310953.478	522661.391	91.5	91.6
10L	5310967.409	522655.092	92.1	91.1
10R	5310967.894	522657.688	90.7	90.1
11L	5310981.927	522650.537	92.3	90.9
11R	5310983.206	522654.172	90.8	91.1
12L	5310996.473	522646.254	91.6	91.2
12R	5310997.244	522649.531	91.9	90.6
13L	5311011.012	522642.343	93.2	93.1
13R	5311012.070	522645.032	92.2	91.4
14L	5311025.526	522637.257	91.8	91.6
14R	5311026.555	522640.914	90.0	88.8
15L	5311040.166	522632.989	92.3	91.8
15R	5311041.239	522635.562	91.0	91.6

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
16L	5311054.353	522627.556	90.2	88.9
16R	5311055.492	522631.335	89.5	88.6
17L	5311068.619	522623.299	91.4	90.6
17R	5311069.751	522625.739	90.2	88.5
18L	5311083.016	522618.023	91.3	90.5
18R	5311084.095	522620.776	90.6	89.6
19L	5311097.637	522613.570	95.0	94.4
19R	5311098.641	522615.891	90.9	88.3
20L	5311111.995	522607.981	92.1	90.9
20R	5311112.981	522611.211	90.4	89.1
21L	5311127.282	522603.114	94.0	91.7
21R	5311128.342	522606.607	92.5	91.0
22L	5311141.139	522597.853	92.0	91.2
22R	5311142.700	522601.123	91.1	91.7
23L	5311156.747	522593.391	92.8	90.9
23R	5311157.578	522595.950	89.3	91.2
24L	5311170.673	522587.818	92.1	91.1
24R	5311171.959	522590.654	89.3	88.6
25L	5311185.622	522583.321	91.3	90.1
25R	5311186.503	522586.217	92.2	93.3
26L	5311200.557	522577.953	92.5	93.0
26R	5311201.294	522580.947	91.6	90.9
27L	5311215.203	522572.699	92.6	91.6
27R	5311216.187	522576.109	92.7	92.4
28L	5311229.432	522567.773	91.9	92.5
28R	5311230.068	522570.702	92.7	90.8
29L	5311243.241	522563.205	91.7	91.0
29R	5311244.747	522565.755	92.1	94.5
30L	5311258.476	522558.287	92.5	91.4
30R	5311259.194	522560.963	91.8	92.7

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
01L	5310831.771	522681.653	446	207	88	190
01R	5310832.140	522685.379	587	272	88	190
02L	5310847.648	522679.586	645	242	93	200
02R	5310848.250	522683.101	609	245	91	197
03L	5310863.220	522676.701	601	183	99	209
03R	5310863.773	522680.682	673	236	95	203
04L	5310878.099	522674.453	788	209	102	216
04R	5310878.585	522678.012	957	253	102	216
05L	5310892.916	522671.577	779	206	102	216
05R	5310893.538	522675.222	1065	282	102	216
06L	5310907.730	522668.766	898	255	100	213
06R	5310908.375	522672.227	945	250	102	216
07L	5310922.781	522665.331	941	216	106	222
07R	5310923.856	522669.251	946	233	104	219
08L	5310937.910	522661.989	965	255	102	216
08R	5310938.736	522665.622	986	243	104	219
09L	5310952.713	522659.210	1040	239	106	222
09R	5310953.478	522661.391	1164	250	108	226
10L	5310967.409	522655.092	1067	245	106	222
10R	5310967.894	522657.688	1175	252	108	226
11L	5310981.927	522650.537	1851	227	122	252
11R	5310983.206	522654.172	1121	277	104	219
12L	5310996.473	522646.254	985	227	106	222
12R	5310997.244	522649.531	1076	247	106	222
13L	5311011.012	522642.343	1094	252	106	222
13R	5311012.070	522645.032	1278	274	108	226
14L	5311025.526	522637.257	963	222	106	222
14R	5311026.555	522640.914	1084	267	104	219
15L	5311040.166	522632.989	1073	247	106	222
15R	5311041.239	522635.562	1157	248	108	226

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
16L	5311054.353	522627.556	1021	235	106	222
16R	5311055.492	522631.335	1036	238	106	222
17L	5311068.619	522623.299	1142	245	108	226
17R	5311069.751	522625.739	1018	234	106	222
18L	5311083.016	522618.023	934	247	102	216
18R	5311084.095	522620.776	937	231	104	219
19L	5311097.637	522613.570	1247	287	106	222
19R	5311098.641	522615.891	987	227	106	222
20L	5311111.995	522607.981	935	247	102	216
20R	5311112.981	522611.211	901	222	104	219
21L	5311127.282	522603.114	1260	270	108	226
21R	5311128.342	522606.607	1316	303	106	222
22L	5311141.139	522597.853	1097	235	108	226
22R	5311142.700	522601.123	1182	253	108	226
23L	5311156.747	522593.391	1215	279	106	222
23R	5311157.578	522595.950	1176	270	106	222
24L	5311170.673	522587.818	889	235	102	216
24R	5311171.959	522590.654	1024	271	102	216
25L	5311185.622	522583.321	961	273	100	213
25R	5311186.503	522586.217	1071	304	100	213
26L	5311200.557	522577.953	896	254	100	213
26R	5311201.294	522580.947	904	275	99	209
27L	5311215.203	522572.699	790	240	99	209
27R	5311216.187	522576.109	1357	312	106	222
28L	5311229.432	522567.773	925	262	100	213
28R	5311230.068	522570.702	1087	288	102	216
29L	5311243.241	522563.205	723	220	99	209
29R	5311244.747	522565.755	1199	317	102	216
30L	5311258.476	522558.287	943	287	99	209
30R	5311259.194	522560.963	984	321	97	206

Maryland Site

Maryland MD-170 IC Project - TB03 (June 25, 2014)
UTM 18N Meters

Core Density and NDG Density

ID	Northing	Easting	Core	NDG
	[m]	[m]	[%Gmm]	[%Gmm]
01L	4336517.645	353490.406	95.1	87.4
01R	4336518.017	353489.148	95.7	90.2
02L	4336508.443	353488.605	94.8	91.0
02R	4336508.827	353487.304	96.2	89.8
03L	4336499.244	353486.635	96.1	86.5
03R	4336499.461	353485.426	96.3	88.9
04L	4336489.804	353484.965	95.5	91.4
04R	4336490.094	353483.689	96.2	89.6
05L	4336480.718	353483.482	93.2	89.7
05R	4336480.923	353482.037	93.5	91.5
06L	4336473.190	353482.327	96.7	91.3
06R	4336473.473	353480.786	96.2	90.1
07L	4336463.866	353480.821	96.6	90.4
07R	4336464.207	353479.254	95.1	88.4
08L	4336451.521	353478.730	89.8	91.5
08R	4336451.747	353477.282	92.2	89.0
09L	4336442.067	353477.453	96.5	90.0
09R	4336442.219	353475.906	92.8	91.6
10L	4336433.163	353476.223	96.7	91.1
10R	4336433.398	353474.214	92.3	90.1
11L	4336423.967	353475.353	96.3	90.9
11R	4336424.178	353473.691	94.9	91.1
12L	4336414.796	353474.391	95.5	91.2
12R	4336414.781	353472.812	94.4	90.6
13L	4336405.588	353473.672	96.3	93.1
13R	4336405.637	353472.108	95.7	91.4
14L	4336396.103	353473.065	95.6	91.6
14R	4336396.173	353471.650	96.0	88.8
15L	4336386.590	353472.495	95.1	91.8
15R	4336386.721	353471.017	94.8	91.6

ID	Northing [m]	Easting [m]	Core [%Gmm]	NDG [%Gmm]
16L	4336376.958	353472.023	95.9	88.9
16R	4336377.028	353470.578	95.0	88.6
17L	4336367.781	353471.724	95.6	90.6
17R	4336367.814	353470.224	95.8	88.5
18L	4336357.545	353471.336	95.1	90.5
18R	4336357.469	353469.831	92.8	89.6
19L	4336348.212	353471.165	93.1	94.4
19R	4336348.264	353469.541	90.2	88.3
20L	4336339.135	353471.074	94.3	90.9
20R	4336339.172	353469.585	92.4	89.1
21L	4336329.793	353471.229	93.9	91.7
21R	4336329.732	353469.775	92.4	91.0
22L	4336320.430	353471.404	94.8	91.2
22R	4336320.329	353469.873	91.9	91.7
23L	4336312.435	353471.680	93.7	90.9
23R	4336312.432	353470.213	91.4	91.2
24L	4336303.526	353472.208	94.9	91.1
24R	4336303.285	353470.761	93.5	88.6
25L	4336294.135	353472.932	94.1	90.1
25R	4336293.952	353471.398	93.3	93.3
26L	4336284.954	353473.690	94.2	93.0
26R	4336284.695	353472.201	93.4	90.9
27L	4336275.786	353474.599	93.4	91.6
27R	4336275.484	353473.153	92.1	92.4
28L	4336266.684	353475.696	93.0	92.5
28R	4336266.306	353474.184	91.8	90.8
29L	4336257.519	353476.915	93.3	91.0
29R	4336257.245	353475.485	91.8	94.5
30L	4336248.674	353478.248	93.6	91.4
30R	4336248.241	353476.755	90.7	92.7

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
01L	4336517.645	353490.406	10509	846	56	133
01R	4336518.017	353489.148	9942	987	53	127
02L	4336508.443	353488.605	9598	584	60	140
02R	4336508.827	353487.304	9779	684	58	136
03L	4336499.244	353486.635	5625	558	53	127
03R	4336499.461	353485.426	13281	753	61	142
04L	4336489.804	353484.965	12075	555	64	147
04R	4336490.094	353483.689	16109	690	65	149
05L	4336480.718	353483.482	8527	596	58	136
05R	4336480.923	353482.037	9755	842	55	131
06L	4336473.190	353482.327	15729	723	64	147
06R	4336473.473	353480.786	10946	621	61	142
07L	4336463.866	353480.821	12690	583	64	147
07R	4336464.207	353479.254	14103	858	60	140
08L	4336451.521	353478.730	17547	928	62	143
08R	4336451.747	353477.282	19382	831	65	149
09L	4336442.067	353477.453	18327	785	65	149
09R	4336442.219	353475.906	19507	1463	57	134
10L	4336433.163	353476.223	16360	752	64	147
10R	4336433.398	353474.214	44166	2504	61	142
11L	4336423.967	353475.353	18556	915	63	145
11R	4336424.178	353473.691	27816	1371	63	145
12L	4336414.796	353474.391	18753	991	62	143
12R	4336414.781	353472.812	21265	1293	60	140
13L	4336405.588	353473.672	17281	852	63	145
13R	4336405.637	353472.108	25067	1152	64	147
14L	4336396.103	353473.065	13494	821	60	140
14R	4336396.173	353471.650	19091	941	63	145
15L	4336386.590	353472.495	14512	715	63	145
15R	4336386.721	353471.017	15221	993	59	138

ID	Northing	Easting	Elwd20	Elwd	Temp	Temp
	[m]	[m]	[MN/^2]	[MN/^2]	[°C]	[°F]
16L	4336376.958	353472.023	14005	794	61	142
16R	4336377.028	353470.578	22610	1375	60	140
17L	4336367.781	353471.724	15066	854	61	142
17R	4336367.814	353470.224	21148	1199	61	142
18L	4336357.545	353471.336	17320	854	63	145
18R	4336357.469	353469.831	25701	1359	62	143
19L	4336348.212	353471.165	15032	852	61	142
19R	4336348.264	353469.541	22975	1215	62	143
20L	4336339.135	353471.074	16750	885	62	143
20R	4336339.172	353469.585	19709	906	64	147
21L	4336329.793	353471.229	19804	910	64	147
21R	4336329.732	353469.775	23398	1003	65	149
22L	4336320.430	353471.404	22113	948	65	149
22R	4336320.329	353469.873	19649	1039	62	143
23L	4336312.435	353471.680	17002	964	61	142
23R	4336312.432	353470.213	19408	1180	60	140
24L	4336303.526	353472.208	15126	858	61	142
24R	4336303.285	353470.761	16861	956	61	142
25L	4336294.135	353472.932	17278	794	64	147
25R	4336293.952	353471.398	22254	1176	62	143
26L	4336284.954	353473.690	20657	949	64	147
26R	4336284.695	353472.201	15822	962	60	140
27L	4336275.786	353474.599	14896	845	61	142
27R	4336275.484	353473.153	14391	875	60	140
28L	4336266.684	353475.696	13693	776	61	142
28R	4336266.306	353474.184	12358	752	60	140
29L	4336257.519	353476.915	11305	687	60	140
29R	4336257.245	353475.485	13466	878	59	138
30L	4336248.674	353478.248	11669	761	59	138
30R	4336248.241	353476.755	9850	689	58	136

Kentucky Site

Kentucky I-65 IC Project TB-02 (July 15, 2014)
UTM 16N (meters)

Core Density and NDG Density

	Northing	Easting	Core	NDG
ID	[m]	[m]	[%Gmm]	[%Gmm]
01L	4128663.183	597333.562	96.4	89.9
01R	4128662.761	597331.657	97.0	89.9
02L	4128647.453	597336.007	96.1	91.6
02R	4128647.175	597334.064	97.5	93.0
03L	4128630.269	597339.211	97.5	90.8
03R	4128629.928	597336.970	97.6	95.3
04L	4128613.947	597342.102	96.9	95.3
04R	4128613.405	597339.977	97.5	93.8
05L	4128592.891	597345.950	94.5	92.9
05R	4128592.475	597343.717	94.8	95.6
06L	4128577.846	597348.396	98.0	92.4
06R	4128577.526	597346.372	97.5	92.4
07L	4128562.823	597351.094	97.9	87.8
07R	4128562.424	597348.975	96.4	90.2
08L	4128547.749	597353.673	91.0	90.7
08R	4128547.363	597351.873	93.4	90.9
09L	4128532.703	597356.079	97.9	94.8
09R	4128532.431	597354.243	94.1	96.5
10L	4128517.756	597358.833	98.0	93.1
10R	4128517.242	597356.877	93.6	93.5
11L	4128502.817	597361.365	97.7	88.7
11R	4128502.328	597359.394	96.2	91.9
12L	4128487.707	597363.784	96.8	90.7
12R	4128487.190	597361.815	95.7	93.3
13L	4128472.888	597365.827	97.6	88.2
13R	4128472.466	597363.900	97.0	91.6
14L	4128457.802	597367.738	96.9	84.8
14R	4128456.421	597366.522	97.3	91.6
15L	4128441.644	597369.993	96.4	93.4
15R	4128441.438	597368.049	96.1	93.6

	Northing	Easting	Core	NDG
ID	[m]	[m]	[%Gmm]	[%Gmm]
16L	4128426.464	597371.507	97.2	92.0
16R	4128426.185	597369.509	96.3	89.5
17L	4128411.462	597372.529	97.0	83.5
17R	4128411.143	597370.430	97.1	91.4
18L	4128396.209	597373.403	96.4	81.8
18R	4128395.913	597371.144	94.1	94.1
19L	4128381.102	597374.027	94.4	88.6
19R	4128380.901	597371.723	91.5	96.3
20L	4128366.123	597374.335	95.7	89.5
20R	4128366.351	597371.950	93.6	86.0
21L	4128351.104	597374.366	95.3	87.2
21R	4128350.958	597371.996	93.7	91.5
22L	4128336.691	597373.680	96.1	89.6
22R	4128335.658	597371.822	93.2	94.5
23L	4128320.603	597373.561	95.0	94.8
23R	4128320.643	597371.446	92.7	99.3
24L	4128305.688	597372.867	96.3	95.9
24R	4128305.707	597370.638	94.8	95.7
25L	4128290.544	597371.965	95.4	90.9
25R	4128291.642	597369.253	94.6	95.5
26L	4128276.617	597370.417	95.5	92.7
26R	4128276.751	597367.955	94.7	94.8
27L	4128261.794	597368.771	94.7	89.3
27R	4128262.113	597366.334	93.3	91.1
28L	4128246.867	597366.960	94.3	92.4
28R	4128247.145	597364.724	93.1	91.7
29L	4128231.728	597364.974	94.6	88.4
29R	4128232.089	597362.450	93.1	94.0
30L	4128216.646	597362.517	94.9	91.0
30R	4128216.947	597360.164	92.0	91.4

Backcalculated LWD-a Data

	Northing	Easting	Elwd20	Elwd	Temp	Temp
ID	[m]	[m]	(MN/m^2)	[MN/^2]	[°C]	[°F]
01L	4128663.183	597333.562	10798	999	54	129
01R	4128662.761	597331.657	16281	698	65	149
02L	4128647.453	597336.007	32864	1142	68	154
02R	4128647.175	597334.064	24901	928	67	152
03L	4128630.269	597339.211	28288	854	70	158
03R	4128629.928	597336.970	24494	740	70	158
04L	4128613.947	597342.102	31571	1022	69	156
04R	4128613.405	597339.977	34617	975	71	160
05L	4128592.891	597345.950	30714	1067	68	154
05R	4128592.475	597343.717	32639	1057	69	156
06L	4128577.846	597348.396	38958	954	73	163
06R	4128577.526	597346.372	27349	770	71	160
07L	4128562.823	597351.094	33868	954	71	160
07R	4128562.424	597348.975	36026	946	72	161
08L	4128547.749	597353.673	26044	970	67	152
08R	4128547.363	597351.873	31706	1101	68	154
09L	4128532.703	597356.079	44882	1264	71	160
09R	4128532.431	597354.243	38596	1250	69	156
10L	4128517.756	597358.833	33405	1009	70	158
10R	4128517.242	597356.877	41676	1094	72	161
11L	4128502.817	597361.365	33782	827	73	163
11R	4128502.328	597359.394	38959	889	74	165
12L	4128487.707	597363.784	36239	887	73	163
12R	4128487.190	597361.815	45833	1046	74	165
13L	4128472.888	597365.827	35157	748	75	167
13R	4128472.466	597363.900	35795	876	73	163
14L	4128457.802	597367.738	45477	968	75	167
14R	4128456.421	597366.522	47398	1335	71	160
15L	4128441.644	597369.993	40343	987	73	163
15R	4128441.438	597368.049	47440	1336	71	160

	Northing	Easting	Elwd20	Elwd	Temp	Temp
ID	[m]	[m]	(MN/m²)	[MN/^2]	[°C]	[°F]
16L	4128426.464	597371.507	21270	1124	62	143
16R	4128426.185	597369.509	21675	1068	63	145
17L	4128411.462	597372.529	19514	1032	62	143
17R	4128411.143	597370.430	23682	1167	63	145
18L	4128396.209	597373.403	20709	952	64	147
18R	4128395.913	597371.144	26951	1239	64	147
19L	4128381.102	597374.027	24895	995	66	151
19R	4128380.901	597371.723	30412	1303	65	149
20L	4128366.123	597374.335	27454	1176	65	149
20R	4128366.351	597371.950	26538	1137	65	149
21L	4128351.104	597374.366	26682	1066	66	151
21R	4128350.958	597371.996	31207	1247	66	151
22L	4128336.691	597373.680	26700	995	67	152
22R	4128335.658	597371.822	29422	1176	66	151
23L	4128320.603	597373.561	27629	960	68	154
23R	4128320.643	597371.446	28138	1206	65	149
24L	4128305.688	597372.867	28155	912	69	156
24R	4128305.707	597370.638	35660	1239	68	154
25L	4128290.544	597371.965	36524	1103	70	158
25R	4128291.642	597369.253	40624	1411	68	154
26L	4128276.617	597370.417	31571	1022	69	156
26R	4128276.751	597367.955	35310	1226	68	154
27L	4128261.794	597368.771	32032	1193	67	152
27R	4128262.113	597366.334	30949	1153	67	152
28L	4128246.867	597366.960	32950	1227	67	152
28R	4128247.145	597364.724	36659	1273	68	154
29L	4128231.728	597364.974	35087	1136	69	156
29R	4128232.089	597362.450	31548	1261	66	151
30L	4128216.646	597362.517	27584	1102	66	151
30R	4128216.947	597360.164	32790	1139	68	154

Washington State Site

Washington State , TB02 (Aug. 26, 2014)
UTM 10N (meters)

Core Density and NDG Density

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
01L	5427557.974	537668.510	93.3	91.9
01R	5427557.855	537666.896	92.2	92.0
02L	5427543.091	537668.532	93.6	91.8
02R	5427543.091	537666.921	91.3	90.7
03L	5427526.991	537668.740	94.3	92.3
03R	5427526.884	537666.952	92.9	91.8
04L	5427511.471	537668.754	93.5	91.9
04R	5427511.730	537666.963	93.1	92.3
05L	5427496.624	537668.837	94.0	92.8
05R	5427496.679	537666.949	93.4	92.2
06L	5427476.284	537668.729	93.0	92.0
06R	5427476.083	537667.073	92.6	91.9
07L	5427466.150	537668.890	93.0	92.0
07R	5427466.473	537666.974	93.3	92.5
08L	5427450.776	537668.861	93.4	92.2
08R	5427450.596	537666.865	92.8	92.6
09L	5427435.859	537669.032	93.5	91.9
09R	5427435.801	537667.027	92.8	92.0
10L	5427420.652	537668.854	93.4	92.7
10R	5427420.613	537666.901	92.2	90.8
11L	5427405.367	537668.922	92.2	90.8
11R	5427405.626	537666.909	93.0	91.1
12L	5427390.224	537669.056	92.2	91.1
12R	5427390.197	537666.849	91.2	90.4
13L	5427375.170	537669.013	93.3	92.0
13R	5427375.173	537666.826	91.0	90.0
14L	5427359.732	537669.011	92.2	92.1
14R	5427359.896	537666.878	92.9	90.4
15L	5427344.376	537669.145	91.1	90.2
15R	5427344.336	537666.888	92.0	90.8

ID	Northing	Easting	Core Density	NDG Density
	[m]	[m]	[%Gmm]	[%Gmm]
16L	5427329.026	537669.024	93.6	92.9
16R	5427329.108	537666.888	91.0	90.4
17L	5427314.478	537669.046	92.7	92.0
17R	5427314.402	537666.739	91.1	90.7
18L	5427298.574	537668.892	92.2	91.7
18R	5427298.634	537666.664	91.8	90.9
19L	5427284.202	537668.960	92.6	91.5
19R	5427284.114	537666.598	92.9	91.6
20L	5427268.907	537668.951	93.1	93.4
20R	5427268.734	537666.790	91.1	90.6
21L	5427253.951	537668.930	93.1	92.9
21R	5427253.515	537666.757	92.3	91.5
22L	5427238.366	537668.685	93.8	93.8
22R	5427238.290	537666.576	92.2	91.8
23L	5427224.056	537668.796	93.5	93.3
23R	5427223.910	537666.566	92.8	90.9
24L	5427208.666	537668.664	93.7	93.1
24R	5427208.639	537666.603	90.6	91.2
25L	5427193.234	537668.624	93.8	93.2
25R	5427193.201	537666.606	91.4	91.1
26L	5427177.933	537668.807	92.5	92.1
26R	5427177.872	537666.434	91.5	90.1
27L	5427163.394	537668.735	92.9	92.4
27R	5427163.300	537666.527	91.1	90.4
28L	5427148.459	537668.781	94.2	93.3
28R	5427148.273	537666.607	93.1	92.4
29L	5427133.301	537668.804	93.1	92.5
29R	5427133.332	537666.623	90.8	91.3
30L	5427117.485	537668.896	92.8	91.5
30R	5427117.434	537666.778	91.7	90.4

Backcalculated LWD-a Data

ID	Northing	Easting	Elwd20	Elwd	Temp(F)
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°F]
01L	5427557.974	537668.510	3961	422	125
01R	5427557.855	537666.896	5003	403	133
02L	5427543.091	537668.532	7102	432	140
02R	5427543.091	537666.921	9441	352	152
03L	5427526.991	537668.740	8669	458	143
03R	5427526.884	537666.952	10382	415	151
04L	5427511.471	537668.754	9303	492	143
04R	5427511.730	537666.963	8582	394	147
05L	5427496.624	537668.837	11304	557	145
05R	5427496.679	537666.949	5916	335	142
06L	5427476.284	537668.729	9623	442	147
06R	5427476.083	537667.073	6882	295	149
07L	5427466.150	537668.890	6647	328	145
07R	5427466.473	537666.974	7272	312	149
08L	5427450.776	537668.861	7351	338	147
08R	5427450.596	537666.865	8362	334	151
09L	5427435.859	537669.032	7775	311	151
09R	5427435.801	537667.027	9871	320	156
10L	5427420.652	537668.854	7234	310	149
10R	5427420.613	537666.901	6159	264	149
11L	5427405.367	537668.922	6412	316	145
11R	5427405.626	537666.909	6159	264	149
12L	5427390.224	537669.056	8064	346	149
12R	5427390.197	537666.849	5968	256	149
13L	5427375.170	537669.013	9108	419	147
13R	5427375.173	537666.826	4945	227	147
14L	5427359.732	537669.011	7531	346	147
14R	5427359.896	537666.878	4330	199	147
15L	5427344.376	537669.145	7537	323	149
15R	5427344.336	537666.888	6292	251	151

ID	Northing	Easting	Elwd20	Elwd	Temp(F)
	[m]	[m]	[MN/m^2]	[MN/m^2]	[°F]
16L	5427329.026	537669.024	9484	379	151
16R	5427329.108	537666.888	5899	253	149
17L	5427314.478	537669.046	7172	330	147
17R	5427314.402	537666.739	6559	262	151
18L	5427298.574	537668.892	6967	320	147
18R	5427298.634	537666.664	6753	310	147
19L	5427284.202	537668.960	6415	295	147
19R	5427284.114	537666.598	6635	284	149
20L	5427268.907	537668.951	7724	355	147
20R	5427268.734	537666.790	7836	386	145
21L	5427253.951	537668.930	8131	348	149
21R	5427253.515	537666.757	9006	360	151
22L	5427238.366	537668.685	9202	394	149
22R	5427238.290	537666.576	9342	400	149
23L	5427224.056	537668.796	7718	355	147
23R	5427223.910	537666.566	9017	414	147
24L	5427208.666	537668.664	9225	369	151
24R	5427208.639	537666.603	8565	342	151
25L	5427193.234	537668.624	8573	319	152
25R	5427193.201	537666.606	9757	295	158
26L	5427177.933	537668.807	8804	328	152
26R	5427177.872	537666.434	8815	328	152
27L	5427163.394	537668.735	8388	313	152
27R	5427163.300	537666.527	9253	279	158
28L	5427148.459	537668.781	10023	400	151
28R	5427148.273	537666.607	10145	378	152
29L	5427133.301	537668.804	8788	305	154
29R	5427133.332	537666.623	9311	302	156
30L	5427117.485	537668.896	10619	369	154
30R	5427117.434	537666.778	12727	412	156

Backcalculated FWD Data

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[psi]
01L	5427557.974	537668.51	42.63	78738
01R	5427557.855	537666.8958		
02L	5427543.091	537668.5323	43.73	75000
02R	5427543.091	537666.9211		
03L	5427526.991	537668.7399	51.76	86793
03R	5427526.884	537666.9516		
04L	5427511.471	537668.7545	49.58	103461
04R	5427511.73	537666.9635		
05L	5427496.624	537668.8368	41.06	88282
05R	5427496.679	537666.9485		
06L	5427476.284	537668.7292	44.80	89960
06R	5427476.083	537667.0729		
07L	5427466.15	537668.8901	49.64	81266
07R	5427466.473	537666.9735		
08L	5427450.776	537668.8609	43.45	92122
08R	5427450.596	537666.865		
09L	5427435.859	537669.0319	41.17	84054
09R	5427435.801	537667.0272		
10L	5427420.652	537668.8535	48.77	91304
10R	5427420.613	537666.9013		
11L	5427405.367	537668.9221	51.38	70000
11R	5427405.626	537666.9086		
12L	5427390.224	537669.0556	63.06	65000
12R	5427390.197	537666.8495		
13L	5427375.17	537669.013	56.13	65000
13R	5427375.173	537666.826		
14L	5427359.732	537669.0114	51.98	75429
14R	5427359.896	537666.8784		
15L	5427344.376	537669.1452	47.28	96347
15R	5427344.336	537666.8876		

ID	Northing	Easting	Dfwd	Efwd
	[m]	[m]	[mils]	[psi]
16L	5427329.026	537669.0242	37.06	96516
16R	5427329.108	537666.8879		
17L	5427314.478	537669.0459	53.52	70000
17R	5427314.402	537666.7388		
18L	5427298.574	537668.8923	41.62	88115
18R	5427298.634	537666.6636		
19L	5427284.202	537668.9602	53.15	84834
19R	5427284.114	537666.5983		
20L	5427268.907	537668.9514	53.35	85043
20R	5427268.734	537666.7903		
21L	5427253.951	537668.93	44.90	90231
21R	5427253.515	537666.7568		
22L	5427238.366	537668.6853	37.00	84451
22R	5427238.29	537666.5758		
23L	5427224.056	537668.7959	48.00	96365
23R	5427223.91	537666.5657		
24L	5427208.666	537668.6637	51.94	87270
24R	5427208.639	537666.6026		
25L	5427193.234	537668.624	54.55	75000
25R	5427193.201	537666.6062		
26L	5427177.933	537668.8072	49.61	76414
26R	5427177.872	537666.434		
27L	5427163.394	537668.735	60.16	75000
27R	5427163.3	537666.5267		
28L	5427148.459	537668.781	50.72	84910
28R	5427148.273	537666.6075		
29L	5427133.301	537668.8039	95.00	60000
29R	5427133.332	537666.623		
30L	5427117.485	537668.8956	65.03	65000
30R	5427117.434	537666.7782		

Appendix C Validation of IC-Based Density Model

The density models were implemented in an Excel spreadsheet with the Solver function. The Excel Solver function uses an iterative computing technique to minimize the differences between the model prediction and actual measured data in order to produce fitted model parameters. For model validation for a give test site, IC data and intensive in-place asphalt density measurements using the NDG and cores were collected in a test strip for a given site. The IC data and in-place density data were analyzed using the Veda software. IC data with respect to asphalt density measurements were extracted for both all-passes and final coverage data. Pass-by-pass data and a subset of the final coverage data set were used to fit the IC-density model using the Excel Solver function. During the solving process, all unconstrained variables were made positive and the evolutionary method was used to find a good solution to a reasonably well-scaled model. The fitted model was then validated using the remaining data set. See Chapter 5 for detailed development and description of the IC-Based Density Model.

The followings are the validation data for the IC-based density model:

- Model Calibration: Selected subset of field measurement data were used to produce fitted model parameters by minimizing the prediction error.
- Model Validation: The calibrated model was then used to predict densities for the remaining of the field measurement location and the comparison between the actual in-place densities and predicted ones were compared.

Due to the GPS shadow issues at the Maryland site, the density model validation was not performed for this site.

Data column headers:

- ID: location ID for coring or NDG measurements
- Dens: core density and NDG density
- ICMV: specific ICMV from a specific vendor, mostly from the breakdown compaction
- Freq: frequency of roller vibration
- Amp: amplitudes of roller vibration

- Speed: roller speed
- Temp: asphalt surface temperatures
- Passes: roller pass counts
- PredDen1: predicted densities by the IC-based model in Form I
- PredDen2: predicted densities by the IC-based model in Form II
- DenDiff: differences between measured densities and predicted densities
- DenDiff^2: squares of differences between measured densities and predicted densities

Other density model parameters can be referenced in Chapter 5.

Utah Site

Sakai breakdown compaction

Model Calibration

ID	Dens	ICMV	Freq	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		Hz	kph	C				%Gmm	
1-1	94.6	17.0	64.6	8.3	71	3.7	0.086	17.018	92.6	4.2
5-2	92.5	16.9	64.8	8.4	80	7.0	0.098	16.938	92.8	0.1
25-1	91.1	10.5	64.8	8.6	90	3.2	0.109	10.500	92.3	1.5
11-2	93.8	22.6	64.8	8.5	71	7.2	0.087	22.600	92.9	0.8
18-1	93.4	14.6	64.8	8.8	95	1.7	0.116	14.564	92.0	2.1
23-2	92.1	14.5	64.7	8.3	70	7.2	0.086	14.497	92.9	0.7
29-2	92.3	12.3	65.1	8.5	79	6.8	0.096	12.279	92.8	0.3
21-1	91.2	13.0	64.7	7.2	84	1.9	0.103	13.043	92.1	0.7
12-1	91.3	12.1	65.1	8.3	88	1.4	0.107	12.100	91.9	0.3
14-1	90.7	12.4	65.0	8.5	83	2.4	0.101	12.367	92.2	2.3

ρ_0	Gmm	α1	α2	α3	α4	β	k1	Tr
84.73	100	0	0	0	0.001	0.107065	26	80

Model Validation

Validation Input

ID	Dens	ICMV	Freq	Speed	Temp	Passes
1-1	94.6	17.0	64.6	8.3	71	3.7
1-2	94.2	22.6	64.4	8.5	65	11.3
2-1	91.4	15.9	64.5	8.5	80	6.5
2-2	92.4	15.3	65.2	8.4	91	2.0
3-1	92.0	21.2	65.0	8.3	81	6.9
3-2	91.7	13.5	64.7	8.5	82	2.4
4-1	91.9	16.5	64.8	8.4	76	7.0
5-1	91.6	13.0	65.0	8.4	91	1.9
5-2	92.5	16.9	64.8	8.4	80	7.0
6-1	92.0	10.9	64.8	8.5	86	1.8
6-2	93.0	14.8	64.9	8.3	80	7.2
7-1	92.4	11.3	64.4	8.6	77	3.0
7-2	93.7	15.3	64.5	8.5	83	7.5
8-1	91.1	10.5	64.8	8.6	90	3.2
8-2	92.6	11.5	64.8	8.4	84	7.0
9-1	93.2	11.5	64.8	8.4	84	7.0
9-2	93.9	11.9	65.3	8.5	84	7.3
10-1	92.5	13.6	64.5	8.4	96	1.7
10-2	95.0	16.2	64.9	8.3	68	13.1
11-1	91.9	16.1	64.6	8.6	76	3.1
11-2	93.8	22.6	64.8	8.5	71	7.2
12-1	91.3	12.1	65.1	8.3	88	1.4
12-2	92.6	16.5	65.0	8.4	75	7.9
13-1	92.1	13.7	65.1	8.5	87	1.8
13-2	90.9	14.5	64.9	8.4	76	7.6
14-1	90.7	12.4	65.0	8.5	83	2.4
14-2	92.7	18.3	65.0	8.3	77	7.7
15-1	92.0	13.1	65.0	8.4	95	2.1
15-2	92.7	13.9	65.0	8.3	85	7.4
16-1	91.8	13.8	64.9	8.3	96	2.1
16-2	93.7	17.4	64.9	8.4	85	7.3
17-1	91.5	12.8	65.0	8.5	94	2.5
17-2	93.1	11.4	64.8	8.3	87	7.2
18-1	93.4	14.6	64.8	8.8	95	1.7
18-2	94.1	22.9	62.2	7.7	69	12.3

ID	Dens	ICMV	Freq	Speed	Temp	Passes
19-1	92.3	9.9	64.9	8.4	88	1.0
19-2	93.3	16.4	65.1	8.2	76	8.6
20-1	91.5	12.0	65.1	8.7	87	1.2
20-2	92.7	14.2	64.7	8.0	78	7.7
21-1	91.2	13.0	64.7	7.2	84	1.9
21-2	92.7	12.0	51.5	8.3	52	8.9
22-1	88.3	12.4	64.7	8.0	79	1.4
22-2	91.2	15.5	64.8	8.3	65	7.2
23-1	91.1	11.3	64.9	8.3	84	1.0
23-2	92.1	14.5	64.7	8.3	70	7.2
24-1	91.4	10.5	65.4	8.4	86	1.1
24-2	92.4	14.2	64.8	8.4	69	6.9
25-1	91.1	10.6	65.2	8.4	84	1.0
25-2	91.6	13.3	64.7	8.5	69	7.7
26-1	91.7	10.2	65.5	8.5	91	1.0
26-2	92.3	13.5	65.1	8.5	77	7.3
27-1	91.9	11.0	65.1	8.4	92	1.0
27-2	92.7	14.0	64.9	8.4	77	7.0
28-1	91.7	11.0	64.7	8.6	92	1.0
28-2	92.1	12.9	64.7	8.5	75	6.6
29-1	91.9	11.6	65.0	8.8	97	1.0
29-2	92.3	12.3	65.1	8.5	79	6.8
30-1	91.8	11.2	65.0	8.6	97	1.1
30-2	92.7	12.0	65.0	8.6	79	7.1
30-2	90.5	23.0	65.9	6.6	55	4.2

Validation Output

ID	ICMV	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	PredDens1	PredDen2	DenDiff	DenDiff^2
1-1	17.0	0.086	17.018	84.817	0.50	92.56	93.06	-1.54	2.37
2-1	15.9	0.098	15.905	84.828	-0.50	92.80	92.30	0.90	0.81
2-2	15.3	0.111	15.267	84.842	0.34	92.06	92.40	0.00	0.00
3-2	13.5	0.100	13.529	84.831	-0.50	92.23	91.73	0.03	0.00
4-1	16.5	0.093	16.459	84.824	-0.50	92.86	92.36	0.46	0.21
5-1	13.0	0.111	13.020	84.842	-0.43	92.03	91.60	0.00	0.00
5-2	16.9	0.098	16.938	84.829	-0.34	92.84	92.50	0.00	0.00
6-1	10.9	0.106	10.940	84.837	-0.03	92.03	92.00	0.00	0.00
6-2	14.8	0.098	14.820	84.829	0.14	92.86	93.00	0.00	0.00
7-1	11.3	0.095	11.250	84.826	0.02	92.38	92.40	0.00	0.00
7-2	15.3	0.101	15.331	84.832	0.50	92.86	93.36	-0.34	0.12
8-1	10.5	0.110	10.500	84.841	-0.50	92.34	91.84	0.74	0.54
8-2	11.5	0.103	11.494	84.833	-0.21	92.81	92.60	0.00	0.00
9-1	11.5	0.103	11.494	84.833	0.39	92.81	93.20	0.00	0.00
9-2	11.9	0.104	11.915	84.834	0.50	92.83	93.33	-0.57	0.32
10-1	13.6	0.118	13.600	84.849	0.50	91.92	92.42	-0.08	0.01
10-2	16.2	0.083	16.234	84.814	0.50	93.27	93.77	-1.23	1.52
11-1	16.1	0.094	16.092	84.824	-0.50	92.41	91.91	0.01	0.00
12-2	16.5	0.092	16.480	84.823	-0.34	92.94	92.60	0.00	0.00
13-1	13.7	0.106	13.675	84.837	0.09	92.01	92.10	0.00	0.00
13-2	14.5	0.093	14.469	84.824	-0.50	92.91	92.41	1.51	2.29
14-1	12.4	0.102	12.367	84.832	-0.50	92.22	91.72	1.02	1.05
14-2	18.3	0.094	18.347	84.825	-0.21	92.91	92.70	0.00	0.00
15-1	13.1	0.116	13.075	84.847	-0.06	92.06	92.00	0.00	0.00
15-2	13.9	0.104	13.897	84.835	-0.14	92.84	92.70	0.00	0.00
16-1	13.8	0.117	13.753	84.848	-0.26	92.06	91.80	0.00	0.00
16-2	17.4	0.104	17.426	84.835	0.50	92.83	93.33	-0.37	0.14
17-1	12.8	0.115	12.807	84.846	-0.50	92.17	91.67	0.17	0.03
17-2	11.4	0.107	11.351	84.838	0.30	92.80	93.10	0.00	0.00
18-1	14.6	0.116	14.564	84.847	0.50	91.95	92.45	-0.95	0.90
19-1	9.9	0.108	9.850	84.839	0.50	91.68	92.18	-0.12	0.02
19-2	16.4	0.093	16.389	84.823	0.32	92.98	93.30	0.00	0.00
21-2	12.0	0.063	12.000	84.794	-0.50	93.21	92.71	0.01	0.00
22-1	12.4	0.097	12.393	84.828	-0.50	91.95	91.45	3.15	9.90
22-2	15.5	0.080	15.465	84.811	-0.50	92.97	92.47	1.27	1.61
23-1	11.3	0.104	11.267	84.834	-0.50	91.70	91.20	0.10	0.01

ID	ICMV	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	PredDens1	PredDen2	DenDiff	DenDiff^2
24-1	10.5	0.105	10.515	84.836	-0.34	91.74	91.40	0.00	0.00
24-2	14.2	0.085	14.229	84.815	-0.50	92.91	92.41	0.01	0.00
25-1	10.6	0.103	10.600	84.834	-0.50	91.70	91.20	0.10	0.01
25-2	13.3	0.085	13.263	84.816	-0.50	92.97	92.47	0.87	0.76
26-1	10.2	0.112	10.157	84.842	0.04	91.66	91.70	0.00	0.00
26-2	13.5	0.094	13.523	84.825	-0.50	92.88	92.38	0.08	0.01
27-1	11.0	0.113	11.025	84.844	0.25	91.65	91.90	0.00	0.00
27-2	14.0	0.094	13.994	84.825	-0.16	92.86	92.70	0.00	0.00
28-1	11.0	0.113	10.950	84.844	0.05	91.65	91.70	0.00	0.00
28-2	12.9	0.093	12.941	84.823	-0.50	92.84	92.34	0.24	0.06
29-1	11.6	0.119	11.563	84.850	0.28	91.62	91.90	0.00	0.00
29-2	12.3	0.097	12.279	84.828	-0.50	92.83	92.33	0.03	0.00
30-1	11.2	0.119	11.225	84.850	0.11	91.69	91.80	0.00	0.00
30-2	12.0	0.097	12.011	84.828	-0.15	92.85	92.70	0.00	0.00

Florida Site

Sakai breakdown compaction

Model Calibration

ID	Dens	ICMV	Freq	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		Hz	kph	C				%Gmm	%Gmm^2
1-1	92.3	15.7	65.7	8.3	56.2	3.7	0.768	15.748	90.06	5.01
5-2	92.1	23.7	65.8	5.5	47.5	3.1	0.844	23.694	89.73	5.60
10-2	89.4	23.0	65.5	5.6	55.1	2.9	0.895	22.963	89.57	0.03
15-1	89.1	25.8	66.0	8.1	40.7	6.9	0.825	25.783	90.34	1.53
21-1	89.9	23.8	66.3	5.9	59.1	3.8	0.944	23.790	89.87	0.00
25-1	92.1	21.7	66.2	7.3	55.3	3.3	0.872	21.726	89.78	5.39
30-1	91.1	24.4	66.1	6.4	52.7	3.6	0.901	24.406	89.86	1.54
18-1	92.0	31.2	65.9	4.5	55.2	3.8	1.049	31.182	89.74	5.10
28-1	88.8	32.8	55.5	6.8	53.4	2.2	1.065	32.824	88.23	0.33
T1	84.9	12.1	65.7	5.4	77.8	1.0	0.882	12.075	84.57	0.09
T1	87.5	18.1	65.1	5.6	65.1	2.0	0.887	18.073	88.61	1.21
T1	88.5	20.4	65.3	6.1	69.7	3.0	0.968	20.375	89.46	0.86
T1	88.1	20.7	65.2	6.4	61.2	4.0	0.902	20.653	89.98	3.58
T1	89.7	21.5	65.0	7.8	66.1	5.0	0.960	21.523	90.12	0.18

ρ_0	Gmm	α1	α2	α3	α4	β	k1
79.5	90.473	0.019	0	0	0.008	2.069	26

Model Validation

Validation Input

ID	Dens	ICMV	Freq	Speed	Temp	Passes
1-1	92.3	15.7	65.7	8.3	56.2	3.7
1-2	94.0	13.6	65.4	6.4	52.3	4.5
2-1	91.7	13.5	65.5	6.5	57.0	2.6
2-2	92.2	11.7	65.6	6.0	57.8	4.6
3-1	90.2	14.5	65.4	8.4	61.6	3.3
3-2	91.9	13.3	65.4	6.6	58.8	4.6
4-1	91.1	17.3	65.2	8.8	62.9	2.2
4-2	91.9	16.2	54.9	6.3	57.8	4.2
5-1	92.9	20.6	65.6	6.8	53.0	2.4
5-2	92.1	23.7	65.8	5.5	47.5	3.1
6-1	91.3	21.4	65.4	6.4	50.2	3.4
6-2	87.7	26.1	65.7	6.1	45.8	3.3
7-1	89.5	22.4	65.3	6.4	52.2	3.9
7-2	89.1	17.8	65.6	5.6	55.5	2.9
8-1	92.4	16.6	65.4	6.3	55.1	3.8
8-2	90.1	18.5	66.0	5.5	52.9	3.1
9-1	92.3	19.5	65.5	6.5	58.9	3.3
9-2	89.5	22.9	65.7	5.6	53.0	3.3
10-1	92.9	21.6	65.9	6.8	61.1	3.5
10-2	89.4	23.0	65.5	5.6	55.1	2.9
11-1	92.3	13.1	25.9	5.3	38.5	2.3
11-2	89.5	38.3	18.8	5.2	42.6	2.7
12-1	90.4	17.5	66.2	8.7	55.4	3.9
12-2	90.5	18.8	65.6	7.1	58.9	3.4
13-1	89.9	18.2	66.0	7.9	54.8	3.9
13-2	90.7	18.2	66.1	7.4	61.9	3.3
14-1	91.0	23.5	65.8	5.8	51.8	5.0
14-2	91.8	24.2	65.4	6.3	49.2	4.6
15-1	89.1	25.8	66.0	8.1	40.7	6.9
15-2	89.5	29.1	65.6	6.8	40.6	5.6
16-1	90.2	26.3	65.6	4.2	52.7	4.5
16-2	92.3	23.3	66.3	5.5	54.7	7.9
17-1	92.0	28.1	65.9	3.8	56.3	4.4
17-2	94.5	22.0	66.0	7.1	55.4	6.2

ID	Dens	ICMV	Freq	Speed	Temp	Passes
18-1	92.0	31.2	65.9	4.5	55.2	3.8
18-2	92.3	27.6	66.0	5.9	50.4	5.5
19-1	87.6	28.8	66.2	5.3	52.9	3.5
19-2	88.4	35.9	66.3	6.8	47.7	5.9
20-1	90.0	53.8	58.3	6.2	57.5	3.4
20-2	90.1	47.0	60.4	5.5	52.5	6.2
21-1	89.9	23.8	66.3	5.9	59.1	3.8
21-2	90.6	25.4	66.5	5.8	55.3	4.9
22-1	91.1	23.9	66.1	6.2	55.7	2.6
22-2	91.4	26.4	66.1	6.0	50.3	4.2
23-1	89.0	37.7	66.7	5.3	40.2	3.2
23-2	87.3	30.0	66.4	5.5	41.7	4.5
24-1	92.0	24.1	65.8	7.5	51.7	3.6
24-2	91.3	24.0	65.7	6.0	53.9	4.3
25-1	92.1	21.7	66.2	7.3	55.3	3.3
25-2	92.7	23.8	66.1	6.0	56.3	3.5
26-1	90.8	22.1	65.9	7.7	52.9	2.4
26-2	91.7	25.9	66.1	7.2	54.3	4.5
27-1	88.0	30.9	66.0	7.9	44.8	2.3
27-2	88.8	31.5	60.5	7.2	43.3	5.7
28-1	88.8	32.8	55.5	6.8	53.4	2.2
28-2	90.0	27.6	65.1	6.9	53.0	5.0
29-1	90.1	24.9	66.2	5.8	52.6	3.3
29-2	89.6	21.4	66.4	6.8	58.2	4.2
30-1	91.1	24.4	66.1	6.4	52.7	3.6
30-2	90.5	23.0	65.9	6.6	54.8	4.2
T1	79.5	12.1	65.7	5.4	77.8	1.0
T1	84.9	18.1	65.1	5.6	65.1	2.0
T1	87.5	20.4	65.3	6.1	69.7	3.0
T1	88.5	20.7	65.2	6.4	61.2	4.0
T1	88.1	21.5	65.0	7.8	66.1	5.0
T1	89.7	21.3	65.0	6.3	60.3	6.0

Validation Output

ID	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	$\Delta\rho 2$	Pred Dens1	Pred Den2	DenDiff	DenDiff^2
1-1	0.768	15.748	80.259	0.500	0.036	90.06	90.56	-1.74	3.02
1-2	0.695	13.581	80.186	0.500	0.036	90.24	90.74	-3.26	10.60
2-1	0.733	13.510	80.223	0.500	0.073	89.69	90.19	-1.51	2.28
2-2	0.706	11.739	80.197	0.500	0.073	90.25	90.75	-1.45	2.10
3-1	0.790	14.521	80.281	0.288	0.109	89.91	90.20	0.00	0.00
3-2	0.745	13.333	80.235	0.500	0.109	90.22	90.72	-1.18	1.39
4-1	0.854	17.300	80.344	0.500	0.145	89.00	89.50	-1.60	2.56
4-2	0.791	16.241	80.282	0.500	0.145	90.12	90.62	-1.28	1.63
5-1	0.833	20.621	80.323	0.500	0.181	89.35	89.85	-3.05	9.31
5-2	0.844	23.694	80.335	0.500	0.181	89.73	90.23	-1.87	3.48
6-1	0.823	21.374	80.313	0.500	0.218	89.91	90.41	-0.89	0.79
6-2	0.875	26.133	80.365	-0.500	0.218	89.79	89.29	1.59	2.54
7-1	0.860	22.423	80.350	-0.496	0.254	90.00	89.50	0.00	0.00
7-2	0.801	17.812	80.292	-0.500	0.254	89.72	89.22	0.12	0.01
8-1	0.775	16.571	80.265	0.500	0.290	90.07	90.57	-1.83	3.34
8-2	0.792	18.500	80.282	0.248	0.290	89.85	90.10	0.00	0.00
9-1	0.862	19.519	80.352	0.500	0.326	89.81	90.31	-1.99	3.97
9-2	0.875	22.894	80.366	-0.300	0.326	89.80	89.50	0.00	0.00
10-1	0.919	21.612	80.410	0.500	0.363	89.82	90.32	-2.58	6.65
10-2	0.895	22.963	80.385	-0.174	0.363	89.57	89.40	0.00	0.00
11-1	0.569	13.093	80.060	0.500	0.375	89.87	90.37	-1.93	3.72
12-1	0.794	17.470	80.284	0.325	0.388	90.08	90.40	0.00	0.00
12-2	0.849	18.818	80.339	0.500	0.388	89.85	90.35	-0.15	0.02
13-1	0.802	18.188	80.293	-0.159	0.401	90.06	89.90	0.00	0.00
13-2	0.862	18.153	80.352	0.500	0.401	89.80	90.30	-0.40	0.16
14-1	0.877	23.538	80.368	0.500	0.414	90.18	90.68	-0.32	0.10
14-2	0.867	24.174	80.358	0.500	0.414	90.14	90.64	-1.16	1.35
15-1	0.825	25.783	80.316	-0.500	0.544	90.34	89.84	0.74	0.54
15-2	0.887	29.113	80.378	-0.500	0.544	90.23	89.73	0.23	0.05
16-1	0.936	26.285	80.426	0.145	0.580	90.06	90.20	0.00	0.00
16-2	0.898	23.333	80.389	0.500	0.580	90.35	90.85	-1.45	2.09
17-1	1.000	28.120	80.491	0.500	0.616	89.97	90.47	-1.53	2.33
17-2	0.879	22.046	80.370	0.500	0.616	90.28	90.78	-3.72	13.84
18-1	1.049	31.182	80.540	0.500	0.653	89.74	90.24	-1.76	3.09
18-2	0.941	27.588	80.432	0.500	0.653	90.19	90.69	-1.61	2.59

ID	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	$\Delta\rho2$	Pred Dens1	Pred Den2	DenDiff	DenDiff^2
19-1	0.985	28.794	80.475	-0.500	0.689	89.71	89.21	1.61	2.60
21-1	0.944	23.790	80.434	0.033	0.761	89.87	89.90	0.00	0.00
21-2	0.941	25.366	80.431	0.476	0.761	90.12	90.60	0.00	0.00
22-1	0.917	23.936	80.408	0.500	0.810	89.31	89.81	-1.29	1.67
22-2	0.919	26.444	80.409	0.500	0.810	90.01	90.51	-0.89	0.78
23-2	0.912	29.953	80.403	-0.500	0.858	90.08	89.58	2.28	5.18
24-1	0.886	24.071	80.377	0.500	0.906	89.88	90.38	-1.62	2.63
24-2	0.903	23.967	80.393	0.500	0.906	90.05	90.55	-0.75	0.56
25-1	0.872	21.726	80.363	0.500	0.906	89.78	90.28	-1.82	3.32
25-2	0.919	23.776	80.410	0.500	0.906	89.82	90.32	-2.38	5.69
26-1	0.860	22.135	80.351	0.500	0.943	89.25	89.75	-1.05	1.11
26-2	0.943	25.940	80.433	0.500	0.943	90.04	90.54	-1.16	1.34
27-1	0.956	30.882	80.446	-0.500	0.979	88.85	88.35	0.35	0.12
27-2	0.955	31.508	80.445	-0.500	0.979	90.20	89.70	0.90	0.81
28-1	1.065	32.824	80.555	0.500	1.015	88.23	88.73	-0.07	0.01
28-2	0.963	27.591	80.453	-0.120	1.015	90.12	90.00	0.00	0.00
29-1	0.910	24.944	80.400	0.359	1.051	89.74	90.10	0.00	0.00
29-2	0.891	21.431	80.382	-0.431	1.051	90.03	89.60	0.00	0.00
30-1	0.901	24.406	80.391	0.500	1.088	89.86	90.36	-0.74	0.55
30-2	0.891	22.955	80.382	0.473	1.088	90.03	90.50	0.00	0.00
T1	0.882	12.075	80.372	-0.500	-1.000	84.57	84.07	4.58	20.99
T1	0.887	18.073	80.377	-0.500	-1.000	88.61	88.11	3.23	10.43
T1	0.968	20.375	80.459	-0.500	-1.000	89.46	88.96	1.45	2.11
T1	0.902	20.653	80.392	-0.500	-1.000	89.98	89.48	0.94	0.89
T1	0.960	21.523	80.451	-0.500	-1.000	90.12	89.62	1.53	2.34
T1	0.906	21.267	80.397	-0.500	-0.565	90.26	89.76	0.06	0.00

Ohio Site

Sakai breakdown compaction

Model Calibration

ID	Dens	ICMV	Freq	Passes	Speed	Temp	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		Hz		kph	C			%Gmm	%Gmm^2
L4	86.5	25.5	64.4	2.3	9.4	78.2	0.645	25.486	90.45	15.49
L10	91.8	16.1	64.6	2.3	9.1	84.2	0.445	16.149	91.55	0.05
L16	89.2	16.2	64.7	2.1	9.2	82.8	0.446	16.191	91.33	4.37
L22	91.9	18.5	64.2	2.1	10.9	84.3	0.495	18.497	90.97	0.90
L28	93.3	17.8	64.2	2.2	9.7	89.4	0.480	17.831	91.14	4.51
R5	90.6	15.9	64.6	2.8	9.5	90.3	0.440	15.931	92.10	2.31
R10	92.2	11.2	64.4	2.4	9.7	95.9	0.339	11.218	92.43	0.06
R16	91.0	14.8	64.7	2.1	10.2	86.3	0.417	14.837	91.45	0.17
R22	92.4	17.4	64.0	2.9	9.2	90.8	0.471	17.406	92.10	0.11
R28	93.8	11.8	46.4	3.1	10.6	96.9	0.323	11.750	93.20	0.37
T1	89.5	13.5	64.5	1.0	8.5	98.5	0.388	13.494	89.29	0.03
T1	90.4	24.4	64.6	2.0	9.8	86.3	0.621	24.362	90.05	0.14
T2	89.3	11.8	64.2	1.0	8.9	98.2	0.350	11.773	89.64	0.11
T2	89.7	17.4	64.5	2.0	9.0	88.5	0.472	17.400	90.94	1.43
T3	88.3	11.8	64.2	1.0	8.9	98.2	0.350	11.760	89.64	1.87
T3	90.6	17.4	64.5	2.0	9.0	88.5	0.472	17.400	90.94	0.12
T4	91.9	10.1	64.1	1.0	10.2	88.6	0.315	10.134	90.00	3.77
T4	92.5	24.4	64.5	2.0	9.8	82.0	0.622	24.429	90.04	6.28
T4	93.8	22.0	64.6	3.0	9.8	78.9	0.571	22.025	91.60	5.04

ρ_0	Gmm	k1	$\alpha1$	$\alpha2$	$\alpha3$	$\alpha4$	β	Tr
78	99	26	0.0215	0.0015	0	1E-05	0.5018	80

Model Validation

Validation Input

ID	Dens	ICMV	Freq	Passes	Speed	Temp
L1	89.3	21.2	64.3	2.0	8.9	81.1
L2	91.7	20.2	64.2	2.0	9.2	80.4
L3	91.8		38.0	3.1	11.2	80.8
L4	86.5	25.5	64.4	2.3	9.4	78.2
L5	91.7	19.1	64.4	2.0	9.4	85.0
L6	92.3	19.9	64.6	2.0	9.4	88.5
L7	93.4	18.7	64.7	2.2	10.0	85.8
L8	90.2	19.0	64.7	2.1	9.2	74.4
L9	89.1	19.8	64.7	2.3	9.1	80.5
L10	91.8	16.1	64.6	2.3	9.1	84.2
L11	92.5	18.5	64.6	2.2	9.4	86.2
L12	92.0	18.8	64.7	4.0	10.2	78.9
L13	91.5	18.2	64.1	2.1	10.5	80.8
L14	89.2	17.6	63.9	2.2	10.6	74.2
L15	92.2		20.1	3.0	11.5	81.3
L16	89.2	16.2	64.7	2.1	9.2	82.8
L17	90.5	17.1	64.4	2.1	9.3	84.9
L18	91.7	17.4	64.6	2.2	9.8	90.4
L19	92.8	19.4	64.1	2.6	9.4	84.2
L20	89.7	15.7	64.5	2.2	8.9	78.0
L21	89.4	15.7	64.8	2.1	10.0	82.3
L22	91.9	18.5	64.2	2.1	10.9	84.3
L23	91.9	16.4	64.6	2.0	9.8	91.5
L24	92.4	15.2	62.5	2.9	10.4	83.5
L25	90.1	11.4	64.8	2.5	9.5	85.9
L26	91.2	15.5	64.6	2.4	9.8	83.2
L27	91.6	18.8	65.1	2.2	9.6	84.3
L28	93.3	17.8	64.2	2.2	9.7	89.4
L29	93.4	18.9	63.2	3.5	10.4	81.9
L30	92.5	13.6	64.9	2.3	9.8	84.0
R1	89.9	15.3	64.5	2.8	9.0	88.1
R2	92.3		38.4	3.4	10.0	80.6
R3	93.5	23.0	64.2	4.5	10.0	75.5
R4	92.5		59.9	4.1	9.3	76.3
R5	90.6	15.9	64.6	2.8	9.5	90.3

ID	Dens	ICMV	Freq	Passes	Speed	Temp
R6	92.5	15.8	64.7	2.8	9.7	94.8
R7	93.4	15.7	63.7	2.8	9.6	96.6
R8	94.4	13.9	64.9	3.0	10.1	92.1
R9	90.3	12.9	65.0	2.7	10.0	88.2
R10	92.2	11.2	64.4	2.4	9.7	95.9
R11	93.1		60.4	3.6	9.7	79.9
R12	93.4	14.8	64.0	4.3	10.7	83.6
R13	92.0	15.9	64.4	2.9	10.1	89.9
R14	91.2	17.4	64.5	2.1	8.7	82.1
R15	92.0	17.6	55.2	2.2	10.6	92.7
R16	91.0	14.8	64.7	2.1	10.2	86.3
R17	90.9	16.0	64.6	2.6	9.7	93.4
R18	91.6	15.9	64.3	2.9	9.4	93.1
R19	92.9	18.4	64.3	2.8	9.6	90.3
R20	94.0		52.0	5.1	9.2	85.0
R21	92.0	16.9	64.9	2.9	9.2	85.0
R22	92.4	17.4	64.0	2.9	9.2	90.8
R23	92.1	17.7	64.4	3.0	9.4	98.6
R24	93.5		49.2	3.9	11.5	80.4
R25	92.6	15.5	64.4	2.9	11.6	90.6
R26	91.8	17.4	65.0	2.9	9.9	90.4
R27	91.9	17.9	64.5	3.0	10.0	91.8
R28	93.8	11.8	46.4	3.1	10.6	96.9
R29	93.7	13.9	64.6	3.5	11.7	89.1
R30	93.6	15.5	64.5	2.8	10.3	87.8
T1	89.5	13.5	64.5	1.0	8.5	98.5
T1	90.4	24.4	64.6	2.0	9.8	86.3
T2	89.3	11.8	64.2	1.0	8.9	98.2
T2	89.7	17.4	64.5	2.0	9.0	88.5
T3	88.3	11.8	64.2	1.0	8.9	98.2
T3	90.6	17.4	64.5	2.0	9.0	88.5
T4	91.9	10.1	64.1	1.0	10.2	88.6
T4	92.5	24.4	64.5	2.0	9.8	82.0
T4	93.8	22.0	64.6	3.0	9.8	78.9

Validation Output

ID	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	PredDens1	PredDen2	DenDiff	DenDiff2^2
L1	0.551	21.169	78.551	-1.000	90.44	89.44	1.09	0.01
L2	0.531	20.213	78.531	1.000	90.56	91.56	-1.13	0.02
L4	0.644	25.486	78.644	-1.000	90.45	89.45	3.93	8.60
L5	0.508	19.130	78.508	0.953	90.75	91.70	-0.95	0.00
L6	0.525	19.911	78.525	1.000	90.64	91.64	-1.61	0.37
L7	0.498	18.677	78.498	1.000	91.02	92.02	-2.43	2.03
L8	0.506	19.019	78.506	-0.714	90.88	90.17	0.71	0.00
L9	0.522	19.797	78.522	-1.000	91.00	90.00	1.86	0.74
L10	0.444	16.149	78.444	0.220	91.55	91.77	-0.22	0.00
L11	0.495	18.511	78.495	1.000	91.05	92.05	-1.41	0.17
L12	0.502	18.843	78.502	-0.704	92.74	92.03	0.70	0.00
L13	0.487	18.175	78.487	0.431	91.05	91.48	-0.43	0.00
L14	0.474	17.606	78.474	-1.000	91.25	90.25	2.01	1.03
L16	0.445	16.191	78.445	-1.000	91.33	90.33	2.09	1.18
L17	0.463	17.060	78.463	-0.712	91.17	90.45	0.71	0.00
L18	0.471	17.423	78.471	0.473	91.24	91.71	-0.47	0.00
L19	0.513	19.394	78.513	1.000	91.49	92.49	-1.30	0.09
L20	0.434	15.714	78.434	-1.000	91.48	90.48	1.76	0.58
L21	0.435	15.731	78.435	-1.000	91.32	90.32	1.92	0.85
L22	0.494	18.497	78.494	0.944	90.97	91.92	-0.94	0.00
L23	0.449	16.389	78.449	0.805	91.14	91.94	-0.80	0.00
L24	0.421	15.211	78.421	0.012	92.38	92.39	-0.01	0.00
L25	0.343	11.444	78.343	-1.000	92.49	91.49	2.42	2.02
L26	0.430	15.497	78.430	-0.546	91.71	91.16	0.55	0.00
L27	0.501	18.756	78.501	0.526	91.04	91.57	-0.53	0.00
L28	0.479	17.831	78.479	1.000	91.14	92.14	-2.13	1.27
L29	0.500	18.851	78.500	0.965	92.40	93.36	-0.96	0.00
L30	0.390	13.636	78.390	0.626	91.89	92.52	-0.63	0.00
R1	0.426	15.328	78.426	-1.000	92.22	91.22	2.27	1.61
R3	0.591	23.020	78.591	0.836	92.66	93.50	-0.84	0.00
R5	0.439	15.931	78.439	-1.000	92.10	91.10	1.52	0.27
R6	0.437	15.811	78.437	0.348	92.17	92.52	-0.35	0.00
R7	0.433	15.681	78.433	1.000	92.14	93.14	-1.24	0.06
R8	0.396	13.882	78.396	1.000	92.62	93.62	-1.78	0.61
R9	0.374	12.850	78.374	-1.000	92.47	91.47	2.16	1.34
R10	0.338	11.218	78.338	-0.238	92.43	92.19	0.24	0.00
R12	0.414	14.783	78.414	0.000	93.44	93.44	0.03	0.00

ID	ρ_L	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	PredDens1	PredDen2	DenDiff	DenDiff2^2
R13	0.438	15.897	78.438	0.000	92.22	92.22	0.18	0.03
R14	0.471	17.422	78.471	0.000	91.04	91.04	-0.20	0.04
R15	0.461	17.626	78.461	0.000	91.34	91.34	-0.63	0.39
R16	0.416	14.837	78.416	0.000	91.45	91.45	0.42	0.17
R17	0.442	16.031	78.442	0.000	91.89	91.89	1.02	1.04
R18	0.438	15.883	78.438	0.000	92.27	92.27	0.69	0.48
R19	0.491	18.366	78.491	0.000	91.81	91.81	-1.11	1.23
R21	0.461	16.919	78.461	0.000	92.12	92.12	0.16	0.02
R22	0.470	17.406	78.470	0.000	92.10	92.10	-0.33	0.11
R23	0.476	17.675	78.476	0.000	92.12	92.12	0.06	0.00
R25	0.429	15.483	78.429	0.000	92.32	92.32	-0.32	0.10
R26	0.472	17.406	78.472	0.000	92.09	92.09	0.28	0.08
R27	0.481	17.874	78.481	0.000	92.09	92.09	0.22	0.05
R28	0.322	11.750	78.322	0.000	93.20	93.20	-0.61	0.37
R29	0.396	13.903	78.396	0.000	93.03	93.03	-0.70	0.49
R30	0.431	15.549	78.431	0.000	92.18	92.18	-1.43	2.05
T1	0.387	13.494	78.387	0.000	89.29	89.29	-0.18	0.03
T1	0.620	24.362	78.620	0.000	90.05	90.05	-0.37	0.14
T2	0.349	11.773	78.349	0.000	89.64	89.64	0.33	0.11
T2	0.471	17.400	78.471	0.000	90.94	90.94	1.20	1.43
T3	0.349	11.760	78.349	0.000	89.64	89.64	1.37	1.88
T3	0.471	17.400	78.471	0.000	90.94	90.94	0.34	0.12
T4	0.314	10.134	78.314	0.000	90.00	90.00	-1.94	3.77
T4	0.622	24.429	78.622	0.000	90.04	90.04	-2.51	6.28
T4	0.570	22.025	78.570	0.000	91.60	91.60	-2.24	5.04

Maine Site

Hamm breakdown compaction

Model Calibration

ID	Dens	ICMV	Freq	Speed	Temp	Passes	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		Hz	mph	C			%Gmm	%Gmm^2
4L	94.9	43.0	67.0	2.5	98.9	7.7	42.971	93.43	2.16
10L	95.7	34.8	67.0	3.0	93.1	5.1	34.824	92.40	10.89
16L	95.1	20.1	49.0	2.9	78.5	11.4	20.143	94.91	0.04
21L	93.4	18.7	42.7	2.9	72.9	11.1	18.676	95.01	2.58
26L	93.1	40.0	67.0	3.0	96.6	6.0	40.000	92.81	0.09
29R	95.5	35.1	67.0	3.0	74.3	13.5	35.147	95.33	0.03
24R	94.0	28.9	67.0	2.9	84.1	9.6	28.889	94.40	0.16
18R	94.3	39.6	67.0	2.9	83.4	9.7	39.600	94.44	0.02
13R	94.2	44.9	67.0	2.8	83.5	7.2	44.857	93.70	0.25
7R	95.7	42.8	67.0	3.0	80.4	8.7	42.800	94.27	2.03
T5	86.0	28.9	67.0	2.4	112.8	1.0	28.908	85.35	0.44
T5	87.4	42.5	67.0	3.1	112.7	2.0	42.500	88.27	0.70
T5	89.8	36.7	67.0	3.1	111.7	3.0	36.724	89.94	0.03
T5	90.0	46.1	67.0	3.0	106.8	4.0	46.108	91.17	1.27
T5	91.4	42.3	67.0	3.0	105.8	5.0	42.294	91.96	0.26
T5	91.7	44.9	64.7	2.9	102.2	6.0	44.889	92.64	0.83
T5	91.8	40.5	65.3	3.0	101.9	7.0	40.522	93.10	1.67
T5	92.7	46.7	61.6	2.8	97.5	8.0	46.659	93.58	0.87

ρ_0	Gmm	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$	β
80.1	98.521	0	0	0	0.0128	0.6257

Model Validation

Validation Input

ID	Dens	ICMV	Freq	Speed	Temp	Passes
3R	94.3	65.7	67.0	2.9	89.7	7.4
4L	94.9	43.0	67.0	2.5	98.9	7.7
1L	96.7	41.6	66.9	2.9	77.4	18.3
1R	95.8	50.2	66.5	2.9	78.5	12.3
2L	96.3	33.0	67.0	3.1	78.0	14.1
30L	93.6	28.9	67.0	2.9	85.0	8.2
2R	95.2	63.3	67.0	2.9	82.9	10.3
29R	95.5	35.1	67.0	3.0	74.3	13.5
3L	93.1	44.7	67.0	3.0	92.4	8.7
29L	94.9	28.9	67.0	2.9	74.5	13.3
28R	95.6	16.8	55.4	2.9	70.2	18.5
30R	94.3	36.8	67.0	2.8	83.9	8.1
28L	94.7	23.8	59.6	3.0	73.6	12.8
27R	94.5	25.1	46.6	3.0	80.7	9.5
27L	94.0	31.6	50.8	3.0	84.5	8.4
26R	94.2	30.9	67.0	2.9	91.3	9.5
26L	93.1	40.0	67.0	3.0	96.6	6.0
25R	94.7	30.9	67.0	2.8	88.3	9.7
25L	92.4	38.4	67.0	2.9	90.2	6.5
24R	94.0	28.9	67.0	2.9	84.1	9.6
24L	92.9	41.3	67.0	3.0	81.4	7.1
23R	94.8	24.3	67.0	3.1	77.4	15.2
23L	94.3	30.4	67.0	3.1	79.3	11.1
22R	95.0	24.2	67.0	2.8	76.4	17.6
22L	94.3	28.9	67.0	3.0	75.5	13.0
21R	94.1	16.5	42.1	2.3	70.8	16.8
21L	93.4	18.7	42.7	2.9	72.9	11.1
20R	93.6	40.3	67.0	2.9	93.8	8.4
20L	92.6	31.4	67.0	2.8	94.6	7.7
19R	94.4	42.7	67.0	2.9	89.2	7.8
19L	93.8	28.4	67.0	2.8	87.4	8.1
18R	94.3	39.6	67.0	2.9	83.4	9.7
18L	94.8	28.2	67.0	2.7	85.3	11.5

ID	Dens	ICMV	Freq	Speed	Temp	Passes
17R	95.8	31.9	67.0	2.8	72.5	17.5
17L	95.4	24.0	67.0	2.9	73.3	12.8
16R	95.5	23.0	47.1	2.8	72.7	15.4
16L	95.1	20.1	49.0	2.9	78.5	11.4
15R	94.4	45.1	67.0	2.9	91.4	8.7
15L	94.3	36.2	67.0	2.9	91.5	7.8
14R	95.2	43.2	67.0	2.9	87.7	7.7
14L	94.6	31.3	67.0	2.9	89.3	6.9
13R	94.2	44.9	67.0	2.8	83.5	7.2
13L	94.1	30.5	67.0	2.6	83.9	7.1
12R	95.9	34.8	67.0	2.7	79.4	14.0
12L	95.9	27.1	67.0	2.6	81.2	13.0
11R	96.0	15.9	47.9	3.1	66.8	14.6
11L	95.5	18.2	47.5	3.1	74.2	11.1
10R	95.6	47.1	67.0	2.9	91.5	5.4
10L	95.7	34.8	67.0	3.0	93.1	5.1
9R	95.3	43.6	67.0	3.0	90.5	5.1
9L	94.5	33.6	67.0	3.1	89.3	5.5
8R	94.7	46.8	67.0	3.0	86.4	4.4
4R	95.3	59.4	67.0	2.9	96.7	7.3
5L	95.0	6.3	37.1	3.0	73.5	10.9
5R	95.8	0.0	32.9	3.0	66.1	15.1
6L	95.3	31.8	67.0	3.1	73.1	12.7
6R	96.1	40.0	67.0	3.0	72.1	12.5
7L	96.0	26.1	67.0	3.1	83.4	10.6
7R	95.7	42.8	67.0	3.0	80.4	8.7
8L	94.2	32.8	67.0	3.1	87.0	5.3
T5	86.0	28.9	67.0	2.4	112.8	1.0
T5	87.4	42.5	67.0	3.1	112.7	2.0
T5	89.8	36.7	67.0	3.1	111.7	3.0
T5	90.0	46.1	67.0	3.0	106.8	4.0
T5	91.4	42.3	67.0	3.0	105.8	5.0
T5	91.7	44.9	64.7	2.9	102.2	6.0
T5	91.8	40.5	65.3	3.0	101.9	7.0
T5	92.7	46.7	61.6	2.8	97.5	8.0

Validation Output

ID	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	$\Delta\rho2$	PredDens1	PredDen2	DenDiff	DenDiff^2
3R	50.000	80.100	0.000	0.000	93.59	93.59	-0.71	0.50
4L	42.971	80.100	0.000	0.000	93.43	93.43	-1.47	2.16
1L	41.629	80.100	0.000	0.000	95.78	95.78	-0.92	0.84
1R	50.000	80.100	0.000	0.000	95.07	95.07	-0.73	0.54
2L	32.972	80.100	0.000	0.000	95.33	95.33	-0.97	0.94
30L	28.886	80.100	0.000	0.000	93.99	93.99	0.39	0.15
2R	50.000	80.100	0.000	0.000	94.57	94.57	-0.63	0.39
29R	35.147	80.100	0.000	0.000	95.33	95.33	-0.17	0.03
3L	44.686	80.100	0.000	0.000	93.94	93.94	0.84	0.71
29L	28.943	80.100	0.000	0.000	95.31	95.31	0.41	0.17
28R	16.784	80.100	0.000	0.000	95.95	95.95	0.35	0.12
30R	36.750	80.100	0.000	0.000	93.99	93.99	-0.31	0.10
28L	23.750	80.100	0.000	0.000	95.25	95.25	0.55	0.30
27R	25.071	80.100	0.000	0.000	94.46	94.46	-0.04	0.00
27L	31.556	80.100	0.000	0.000	94.07	94.07	0.07	0.01
26R	30.944	80.100	0.000	0.000	94.19	94.19	-0.01	0.00
26L	40.000	80.100	0.000	0.000	92.81	92.81	-0.29	0.09
25R	30.909	80.100	0.000	0.000	94.30	94.30	-0.40	0.16
25L	38.361	80.100	0.000	0.000	93.23	93.23	0.83	0.69
24R	28.889	80.100	0.000	0.000	94.40	94.40	0.40	0.16
24L	41.257	80.100	0.000	0.000	93.74	93.74	0.84	0.70
23R	24.344	80.100	0.000	0.000	95.48	95.48	0.68	0.46
23L	30.444	80.100	0.000	0.000	94.84	94.84	0.54	0.29
22R	24.171	80.100	0.000	0.000	95.74	95.74	0.74	0.55
22L	28.886	80.100	0.000	0.000	95.24	95.24	0.94	0.88
21R	16.457	80.100	0.000	0.000	95.79	95.79	1.69	2.85
21L	18.676	80.100	0.000	0.000	95.01	95.01	1.61	2.58
20R	40.343	80.100	0.000	0.000	93.81	93.81	0.21	0.04
20L	31.429	80.100	0.000	0.000	93.55	93.55	0.95	0.90
19R	42.667	80.100	0.000	0.000	93.75	93.75	-0.65	0.42
19L	28.412	80.100	0.000	0.000	93.88	93.88	0.08	0.01
18R	39.600	80.100	0.000	0.000	94.44	94.44	0.14	0.02
18L	28.200	80.100	0.000	0.000	94.76	94.76	-0.04	0.00
17R	31.906	80.100	0.000	0.000	95.82	95.82	0.02	0.00
17L	23.971	80.100	0.000	0.000	95.26	95.26	-0.14	0.02
16R	23.029	80.100	0.000	0.000	95.61	95.61	0.11	0.01
16L	20.143	80.100	0.000	0.000	94.91	94.91	-0.19	0.04

ID	kk1/ (k1-k)	$\rho_0+\rho_L$	$\Delta\rho$	$\Delta\rho 2$	PredDens1	PredDen2	DenDiff	DenDiff^2
15R	45.083	80.100	0.000	0.000	93.96	93.96	-0.44	0.19
15L	36.188	80.100	0.000	0.000	93.67	93.67	-0.63	0.40
14R	43.235	80.100	0.000	0.000	93.75	93.75	-1.45	2.10
14L	31.286	80.100	0.000	0.000	93.43	93.43	-1.17	1.37
13R	44.857	80.100	0.000	0.000	93.70	93.70	-0.50	0.25
13L	30.514	80.100	0.000	0.000	93.68	93.68	-0.42	0.18
12R	34.750	80.100	0.000	0.000	95.29	95.29	-0.61	0.38
12L	27.094	80.100	0.000	0.000	95.11	95.11	-0.79	0.63
11R	15.939	80.100	0.000	0.000	95.66	95.66	-0.34	0.12
11L	18.229	80.100	0.000	0.000	94.96	94.96	-0.54	0.29
10R	47.129	80.100	0.000	0.000	92.64	92.64	-2.96	8.78
10L	34.824	80.100	0.000	0.000	92.40	92.40	-3.30	10.89
9R	43.625	80.100	0.000	0.000	92.53	92.53	-2.77	7.68
9L	33.600	80.100	0.000	0.000	92.76	92.76	-1.74	3.03
8R	46.818	80.100	0.000	0.000	92.21	92.21	-2.49	6.18
4R	50.000	80.100	0.000	0.000	93.34	93.34	-1.96	3.84
5L	6.324	80.100	0.000	0.000	94.95	94.95	-0.05	0.00
5R	0.000	80.100	0.000	0.000	95.73	95.73	-0.07	0.00
6L	31.771	80.100	0.000	0.000	95.25	95.25	-0.05	0.00
6R	40.029	80.100	0.000	0.000	95.25	95.25	-0.85	0.73
7L	26.063	80.100	0.000	0.000	94.63	94.63	-1.37	1.88
7R	42.800	80.100	0.000	0.000	94.27	94.27	-1.43	2.03
8L	32.833	80.100	0.000	0.000	92.74	92.74	-1.46	2.14
T5	28.908	80.100	0.000	0.000	85.35	85.35	-0.66	0.44
T5	42.500	80.100	0.000	0.000	88.27	88.27	0.84	0.70
T5	36.724	80.100	0.000	0.000	89.94	89.94	0.18	0.03
T5	46.108	80.100	0.000	0.000	91.17	91.17	1.13	1.27
T5	42.294	80.100	0.000	0.000	91.96	91.96	0.51	0.26
T5	44.889	80.100	0.000	0.000	92.64	92.64	0.91	0.83
T5	40.522	80.100	0.000	0.000	93.10	93.10	1.29	1.67
T5	46.659	80.100	0.000	0.000	93.58	93.58	0.93	0.87

California Site

BOMAG intermediate compaction

Model Calibration

ID	Dens	ICMV	Amp	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		mm	kph	C		□		%Gmm	%Gmm^2
1L	95.7	221.8	0.5	5.4	88.2	2.5	0.268	221.772	92.50	10.22
1R	95.9	225.8	0.6	5.0	83.2	2.6	0.252	225.756	92.61	10.80
10L	94.9	207.5	0.6	6.1	86.0	2.7	0.304	207.546	92.42	6.15
11R	95.8	184.8	0.7	6.3	89.2	2.5	0.315	184.750	92.26	12.50
12L	94.3	231.6	0.6	6.3	88.9	2.3	0.316	231.629	92.09	4.90
13R	94.8	89.8	0.5	6.8	83.6	3.4	0.342	89.797	92.56	5.00
14L	93.9	198.5	0.6	5.3	86.2	2.1	0.264	198.521	92.27	2.65
15R	95.7	201.4	0.6	4.9	85.8	2.5	0.247	201.430	92.58	9.74
16L	94.1	214.3	0.6	5.3	87.8	2.5	0.266	214.329	92.47	2.64
17R	95.7	214.3	0.6	4.9	85.7	2.6	0.246	214.279	92.63	9.45
18L	94.9	229.0	0.5	6.5	82.4	4.1	0.325	229.026	92.81	4.38
19R	95.6	258.2	0.5	6.1	82.0	2.7	0.304	258.182	92.43	10.07
20L	94.5	189.3	0.6	6.5	85.5	2.5	0.328	189.308	92.15	5.51
T3	91.6	211.2	50.0	4.0	88.9	1.0	0.199	211.188	91.01	0.33
T3	92.7	221.7	50.1	4.4	86.8	2.0	0.219	221.650	92.46	0.06
T3	93.1	225.4	50.2	4.9	84.4	3.0	0.244	225.370	92.78	0.08
T3	92.4	221.2	50.2	5.3	87.2	4.0	0.264	221.200	92.93	0.26
T3	92.8	224.5	50.1	4.9	83.5	5.0	0.2454	224.5	93.06	0.07

ρ_0	Gmm	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$	β
52.21723	93.2484	0	0	0.050076	0	1.781557

Model Validation

Validation Input

ID	Dens	ICMV	Amp	Speed	Temp	Passes
1L	95.7	221.8	0.5	5.4	88.2	2.5
1R	95.9	225.8	0.6	5.0	83.2	2.6
10L	94.9	207.5	0.6	6.1	86.0	2.7
11R	95.8	184.8	0.7	6.3	89.2	2.5
12L	94.3	231.6	0.6	6.3	88.9	2.3
13R	94.8	89.8	0.5	6.8	83.6	3.4
14L	93.9	198.5	0.6	5.3	86.2	2.1
15R	95.7	201.4	0.6	4.9	85.8	2.5
16L	94.1	214.3	0.6	5.3	87.8	2.5
17R	95.7	214.3	0.6	4.9	85.7	2.6
18L	94.9	229.0	0.5	6.5	82.4	4.1
19R	95.6	258.2	0.5	6.1	82.0	2.7
20L	94.5	189.3	0.6	6.5	85.5	2.5
21R	94.7	189.8	0.7	6.1	86.0	2.8
22L	93.4	201.6	0.6	6.6	80.1	2.2
23R	95.7	212.4	0.6	5.3	80.0	2.8
24L	93.5	221.2	0.6	6.6	86.0	2.4
25R	96.2	194.1	0.7	5.3	86.0	2.9
26L	95.0	176.8	0.6	6.6	94.0	2.1
27R	95.9	102.9	0.7	5.3	90.4	2.9
28L	94.1	199.3	0.6	6.5	98.0	2.1
29R	95.9	44.8	0.5	7.2	82.0	4.1
2L	94.1	224.7	0.5	5.4	86.3	2.5
2R	95.4	177.3	0.6	4.9	85.4	2.6
30L	95.2	197.9	0.6	6.6	90.8	3.4

ID	Dens	ICMV	Amp	Speed	Temp	Passes
3L	93.1	226.5	0.6	4.9	83.7	2.5
3R	94.9	224.5	0.5	5.4	88.0	2.5
4L	94.7	203.3	0.6	5.1	91.0	2.7
4R	95.5	209.0	0.6	4.9	91.2	2.5
5L	93.6	224.0	0.5	5.1	85.5	2.5
5R	95.5	194.6	0.6	5.0	90.8	2.5
6L	94.9	220.1	0.6	5.3	96.0	2.5
7R	95.2	226.6	0.4	3.1	75.8	4.0
8L	94.2	211.7	0.6	6.1	87.2	2.3
9R	96.0	218.6	0.6	5.9	87.0	2.4
T3	91.6	221.2	0.6	5.3	87.2	4.0
T3	92.7	224.5	0.6	4.9	83.5	5.0

Validation Output

ID	ρ_L	kk1/(k1-k)	$\Delta\rho$	$\Delta\rho2$	PredDens1	PredDen2	DenDiff	DenDiff^2
1L	0.304	221.772	0.500	0.036	92.50	93.00	-1.90	3.60
1R	0.315	225.756	0.500	0.036	92.61	93.11	-2.69	7.22
10L	0.316	207.546	0.500	0.073	92.42	92.92	-1.38	1.90
11R	0.342	184.750	0.500	0.073	92.26	92.76	-2.04	4.14
12L	0.264	231.629	0.288	0.109	92.09	92.37	-1.53	2.33
13R	0.247	100.000	0.500	0.109	92.56	93.06	-2.64	6.95
14L	0.266	198.521	0.500	0.145	92.27	92.77	-1.33	1.76
15R	0.246	201.430	0.500	0.145	92.58	93.08	-2.62	6.87
16L	0.325	214.329	0.500	0.181	92.47	92.97	-1.93	3.71
17R	0.304	214.279	0.500	0.181	92.63	93.13	-2.47	6.12
18L	0.268	229.026	0.500	0.218	92.81	93.31	-2.39	5.72
19R	0.252	258.182	-0.500	0.218	92.43	91.93	-3.97	15.79
20L	0.328	189.308	-0.496	0.254	92.15	91.66	-2.84	8.08
21R	0.307	189.818	-0.500	0.254	92.45	91.95	-2.75	7.55
22L	0.328	201.644	0.500	0.290	91.94	92.44	-0.96	0.93
23R	0.263	212.430	0.248	0.290	92.66	92.91	-2.79	7.80
24L	0.330	221.203	0.500	0.326	92.06	92.56	-0.94	0.88
25R	0.264	194.128	-0.300	0.326	92.67	92.37	-3.83	14.64
26L	0.330	176.800	0.500	0.363	91.80	92.30	-2.70	7.31
27R	0.264	102.949	-0.174	0.363	92.69	92.51	-3.39	11.47
28L	0.325	199.347	0.500	0.375	91.78	92.28	-1.82	3.33
29R	0.360	100.000	0.500	0.375	92.72	93.22	-2.68	7.19
2L	0.269	224.671	0.325	0.388	92.49	92.82	-1.28	1.65
2R	0.244	177.263	0.500	0.388	92.65	93.15	-2.25	5.06
30L	0.330	197.865	-0.159	0.401	92.62	92.46	-2.74	7.50
3L	0.246	226.507	0.500	0.401	92.61	93.11	0.01	0.00
3R	0.269	224.500	0.500	0.414	92.49	92.99	-1.91	3.66
4L	0.255	203.313	0.500	0.414	92.62	93.12	-1.58	2.50
4R	0.246	209.026	-0.500	0.544	92.61	92.11	-3.39	11.51
5L	0.255	224.038	-0.500	0.544	92.54	92.04	-1.56	2.44
5R	0.250	194.610	0.145	0.580	92.59	92.74	-2.76	7.64
6L	0.267	220.114	0.500	0.580	92.49	92.99	-1.91	3.65
7R	0.154	226.641	0.500	0.616	93.12	93.62	-1.58	2.48
8L	0.305	211.730	0.500	0.616	92.13	92.63	-1.57	2.48
9R	0.295	218.571	0.500	0.653	92.30	92.80	-3.20	10.23
T3	0.264	221.200	0.500	0.653	92.93	93.43	1.85	3.40
T3	0.245	224.500	-0.500	0.689	93.06	92.56	-0.14	0.02

Idaho Site

Hamm breakdown compaction

Model Calibration

ID	Dens	ICMV	Amp	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		in.	mph	F		□			
01L	90.1	26.3	0.5	4.5	108.5	2.3	0.196	26.343	91.48	1.90
05L	90.2	25.7	0.5	4.1	115.8	1.6	0.195	25.703	90.07	0.02
10L	92.1	29.7	0.5	3.9	120.4	2.2	0.197	29.735	91.31	0.62
15L	92.3	32.7	0.5	3.8	122.8	2.4	0.199	32.657	91.63	0.45
20L	92.1	28.4	0.5	3.7	122.4	2.1	0.196	28.353	91.18	0.85
25L	91.3	31.4	0.5	3.8	118.2	2.9	0.198	31.400	92.25	0.90
30L	92.5	34.8	0.5	4.4	106.4	3.4	0.202	34.781	92.71	0.04

ρ_0	Gmm	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$	β
52.2172	96	0.00072	0.34295	0.00205	0	0.90259

Model Validation

Validation Input

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
01R	90.5	30.9	0.5	4.2	116.6	1.9
02L	91.5	26.3	0.5	4.6	111.1	4.4
02R	90.1	29.3	0.5	2.9	90.6	1.4
03L	89.3	21.0	0.5	4.3	114.1	1.0
03R	90.0	35.0	0.5	4.0	96.9	1.6
04L	92.2	31.3	0.5	3.6	110.9	2.4
04R	91.0	33.6	0.5	4.0	104.0	2.0
05R	91.3	38.4	0.5	4.0	96.2	2.6
06L	91.1	29.2	0.5	4.0	117.4	2.3
06R	93.4	33.5	0.5	4.0	107.3	2.0
07L	91.8	26.9	0.5	3.9	119.2	2.8
07R	89.5	29.8	0.5	4.0	101.8	1.0
08L	91.7	42.7	0.5	3.9	118.1	1.5
08R	89.9	29.1	0.5	4.0	110.0	1.0
09L	90.3	29.8	0.5	3.8	119.9	2.2
09R	91.5	30.4	0.5	3.9	116.0	2.0
10R	90.7	32.9	0.5	3.9	118.2	1.2
11L	92.3	36.3	0.5	3.8	121.4	1.8
11R	90.8	43.9	0.5	3.7	118.3	1.3
12L	91.6	28.2	0.5	3.2	130.3	1.7
12R	91.9	32.1	0.5	3.7	116.2	2.1
13L	93.2	30.9	0.5	3.7	117.8	2.9
13R	92.2	39.6	0.5	3.7	111.7	2.4
14L	91.8	30.8	0.5	3.7	131.9	1.5
14R	90.0	41.4	0.5	3.8	117.8	1.5
15R	91.0	38.0	0.5	3.7	106.7	2.0
16L	90.2	26.9	0.5	3.7	131.1	1.2
16R	89.5	36.2	0.5	3.8	117.0	1.3
17L	91.4	36.5	0.5	3.2	120.0	2.3
17R	90.2	35.8	0.5	3.7	112.8	1.4

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
18L	91.3	27.1	0.5	3.7	124.9	1.6
18R	90.6	29.1	0.5	3.5	115.5	2.0
19L	95.0	33.4	0.5	3.7	124.0	3.4
19R	90.9	32.5	0.5	3.5	118.3	2.1
20R	90.4	31.7	0.5	3.7	117.8	2.3
21L	94.0	32.4	0.5	3.7	125.3	2.9
21R	92.5	35.0	0.5	3.8	114.7	2.8
22L	92.0	30.2	0.5	3.7	120.9	2.3
22R	91.1	39.2	0.5	3.7	118.9	2.2
23L	92.8	35.1	0.5	3.7	110.4	2.9
23R	89.3	37.3	0.5	4.1	109.1	4.5
24L	92.1	30.8	0.5	3.7	126.8	2.3
24R	89.3	39.3	0.5	4.0	116.5	2.3
25R	92.2	42.2	0.5	3.7	120.6	2.4
26L	92.5	34.4	0.5	3.8	121.9	2.8
26R	91.6	37.9	0.5	4.1	114.6	3.6
27L	92.6	32.1	0.5	3.8	124.3	2.3
27R	92.7	37.9	0.5	4.0	115.2	3.9
28L	91.9	30.5	0.5	4.0	124.3	2.7
28R	92.7	38.8	0.5	4.0	114.4	2.6
29L	91.7	21.1	0.5	4.0	113.6	2.9
29R	92.1	28.0	0.5	4.1	113.6	1.4
30R	91.8	44.4	0.5	4.6	95.3	3.4

Validation Output

ID	ρ_L	kk1/(k1-k)	$\Delta\rho$	$\Delta\rho2$	PredDens1	PredDen2	DenDiff	DenDiff^2
01R	0.195	30.862	0.500	0.036	90.72	91.22	1.12	1.25
02L	0.192	26.297	0.500	0.036	93.41	93.91	4.61	21.24
02R	0.201	29.333	0.500	0.073	89.20	89.70	-0.30	0.09
03L	0.198	20.971	0.500	0.073	87.16	87.66	-4.54	20.57
03R	0.200	35.032	0.288	0.109	89.79	90.08	-0.92	0.85
04L	0.204	31.281	0.500	0.109	91.64	92.14	0.84	0.71
04R	0.197	33.639	0.500	0.145	90.90	91.40	0.30	0.09
05R	0.200	38.351	0.500	0.145	91.88	92.38	-1.02	1.04
06L	0.195	29.222	0.500	0.181	91.49	91.99	0.19	0.04
06R	0.198	33.531	0.500	0.181	90.77	91.27	1.77	3.14
07L	0.199	26.939	0.500	0.218	92.20	92.70	2.20	4.83
07R	0.196	29.759	-0.500	0.218	86.95	86.45	-5.05	25.47
08L	0.207	42.719	-0.496	0.254	89.37	88.88	-2.82	7.97
08R	0.197	29.061	-0.500	0.254	86.97	86.47	-3.43	11.75
09L	0.197	29.848	0.500	0.290	91.38	91.88	1.58	2.50
09R	0.198	30.405	0.248	0.290	90.84	91.09	-0.41	0.17
10R	0.200	32.861	0.500	0.326	88.25	88.75	-1.95	3.81
11L	0.202	36.343	-0.300	0.326	90.40	90.10	-2.20	4.86
11R	0.207	43.912	0.500	0.363	88.37	88.87	-1.93	3.71
12L	0.195	28.174	-0.174	0.363	90.24	90.07	-1.53	2.35
12R	0.199	32.108	0.500	0.375	91.15	91.65	-0.25	0.06
13L	0.198	30.943	0.500	0.375	92.24	92.74	-0.46	0.21
13R	0.204	39.594	0.325	0.388	91.47	91.80	-0.40	0.16
14L	0.198	30.829	0.500	0.388	89.35	89.85	-1.95	3.81
14R	0.206	41.412	-0.159	0.401	89.40	89.24	-0.76	0.58
15R	0.203	38.000	0.500	0.401	90.85	91.35	0.35	0.12
16L	0.195	26.857	0.500	0.414	88.28	88.78	-1.42	2.01
16R	0.202	36.167	0.500	0.414	88.40	88.90	-0.60	0.36
17L	0.201	36.538	-0.500	0.544	91.32	90.82	-0.58	0.33
17R	0.201	35.838	-0.500	0.544	89.15	88.65	-1.55	2.40
18L	0.195	27.114	0.145	0.580	90.00	90.15	-1.15	1.33
18R	0.196	29.081	0.500	0.580	90.93	91.43	0.83	0.69

ID	ρ_L	kk1/ (k1-k)	$\Delta\rho$	$\Delta\rho 2$	PredDens1	PredDen2	DenDiff	DenDiff^2
19L	0.200	33.405	0.500	0.616	92.70	93.20	-1.80	3.25
19R	0.199	32.457	0.500	0.616	91.06	91.56	0.66	0.43
20R	0.198	31.686	0.500	0.653	91.43	91.93	1.53	2.35
21L	0.199	32.382	0.500	0.653	92.22	92.72	-1.28	1.64
21R	0.201	34.962	-0.500	0.689	92.18	91.68	-0.82	0.68
22L	0.197	30.200	-0.500	0.689	91.46	90.96	-1.04	1.09
22R	0.204	39.235	-0.500	0.689	91.13	90.63	-0.47	0.22
23L	0.201	35.139	-0.500	0.689	92.26	91.76	-1.04	1.09
23R	0.203	37.314	-0.500	0.689	93.40	92.90	3.60	12.95
24L	0.198	30.788	-0.500	0.689	91.48	90.98	-1.12	1.26
24R	0.204	39.270	-0.500	0.689	91.38	90.88	1.58	2.50
25R	0.206	42.156	-0.500	0.689	91.54	91.04	-1.16	1.35
26L	0.201	34.429	-0.500	0.689	92.13	91.63	-0.87	0.76
26R	0.204	37.946	-0.500	0.689	92.88	92.38	0.78	0.61
27L	0.199	32.083	-0.500	0.689	91.51	91.01	-1.59	2.54
27R	0.203	37.857	-0.500	0.689	93.09	92.59	-0.11	0.01
28L	0.198	30.486	-0.500	0.689	92.10	91.60	-0.30	0.09
28R	0.204	38.771	-0.500	0.689	91.85	91.35	-1.35	1.83
29L	0.191	21.086	-0.500	0.689	92.44	91.94	0.24	0.06
29R	0.197	27.972	-0.500	0.689	89.11	88.61	-3.49	12.19
30R	0.209	44.371	-0.500	0.689	92.58	92.08	0.28	0.08

Kentucky Site

Hamm breakdown compaction

Model Calibration

ID	Dens	ICMV	Amp	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		in.	mph	F				%Gmm	%Gmm^2
01L	96.4	61.5	0.9	3.5	100.7	5.6	0.077	61.514	95.57	0.67
05L	94.5	72.6	0.9	3.4	109.0	5.6	0.089	72.600	95.35	0.67
10L	98.0	83.6	0.9	3.5	104.6	16.4	0.100	83.639	96.60	1.96
15L	96.4	38.4	0.9	3.3	116.1	3.4	0.053	38.433	95.38	1.02
20L	95.7	71.2	0.9	3.6	110.8	11.1	0.088	71.243	96.32	0.45
25L	95.4	56.7	0.9	3.6	104.9	7.9	0.073	56.650	96.14	0.53
30L	94.9	59.2	0.3	4.0	117.0	6.3	0.077	59.156	95.75	0.80

ρ_0	Gmm	$\alpha1$	$\alpha2$	$\alpha3$	$\alpha4$	β
52.2	98	0.001	0	0.004	0	0.68

Model Validation

Validation Input

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
01R	97.0	61.6	0.9	3.5	98.2	5.1
02L	96.1	78.8	0.9	3.4	101.4	12.7
02R	97.5	71.9	0.9	3.5	99.1	8.5
03L	97.5	69.6	0.9	3.4	98.6	6.1
03R	97.6	61.0	0.9	3.5	97.3	4.3
04L	96.9	65.3	0.9	3.4	110.8	5.8
04R	97.5	61.0	0.9	3.2	107.4	4.4
05R	94.8	75.5	0.9	3.5	104.2	4.6
06L	98.0	72.1	0.9	3.5	111.3	13.6
06R	97.5	56.9	0.9	3.5	106.9	7.3
07L	97.9	69.2	0.9	3.5	101.7	5.2
07R	96.4	74.7	0.9	3.5	102.6	4.8
08L	91.0	65.5	0.9	3.5	103.5	5.5
08R	93.4	75.1	0.9	3.5	100.1	5.5
09L	97.9	70.5	0.9	3.5	107.0	5.6
09R	94.1	65.0	0.9	3.5	102.4	5.3
10R	93.6	80.7	0.9	3.5	103.5	7.6
11L	97.7	50.0	0.9	3.5	102.8	5.0
11R	96.2	52.9	0.9	3.5	102.6	5.8
12L	96.8	55.1	0.9	3.5	105.6	4.8
12R	95.7	67.9	0.9	3.5	104.1	5.8
13L	97.6	67.7	0.9	3.5	106.9	4.7
13R	97.0	70.4	0.9	3.5	101.4	5.8
14L	96.9	44.6	0.9	3.4	111.4	4.4
14R	97.3	39.5	0.9	3.5	109.9	6.1
15R	96.1	64.4	0.9	3.5	111.7	9.9
16L	97.2	39.8	0.9	3.4	79.9	9.0
16R	96.3	67.3	0.9	3.5	106.5	6.4
17L	97.0	34.2	0.9	3.4	87.0	3.1
17R	97.1	67.9	0.9	3.5	104.8	6.3
18L	96.4	48.6	0.9	3.4	100.8	4.0
18R	94.1	66.9	0.9	3.5	106.7	6.4
19L	94.4	58.5	0.9	3.5	81.5	2.6
19R	91.5	62.8	0.9	3.5	115.8	6.3

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
20R	93.6	57.4	0.9	3.6	73.0	2.5
21L	95.3	58.7	0.9	3.6	106.6	6.2
21R	93.7	49.2	0.9	3.5	99.6	3.2
22L	96.1	68.8	0.9	3.6	109.8	6.1
22R	93.2	63.6	0.9	3.6	90.4	2.6
23L	95.0	68.1	0.9	3.6	111.4	6.3
23R	92.7	60.8	0.9	3.0	102.4	3.2
24L	96.3	67.8	0.9	3.6	115.4	6.2
24R	94.8	65.1	0.9	3.6	116.2	6.3
25R	94.6	80.3	0.9	3.6	109.7	12.2
26L	95.5	38.0	0.9	2.9	86.7	3.6
26R	94.7	65.6	0.9	3.6	105.5	5.8
27L	94.7	59.4	0.9	3.2	105.3	3.3
27R	93.3	66.6	0.9	3.6	110.0	6.3
28L	94.3	59.2	0.9	3.2	111.2	2.9
28R	93.1	74.6	0.9	3.4	107.3	10.1
29L	94.6	80.8	0.9	3.5	112.8	6.3
29R	93.1	78.2	0.9	3.5	106.1	13.2
30R	92.0	63.6	0.3	4.0	102.5	6.6

Validation Output

ID	ρ_L	kk1/ (k1-k)	$\Delta\rho$	$\Delta\rho 2$	PredDens1	PredDen2	DenDiff	DenDiff^2
01R	0.088	61.600	0.500	0.036	95.42	95.92	-1.63	2.66
02L	0.086	78.750	0.500	0.036	96.38	96.88	-0.58	0.34
02R	0.077	71.900	0.500	0.073	96.00	96.50	-1.11	1.23
03L	0.081	69.618	0.500	0.073	95.56	96.06	-0.82	0.67
03R	0.076	61.033	0.288	0.109	95.12	95.40	-2.08	4.34
04L	0.092	65.250	0.500	0.109	95.54	96.04	1.20	1.45
04R	0.088	60.970	0.500	0.145	95.18	95.68	-2.34	5.47
05R	0.073	75.500	0.500	0.145	94.92	95.42	-2.08	4.31
06L	0.085	72.139	0.500	0.181	96.53	97.03	-0.88	0.78
06R	0.091	56.879	0.500	0.181	96.05	96.55	0.11	0.01
07L	0.078	69.171	0.500	0.218	95.29	95.79	-1.20	1.45
07R	0.095	74.735	-0.500	0.218	95.00	94.50	-1.61	2.59
08L	0.082	65.486	-0.496	0.254	95.47	94.97	3.95	15.58
08R	0.091	75.086	-0.500	0.254	95.27	94.77	1.34	1.79
09L	0.087	70.514	0.500	0.290	95.38	95.88	-1.97	3.90
09R	0.081	65.000	0.248	0.290	95.40	95.65	1.53	2.33
10R	0.097	80.743	0.500	0.326	95.69	96.19	2.57	6.61
11L	0.066	50.029	-0.300	0.326	95.64	95.34	-2.32	5.37
11R	0.069	52.857	0.500	0.363	95.81	96.31	0.13	0.02
12L	0.071	55.118	-0.174	0.363	95.46	95.29	-1.52	2.31
12R	0.084	67.914	0.500	0.375	95.50	96.00	0.27	0.07
13L	0.084	67.743	0.500	0.375	95.15	95.65	-1.98	3.92
13R	0.087	70.441	0.325	0.388	95.44	95.77	-1.24	1.53
14L	0.060	44.559	0.500	0.388	95.59	96.09	-0.84	0.70
14R	0.055	39.529	-0.159	0.401	96.17	96.01	-1.27	1.61
15R	0.080	64.353	0.500	0.401	96.30	96.80	0.71	0.51
16L	0.055	39.773	0.500	0.414	96.59	97.09	-0.09	0.01
16R	0.083	67.314	0.500	0.414	95.66	96.16	-0.15	0.02
17L	0.049	34.217	-0.500	0.544	95.33	94.83	-2.13	4.53
17R	0.084	67.906	-0.500	0.544	95.63	95.13	-1.99	3.95
18L	0.064	48.636	0.145	0.580	95.34	95.48	-0.96	0.93
18R	0.083	66.875	0.500	0.580	95.67	96.17	2.11	4.47
19L	0.075	58.526	0.500	0.616	94.10	94.60	0.19	0.04
19R	0.079	62.800	0.500	0.616	95.73	96.23	4.76	22.63
20R	0.074	57.389	0.500	0.653	94.06	94.56	0.92	0.85

ID	ρ_L	kk1/ (k1-k)	$\Delta\rho$	$\Delta\rho 2$	PredDens1	PredDen2	DenDiff	DenDiff^2
21L	0.075	58.719	0.500	0.653	95.77	96.27	1.02	1.04
21R	0.065	49.200	-0.500	0.689	94.89	94.39	0.68	0.47
22L	0.085	68.750	-0.500	0.689	95.56	95.06	-1.02	1.05
22R	0.080	63.550	-0.500	0.689	93.92	93.42	0.25	0.06
23L	0.085	68.091	-0.500	0.689	95.63	95.13	0.12	0.01
23R	0.075	60.762	-0.500	0.689	94.56	94.06	1.39	1.94
24L	0.084	67.765	-0.500	0.689	95.59	95.09	-1.16	1.35
24R	0.082	65.111	-0.500	0.689	95.66	95.16	0.33	0.11
25R	0.097	80.257	-0.500	0.689	96.32	95.82	1.21	1.47
26L	0.051	38.000	-0.500	0.689	95.52	95.02	-0.51	0.26
26R	0.082	65.629	-0.500	0.689	95.53	95.03	0.34	0.12
27L	0.074	59.414	-0.500	0.689	94.64	94.14	-0.52	0.27
27R	0.083	66.600	-0.500	0.689	95.64	95.14	1.81	3.28
28L	0.074	59.174	-0.500	0.689	94.41	93.91	-0.42	0.17
28R	0.091	74.571	-0.500	0.689	96.18	95.68	2.60	6.77
29L	0.097	80.846	-0.500	0.689	95.40	94.90	0.33	0.11
29R	0.094	78.222	-0.500	0.689	96.43	95.93	2.84	8.08
30R	0.082	63.625	-0.500	0.689	95.75	95.25	3.29	10.82

Washington State Site

Hamm breakdown compaction

Model Calibration

ID	Dens	ICMV	Amp	Speed	Temp	Passes	ρ_L	kk1/ (k1-k)	PredDen	DenDiff^2
	%Gmm		in.	mph	F		□		%Gmm	%Gmm^2
01L	92.7	60	0.28	4.0	113	7.5	0.16	59.64	92.5	0.0
05L	93.5	63	0.28	4.0	104	8.0	0.16	63.00	92.6	0.7
10L	93.4	69	0.28	4.0	103	7.7	0.16	69.20	92.5	0.9
15L	91.3	64	0.28	4.0	111	6.6	0.16	63.56	92.2	0.7
20L	93.9	61	0.28	4.0	116	4.6	0.16	61.37	91.3	6.9
25L	93.8	60	0.28	4.0	111	7.0	0.16	60.47	92.4	2.0
30L	92.4	59	0.28	4.0	117	6.3	0.16	59.16	92.1	0.1
T2	85.7	42	0.28	3.8	111	1.0	0.14	41.67	85.1	0.4
T2	88.0	57	0.28	3.8	112	2.0	0.15	56.67	88.3	0.1
T2	88.7	55	0.28	3.8	104	3.0	0.15	55.25	90.0	1.7
T2	89.7	61	0.28	3.8	113	4.0	0.16	61.05	90.9	1.5
T2	90.1	55	0.28	3.8	107	5.0	0.15	54.50	91.6	2.4
T2	90.7	60	0.28	3.8	108	6.0	0.16	60.03	92.0	1.7
T2	90.5	60	0.28	3.8	108	7.0	0.16	59.83	92.4	3.4
T2	91.1	60	0.28	3.8	110	8.0	0.16	59.84	92.7	2.3
T4	85.6	49	0.28	4.0	121	1.0	0.15	49.00	84.9	0.6
T4	87.4	55	0.28	4.0	124	2.0	0.15	54.96	88.4	1.0
T4	88.6	57	0.28	4.0	112	3.0	0.15	56.50	90.0	2.0
T4	89.4	58	0.28	4.0	111	4.0	0.16	57.50	90.9	2.2
T4	90.1	60	0.28	4.0	114	5.0	0.16	59.74	91.5	2.0
T4	89.6	54	0.28	4.0	106	6.0	0.15	53.95	92.1	6.2
T4	90.6	56	0.28	4.0	100	7.0	0.15	55.53	92.4	3.4
T4	91.5	64	0.28	4.0	103	8.0	0.16	64.14	92.6	1.2
T5	86.6	39.3	0.28	3.6	120	1	0.14	39.26	85.2	2.1
T5	87.9	51.2	0.28	3.6	118	2	0.15	51.16	88.5	0.3
T5	89.0	52.1	0.28	3.6	119	3	0.15	52.07	90.1	1.1
T5	90.4	56.8	0.28	3.6	117	4	0.15	56.81	90.9	0.3
T5	91.2	66.0	0.28	3.9	115	5	0.16	66.00	91.5	0.1
T5	90.3	58.3	0.28	3.6	110	6	0.16	58.26	92.0	3.1
T5	90.7	59.4	0.28	3.9	113	7	0.16	59.36	92.4	2.7
T5	90.6	58.0	0.28	3.6	106	8	0.16	58.03	92.7	4.2

ρ_0	Gmm	$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$	β
52.2172	96	0.0007	0.404	4E-07	0	0.644

Model Validation

Validation Input

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
01R	92.8	51	0.28	4.0	112.5	8.2
02L	92.6	60	0.28	4.0	116.3	7.0
02R	91.8	60	0.28	4.0	118.0	6.3
03L	93.0	55	0.28	3.7	100.8	8.5
03R	92.7	51	0.28	3.9	104.7	8.7
04L	92.7	63	0.28	4.0	104.5	7.9
04R	93.0	65	0.28	4.0	103.2	9.1
05R	93.0	61	0.28	4.0	98.8	9.1
06L	92.8	69	0.28	4.0	103.7	8.2
06R	92.7	70	0.28	4.0	101.1	9.6
07L	92.8	67	0.28	4.0	112.5	7.9
07R	93.2	51	0.28	4.0	115.1	9.1
08L	93.0	57	0.28	4.0	111.9	8.3
08R	93.3	57	0.28	4.0	99.9	10.1
09L	92.7	56	0.28	4.0	105.1	7.8
09R	92.8	58	0.28	4.0	107.6	9.9
10R	91.8	72	0.28	4.0	91.1	8.7
11L	91.8	62	0.28	4.0	109.5	6.9
11R	92.1	59	0.28	4.0	94.5	8.8
12L	92.1	50	0.28	4.0	106.0	7.6
12R	91.5	66	0.28	4.0	107.1	7.6
13L	92.8	67	0.28	4.0	111.5	6.5
13R	91.2	59	0.28	4.0	100.2	5.5
14L	92.9	65	0.28	4.0	103.5	8.1
14R	91.6	46	0.28	4.0	93.4	6.7
15R	91.9	61	0.28	4.0	115.7	7.1
16L	93.6	64	0.28	4.0	111.4	8.0
16R	91.5	40	0.28	4.0	108.1	5.4
17L	92.8	59	0.28	4.0	112.8	5.7
17R	91.8	56	0.28	4.0	104.9	5.7
18L	92.6	60	0.28	4.0	112.7	6.3
18R	91.9	49	0.28	4.0	114.4	3.5
19L	92.4	48	0.28	4.0	117.9	4.9
19R	92.5	55	0.28	4.0	115.6	4.9

ID	Dens	ICMV	Amp.	Speed	Temp	Passes
20R	91.7	58	0.28	4.0	123.4	3.1
21L	93.5	56	0.28	4.0	117.5	3.4
21R	92.4	53	0.28	4.0	121.6	2.6
22L	94.3	46	0.28	3.8	103.2	4.6
22R	92.6	50	0.28	3.9	91.1	6.9
23L	93.8	72	0.28	3.9	98.4	7.7
23R	92.0	65	0.28	4.0	95.4	8.6
24L	93.7	58	0.28	4.0	98.6	6.7
24R	92.2	60	0.28	4.0	91.2	7.2
25R	92.1	65	0.28	4.0	110.9	6.6
26L	92.9	56	0.28	4.0	105.9	6.1
26R	91.3	64	0.28	4.0	104.6	6.2
27L	93.1	52	0.28	4.0	110.3	6.9
27R	91.6	60	0.28	4.0	112.3	7.0
28L	93.9	62	0.28	4.0	117.7	7.4
28R	93.1	65	0.28	3.9	114.2	5.9
29L	93.2	51	0.28	4.0	118.2	5.7
29R	92.2	55	0.28	4.0	114.1	5.9
30R	91.5	64	0.28	4.0	102.5	6.6
T6	85.9	41.9	0.28	3.1	122	1
T6	88.2	47.9	0.28	3.1	122	2
T6	88.3	70.5	0.28	2.9	122	3
T6	89.7	57.8	0.28	3.6	120	4
T6	91.2	65.3	0.28	4.0	117	5
T6	92.1	61.4	0.28	4.0	110	6
T6	92.4	68.8	0.28	4.0	109	7

Validation Output

ID	ρ_L	kk1/ (k1-k)	$\Delta\rho$	$\Delta\rho2$	PredDens1	PredDen2	DenDiff	DenDiff^2
01R	0.16	51.49	0.50	0.04	92.78	93.28	1.52	2.30
02L	0.15	60.09	0.50	0.04	92.37	92.87	-0.17	0.03
02R	0.15	59.81	0.50	0.07	92.13	92.63	-0.06	0.00
03L	0.16	54.86	0.50	0.07	92.83	93.33	0.60	0.36
03R	0.16	51.15	0.29	0.11	92.90	93.18	0.14	0.02
04L	0.16	63.11	0.50	0.11	92.60	93.10	0.11	0.01
04R	0.16	65.49	0.50	0.15	92.86	93.36	0.52	0.27
05R	0.16	61.03	0.50	0.15	92.90	93.40	0.67	0.44
06L	0.16	68.51	0.50	0.18	92.62	93.12	0.33	0.11
06R	0.15	69.75	0.50	0.18	92.93	93.43	0.18	0.03
07L	0.15	66.91	0.50	0.22	92.55	93.05	0.21	0.04
07R	0.16	50.59	-0.50	0.22	93.00	92.50	-0.13	0.02
08L	0.16	57.30	-0.50	0.25	92.76	92.26	-0.73	0.53
08R	0.15	56.63	-0.50	0.25	93.14	92.64	-0.67	0.44
09L	0.15	56.29	0.50	0.29	92.64	93.14	0.41	0.17
09R	0.16	58.34	0.25	0.29	93.07	93.32	0.48	0.23
10R	0.17	71.86	0.50	0.33	92.72	93.22	1.41	1.99
11L	0.16	61.63	-0.30	0.33	92.31	92.01	0.20	0.04
11R	0.16	59.28	0.50	0.36	92.85	93.35	1.28	1.65
12L	0.15	49.51	-0.17	0.36	92.65	92.47	0.41	0.17
12R	0.16	65.66	0.50	0.38	92.49	92.99	1.48	2.20
13L	0.16	66.76	0.50	0.38	92.11	92.61	-0.23	0.05
13R	0.16	59.21	0.32	0.39	91.79	92.12	0.92	0.85
14L	0.16	64.88	0.50	0.39	92.63	93.13	0.24	0.06
14R	0.15	46.18	-0.16	0.40	92.41	92.25	0.69	0.48
15R	0.16	61.37	0.50	0.40	92.39	92.89	1.02	1.05
16L	0.16	64.46	0.50	0.41	92.61	93.11	-0.45	0.20
16R	0.14	40.14	0.50	0.41	91.97	92.47	0.97	0.93
17L	0.16	58.97	-0.50	0.54	91.90	91.40	-1.44	2.08
17R	0.15	56.28	-0.50	0.54	91.90	91.40	-0.36	0.13
18L	0.16	59.57	0.14	0.58	92.12	92.26	-0.32	0.10
18R	0.15	49.23	0.50	0.58	90.61	91.11	-0.81	0.65
19L	0.15	48.19	0.50	0.62	91.65	92.15	-0.22	0.05
19R	0.15	55.28	0.50	0.62	91.56	92.06	-0.42	0.18

ID	ρ_L	kk1/ (k1-k)	$\Delta\rho$	$\Delta\rho2$	PredDens1	PredDen2	DenDiff	DenDiff^2
20R	0.16	57.92	0.50	0.65	90.11	90.61	-1.10	1.20
21L	0.15	56.22	0.50	0.65	90.38	90.88	-2.63	6.92
21R	0.15	53.39	-0.50	0.69	89.55	89.05	-3.37	11.39
22L	0.15	45.84	-0.50	0.69	91.47	90.97	-3.31	10.96
22R	0.15	50.43	-0.50	0.69	92.43	91.93	-0.70	0.50
23L	0.17	72.06	-0.50	0.69	92.45	91.95	-1.87	3.49
23R	0.16	64.85	-0.50	0.69	92.76	92.26	0.30	0.09
24L	0.16	58.11	-0.50	0.69	92.27	91.77	-1.89	3.57
24R	0.16	60.18	-0.50	0.69	92.43	91.93	-0.24	0.06
25R	0.16	64.89	-0.50	0.69	92.16	91.66	-0.41	0.17
26L	0.15	56.41	-0.50	0.69	92.09	91.59	-1.30	1.69
26R	0.16	63.71	-0.50	0.69	92.04	91.54	0.24	0.06
27L	0.15	51.65	-0.50	0.69	92.40	91.90	-1.24	1.54
27R	0.16	60.03	-0.50	0.69	92.37	91.87	0.32	0.10
28L	0.16	61.58	-0.50	0.69	92.47	91.97	-1.90	3.61
28R	0.16	64.74	-0.50	0.69	91.91	91.41	-1.68	2.84
29L	0.15	50.63	-0.50	0.69	91.97	91.47	-1.73	3.00
29R	0.15	54.94	-0.50	0.69	92.03	91.53	-0.69	0.47
30R	0.16	63.63	-0.50	0.69	92.20	91.70	0.20	0.04
T6	0.14	41.88	-0.50	0.69	85.08	84.58	-1.27	1.61
T6	0.15	47.88	-0.50	0.69	88.53	88.03	-0.19	0.04
T6	0.16	70.50	-0.50	0.69	89.74	89.24	0.92	0.85
T6	0.16	57.76	-0.50	0.69	90.91	90.41	0.71	0.50
T6	0.16	65.33	-0.50	0.69	91.46	90.96	-0.28	0.08
T6	0.16	61.43	-0.50	0.69	91.99	91.49	-0.58	0.34
T6	0.16	68.75	-0.50	0.69	92.27	91.77	-0.65	0.43

Front Cover Images

Nine (9) IC field sites conducted and four IC rollers used under this study.

Back Cover Image

An image to represent 515 asphalt cores taken under this study.