Validation of Uniform Compaction of Hot-Mix Asphalt Pavements in Connecticut

Prepared by: Scott Zinke and James Mahoney
Report Number: CT-2288-F-16-1
June 30, 2016

FINAL REPORT

Project No. SPR 2288

Submitted to the Connecticut Department of Transportation

Connecticut Advanced Pavement Laboratory
Connecticut Transportation Institute
School of Engineering
University of Connecticut

Prepared for:
Connecticut Department of Transportation
Bureau of Policy and Planning
Roadway Information Systems Research Section

Michael Connors
Assistant Planning Director

Disclaimer

Acknowledgments

This report was prepared by the University of Connecticut, in cooperation with the Connecticut Department of Transportation and the United States Department of Transportation, Federal Highway Administration. The opinions, findings and conclusions expressed in the publication are those of the authors and not necessarily those of the Connecticut Department of Transportation or the Federal Highway Administration. This publication is based upon publicly supported research and is copyrighted. It may be reproduced in part or in full, but it is requested that there be customary crediting of the source.

Standard Conversions

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)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		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)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		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)

Technical Report Documentation Page

1. Report No. CT-2288-F-16-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Validation of Uniform Compaction of Hot-Mix Asphalt Pavements in Connecticut		5. Report Date June 30, 2016 6. Performing Organization Code
7. Author(s) Scott Zinke, James Mahoney		8. Performing Organization Report No. CAPLAB 20-2016
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute 270 Middle Turnpike, U-5202 Storrs, Connecticut 06269-5202		10 Work Unit No. (TRIS) N/A 11. Contract or Grant No. SPR-2288 13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		14. Sponsoring Agency Code
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

CT DOT trialed Uniform Compaction (UC) equipment on 2 pilot projects during the 2014 construction season. This equipment included everything that would be used for Intelligent Compaction (IC) with the exception of the stiffness measurement instrumentation. The intention was to investigate whether the use of the equipment would lead to better coverage and speed control to provide a more consistent and uniform overlay. The data from each roller and paver was collected each night of paving. These raw data files were then transferred to the research team for analysis with the VETA mapping software. Acceptance core density was also analyzed on both projects and compared to other 2014 projects in CT that did not use the UC equipment. Results show that the use of the UC equipment did, in fact, significantly improve the uniformity of the pavement from a density perspective. Analysis of the mapping software showed that it may be useful in determining overall coverage, speed and temperature information. The quality and accuracy of the mapping software should be improved prior to using the equipment for locating areas of distress and deficiency. Given the results of the reviewed literature, the stiffness values do not correlate well with pavement density.

17. Key Words	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. The report is available on-line from National Transportation Library at http://ntl.bts.gov.		
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	21. Price
Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized		

Table of Contents

List of Tables

List of Figures

Introduction and Background Summary

The level of compaction of hot-mix asphalt (HMA) at the time of construction is one of the most important factors influencing the long term durability of the pavement. Contractors should be using their own Quality Control plans and personnel to establish roller types and rolling patterns that provide adequate compaction to achieve in-place densities, in turn, ensuring long-term durability. Maintaining consistent rolling patterns throughout the entire day's placement can be difficult due to many factors including:

- Inconsistent rate of material delivery
- Varying paver pass widths
- Sight limitations during night paving that prevent the roller operators from using landmarks
- Changing environmental conditions
- Operator fatigue

Inconsistent rolling patterns may result in considerable differences in the compactive effort applied across the pavement. These differences in compactive effort can translate into substantial variability in uniformity of the pavement. In addition, significant variability in pavement density may result. This will ultimately reduce the pavement's service life.

Intelligent Compaction (IC) uses real-time GPS to track paving equipment during the placement and compaction of the pavement. A monitor is mounted on the rolling equipment that provides instantaneous information to the operator, including where the roller has been, how many roller passes have taken place in that location, roller speed and the temperature of the pavement. IC also utilizes accelerometers mounted to the rollers to measure the pavement's stiffness. This stiffness is intended to be indicative of density and used to identify areas where the density may be inadequate.

Currently, the Connecticut Department of Transportation (CT DOT) is only interested in the GPS tracking portion of Intelligent Compaction, which is sometimes referred to as Uniform Compaction (UC). UC is the term used throughout this report. UC is used to ensure that the pavement receives approximately the same amount of compactive effort in all locations.

The cost to install the GPS tracking equipment, data logger and monitor is more than $25,000 per piece of equipment. The addition of the accelerometers would also greatly increase the cost per piece of equipment outfitted.

Problem Statement

Ideal practice to optimize the HMA pavement’s compaction and ultimately its in-place density requires the contractor to establish rolling patterns and maintain them throughout the day’s production. Maintaining these rolling patterns can be very difficult over the course of a paving day. The use of GPS based UC equipment provides the machinery operators with the ability to ensure that the pavement has received approximately the same amount of compactive effort across its entire width. There is a need, however, to validate that the UC equipment promotes a more uniform density throughout the entire pavement, thereby justifying the additional cost for the UC equipment.

Objectives

The objectives for this project were addressed in five tasks. The first task was to conduct a literature-based review looking at IC and UC. The majority of the reviewed research was found in two very extensive FHWA projects. The second task involved field testing at time of placement of new Hot Mix Asphalt (HMA) wearing surfaces. This testing included nuclear density measurements as well as the use of a GPS rover for spatial location of those measurements. During the 2014 construction season, CT DOT had two pilot projects that required the use of UC equipment. It was these two pilot projects that were used in the validation efforts for the use of the equipment. The third task was to obtain all of the raw data files collected by each piece of equipment on both pilot projects along with all of the acceptance data from the projects. The fourth task was to analyze the data in an effort to determine if the projects employing UC were in fact more uniform than comparable projects that did not utilize the UC equipment. The fifth and final task was assembling the findings into this final report.

Literature Review

The Transtech Group, Inc. [1], defines IC as the compaction of road materials using modern vibratory rollers equipped with an integrated measurement system, a GPS mapping system and an onboard reporting system. Real-time compaction monitoring facilitates the achievement of required density levels by allowing the user access to this collected information in the field so he\she may make decisions and adjustments based upon this data.

GPS receivers are mounted on rollers as well as on placement equipment. Data regarding the precise location of the equipment is recorded continuously during operation. Temperature-measuring devices are also mounted on each piece of equipment and temperature of the material surface is recorded continually during operation. Optionally, accelerometers are mounted either inside or onto the drum of the rollers. These accelerometers collect compaction information through a stiffness measurement continually during operation. The intention of these systems working together is to provide the operator, as well as subsequent analysts, specific information including surface temperature, number of roller passes, roller/paver speed and an indication of stiffness/density at any given location at any time. The benefit to having this information real-time is to allow the operator to make informed decisions regarding speed settings, pass count and when to continue/discontinue or alter compactive effort.

The stated benefits to utilizing uniform compaction are, among other things, improved density, improved productivity and reduction of highway repair costs.

An Intelligent Compaction Implementation project, TPF-5(128), "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base and Asphalt Pavement Material,"was part of the Transportation Pooled Fund Program [2]. This project consisted of a series of 16 IC equipment demonstrations in 12 states over a three year period. The participating State Departments of Transportation (DOTs) were (in 2008), Minnesota, Kansas, Texas, (in 2009) New York, Maryland, Indiana, Mississippi, Georgia, (in 2010) North Dakota, Wisconsin, Pennsylvania and Virginia. Numerous vendors of IC and compaction equipment cooperated with the participating DOTs and members of the FHWA IC project team to execute these trials. The objectives of this large scale investigation were to:

- Demonstrate the technology via its use on both soil/base and HMA projects;
- Develop IC knowledge base and expertise within the DOTs;
- Assist the DOTs with developing IC Quality Control (QC) specifications; and,
- Identify areas where further research and improvement with IC are needed.

There were a number of significant findings with respect to the use of IC with both soils/earthwork and HMA. Because this CT DOT research study focused specifically on HMA wearing surfaces, only the major findings with respect to HMA are presented here. Among the general benefits to IC technology, the following statements are made:

- With HMA IC, tracking roller passes and HMA surface temperatures provide necessary means to maintain a consistent rolling pattern within optimal ranges of temperatures for 100 percent coverage of a construction area.
- IC technologies can be especially beneficial to maintain consistent rolling patterns under lower visibility conditions such as night paving operations.
- IC technology will have profound influence on the responsibilities of various stages of pavement construction and will eventually help produce better and more consistent pavement products.

The reader should note that the pilot projects that took place in Connecticut looked only at UC. The Pooled fund study looked at all aspects of IC including the use of accelerometers. Among the major findings regarding HMA IC, the following statements are made:

- Mapping existing support materials using IC rollers prior to subsequent HMA paving has proved to be effective on identifying weak locations. This was done via examination of the stiffness measurements illustrated on a map. Evidence from the IC field demonstration have shown that the desired densities of the HMA materials would be difficult to achieve at weak support locations, and even premature failure may occur under construction traffic.
- Mapping has been successfully demonstrated on granular subbase, stabilized subbase, and milled asphalt surfaces with IC roller settings at low vibration amplitudes and low frequencies.
- The correlation between Intelligent Compaction Measurement Value (ICMV) (a stiffness value that is back calculated from the data collected by accelerometers mounted in or on the roller drum) and HMA core densities is inconsistent due to factors such as limited spot tests and the different nature of measured properties (e.g., mechanical property vs. material proportioning).
- The relatively low correlation between ICMV and nuclear/non-nuclear density gauge (NG/NNG) measurements can be due to: a) ICMV reflects the stiffness of the entire pavement structure and the underlying support while NG/NNG only measure the top 6” of HMA layers; and/or, b) ICMVs do not yet factor in the temperature effects in the measurements while NG/NNG measurements are independent of HMA temperatures.
- IC data can be used to build a compaction curve for a specific material of a specific project. The compaction curve can then be used to identify the optimal roller pass so that over/under compaction can be prevented.
- IC data can be used to produce semivariograms (graphics showing variance) that serve as the metrics for compaction uniformity. Generally, compaction uniformity increases for subsequent lifts.

FHWA also sponsored a project titled “A Study on Intelligent Compaction and In-Place Asphalt Density” [3]. This study was conducted for the purpose of determining whether or not ICMV numbers could be substituted for core density values for acceptance purposes. One of the major recommendations of the pooled fund study [2], discussed previously, was that further research into the correlation between ICMV and density was needed. It was stated that if the correlation could be established then it would be possible to use IC for acceptance. This investigation continued the work that was done during the pooled fund study. It was conducted between 2011 and 2014 and involved nine construction sites in nine states across the United States. Participating State DOTs were (in 2012) Utah, Florida, (in 2013) Ohio, Maine, California, (in 2014) Idaho, Maryland, Washington and Kentucky.

There were four IC systems used, all from different manufacturers. The manufacturers were BOMAG, Caterpillar, Hamm and Sakai. The Caterpillar system was the system that was used on both of the CT DOT pilot projects. The Caterpillar ICMV number is referred to as a Compaction Meter Value (CMV), which is intended to correlate with material stiffness.

The process that took place at each site involved validation of the GPS mapping system to ensure accuracy of spatial data. In some of the trial locations, pre-mapping of the granular subbase was conducted with the IC rollers as an assessment of the support layers.

At least two spot locations were identified for analysis on each day of paving. Nuclear density gauge (NDG) measurements were then taken following each pass of the IC roller. Following this pass-by-pass data collection, a 1,500 foot long section of pavement was identified and 60 spot locations were selected for testing. Testing that took place at these spot locations included NDG testing, coring, and GPS measurements. Some deflectometer testing was conducted as well. This was done with either light weight deflectometers or falling weight deflectometers, or both. The cores were tested at the respective DOT laboratory facility for bulk density. 515 cores were analyzed for this research. All of the collected IC data was analyzed using Veda [4] (now Veta v3) software as opposed to the individual manufacturer’s software. The authors state that Veda is a more powerful tool for IC data management.

It was found that asphalt core density does not correlate well with the final coverage (last roller pass) ICMV stiffness measurements. Among possible explanations for this were: the increasing viscosity of the asphalt binder as it cools influencing the rebound behavior of the roller drum; ICMV influence depth may be deeper than the asphalt layer at final coverage; and, that ICMV were only recorded during breakdown and intermediate rolling, which does not take into account any compaction or stiffness changes that may occur during finish rolling.

Among the results and recommendations from the second FHWA study for implementing a successful IC field project are the following:

- GPS validation prior to construction is critical to data quality
- Ground-based GPS stations or virtual GPS base stations should be used for real-time differential correction to provide high precision spatial information.
- Universal Transverse Mercator (UTM) is the recommended coordinate system to use. Caution should be exercised when using the State Plane System with surface adjustment factors. All GPS devices on a jobsite need to be using the same coordinate system and correction base station.
- Pre-mapping of granular base conditions is recommended, when applicable.
- IC data transfer should occur on a daily basis to minimize the possibility of data loss.

Among the conclusions and recommendations from the analysis results are the following:

- Pass-by-pass ICMV data correlate well with NDG measurements during breakdown compaction. Because of this, IC can be used as a tool for QC by monitoring the ICMV in real time during construction to maximize the window of opportunity for compaction
- Final ICMV does not correlate well with core densities and should not replace core densities for acceptance determinations
- Current IC technology can be used for method-based specifications such as pass counts and coverage. The recommendation is to require a minimum of 70% of compacted areas to have target passes.

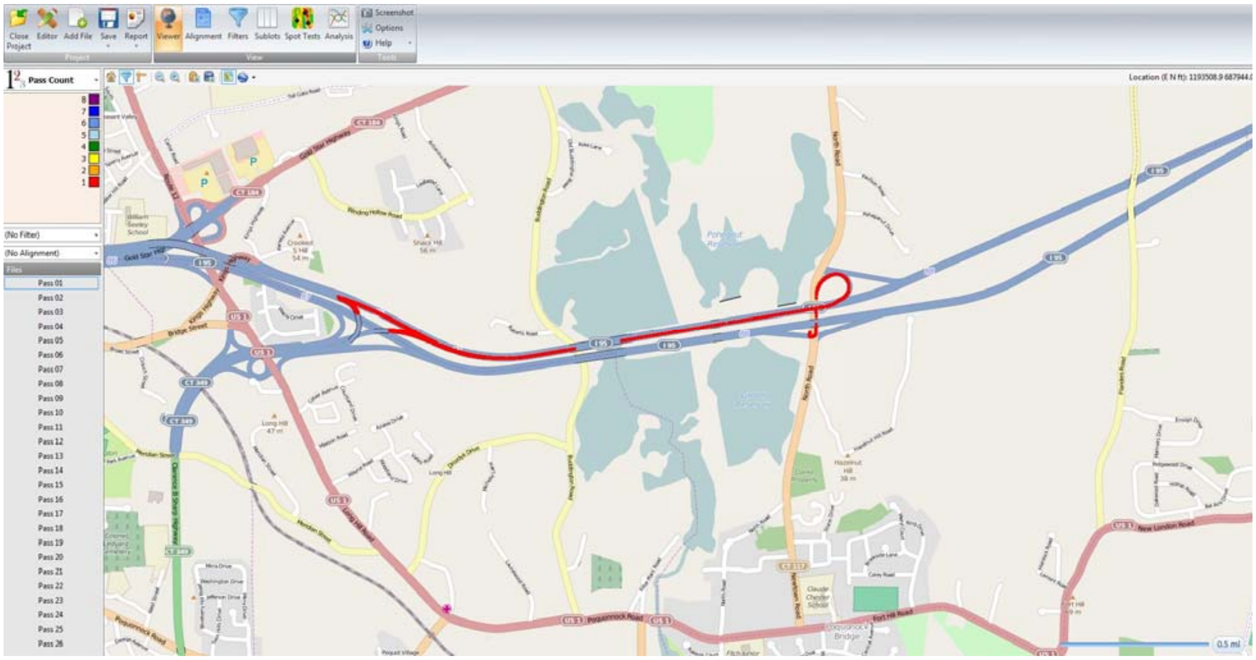
Veta [1] is the software used for analysis of the collected IC data. Although manufacturers of IC equipment have their own software, Veta is standardized for use with data collected using any system. It is map-based software, which allows viewing and analysis of collected geospatial data along with temperature and ICMV data. It allows the collected data to be overlaid onto a map of the construction site. Graphics, maps and reports can then be generated in order to summarize the compaction process. The current version of the software is Veta 3. It was formerly called “Veda”. The software was developed by the Minnesota Department of Transportation and the Transtec Group, and both organizations own the intellectual property rights to Veta. Veta can be downloaded for free from the IC website intelligentcompaction.com. The data flow process consists of IC data collection via the manufacturers IC system, followed by transfer of the data into the Veta software, and finally analysis. Figure 1 shows the data flow process as described in the User’s Guide [4].

Figure 1. IC Data Flow

***Photo courtesy of the Veta 3 User’s Guide**

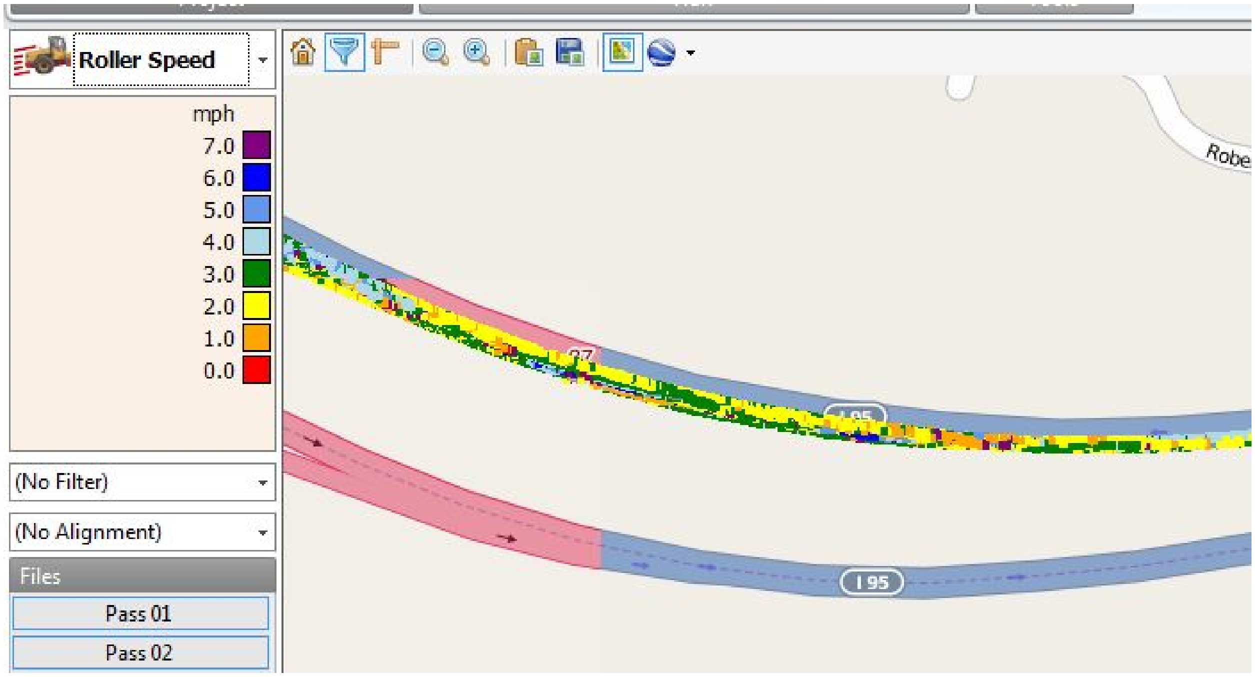
Currently, Veta only functions on the Windows 7, 64-bit platform. Once installed, the IC data can be imported. Prior to displaying the data and maps, the user is required to input the coordinate system that was used to collect the data. Then, the project is opened and a map is displayed, as seen in Figure 2, which is a screen shot of the pass count layer on the I-95 pilot project in Connecticut.

Figure 2. Veta Project Screen



The data that can be viewed includes pass count, vibratory roller settings (frequency and amplitude), pavement surface temperature, ICMV and roller speed. The data is color coded for mapping and graphic purposes, as seen in Figure 3, which shows roller speed at any given location during a selected pass. This image is also from the I-95 pilot project in Connecticut.

Figure 3. Roller Speed Color Coded



This graphic data can be viewed for any of the collected IC data.

Connecticut DOT Pilot Projects

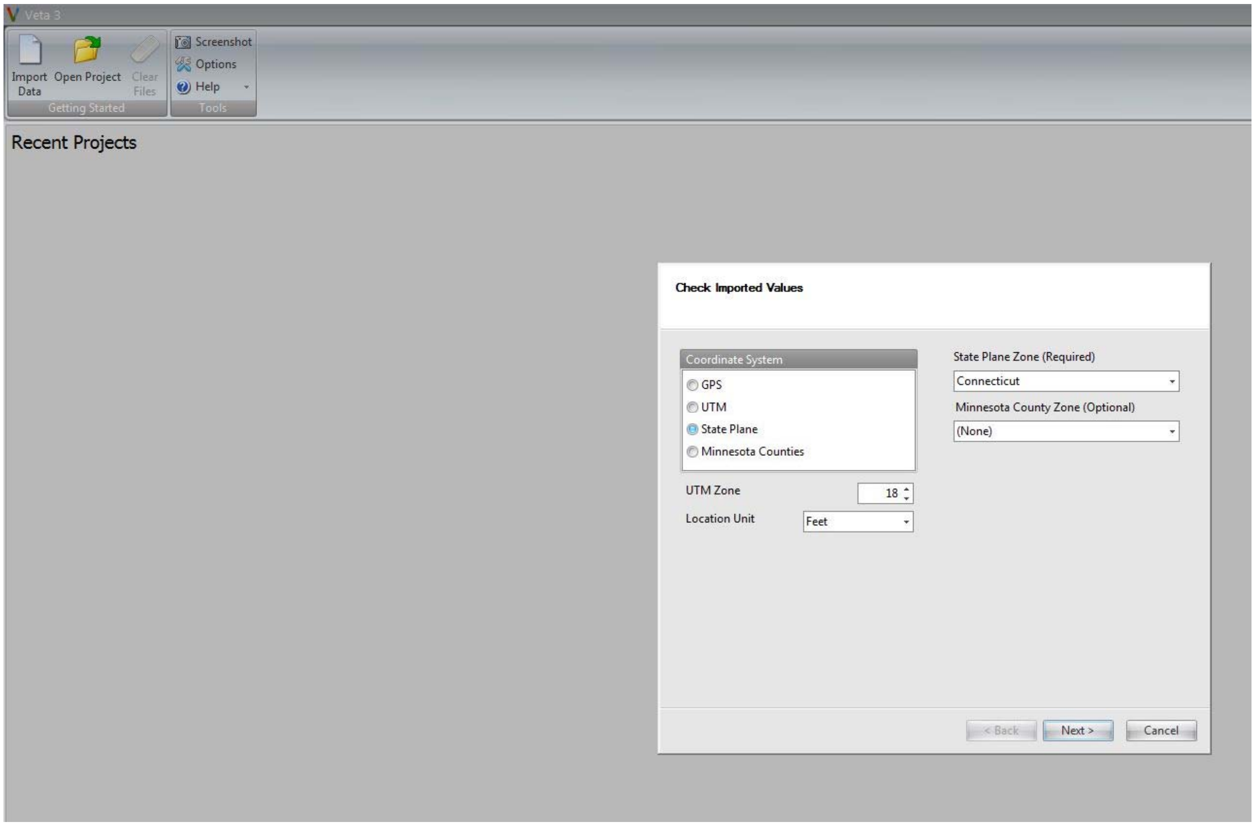
As mentioned previously, CT DOT is currently only interested in the GPS tracking portion of IC to ensure uniformity of the HMA mat. In 2014, CT DOT selected two resurfacing projects on interstate highways for trial of the UC systems. One project is in in southeastern Connecticut on Interstate 95, which included 14 days of paving. The other project is in north central Connecticut on Interstate 84, which involved 18 days of paving. Both projects utilized the IC system developed by Caterpillar. The name of the system is CAT® Accugrade™ Compaction Control System (CCS). Sitech is the name of the company that installed the equipment on the machines, and trained CT DOT personnel and the machine operators. In lieu of utilizing base station equipment on the job site, both contractors used the ACORN real-time positioning system hosted by UCONN. This requires a cellular data device to use files downloaded via the internet for real-time differential correction.

Transfer of the UC data files was initially attempted via email. Because the files contained an extraordinarily large amount of data, this proved difficult. On the second project, data transfer finally was successful utilizing a Trimble® web cloud type service, which allowed easy upload and download of the files.

Veta Mapping of Pilot Projects

Upon collection of the raw data files from each piece of equipment for each night of paving, the files were opened with the Veta software to view the mapping capabilities and evaluate the usefulness of the software. The raw data files were of the type .csv and could be opened and viewed with Microsoft Excel. The first step to view the graphics in Veta was to import the data into the Veta software. Once the file is selected, there are inputs required regarding the coordinate system that was used. These specific inputs are the coordinate system, the UTM zone, distance measurement unit and, in this case, state plane zone. The input screen is shown in Figure 4.

Figure 4. Importing Data Files in Veta



Check Imported Values

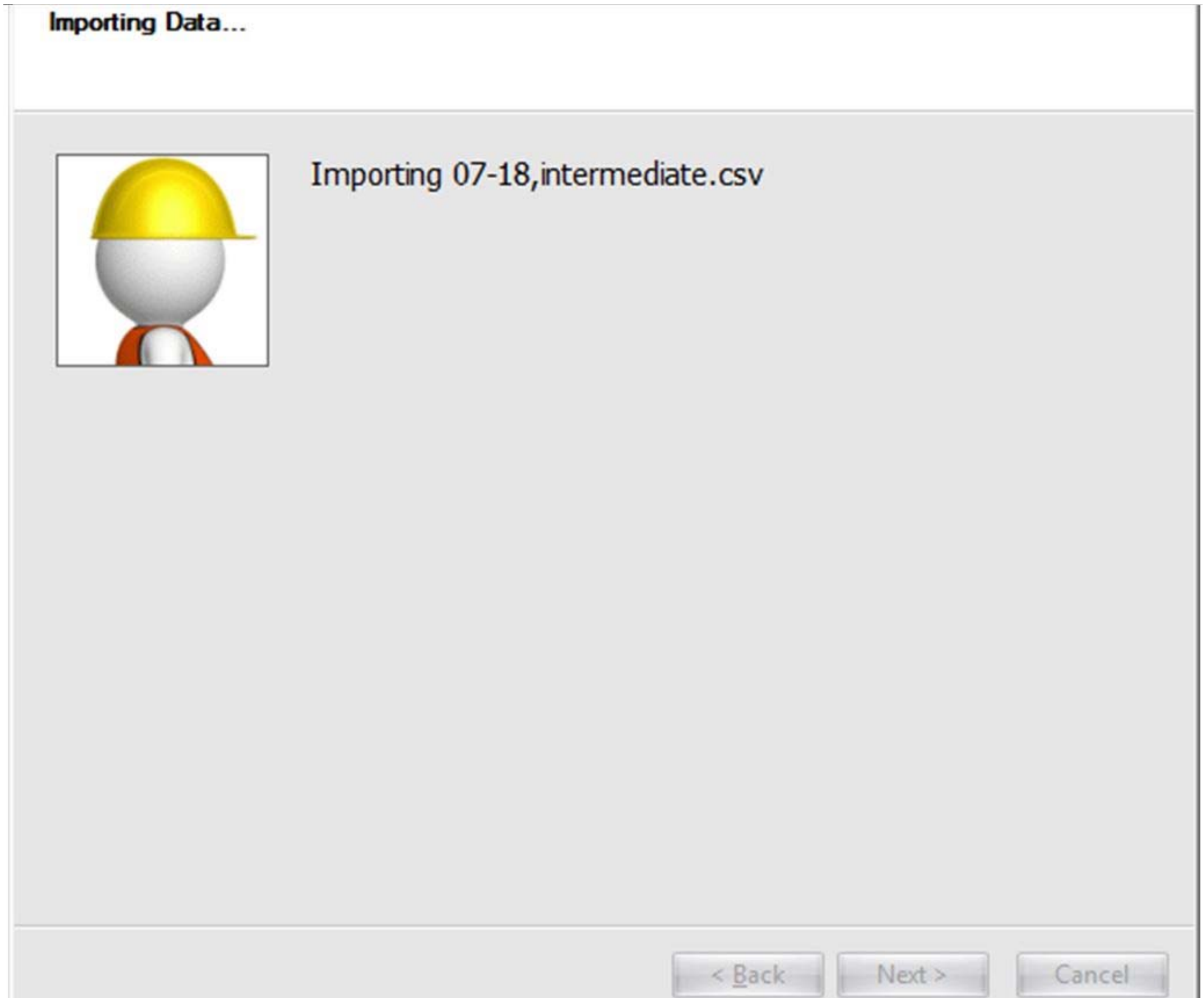
Coordinate System
○ GPS
○ UTM
● State Plane
○ Minnesota Counties

UTM Zone: 18
Location Unit: Feet

State Plane Zone (Required): Connecticut
Minnesota County Zone (Optional): (None)

The software requires the user to input the UTM zone even when it isn't the selected coordinate system. This may be due to state plane zones being based upon UTM projections. Once all of these inputs are complete, as seen in Figures 5 and 6, the map is generated and displayed.

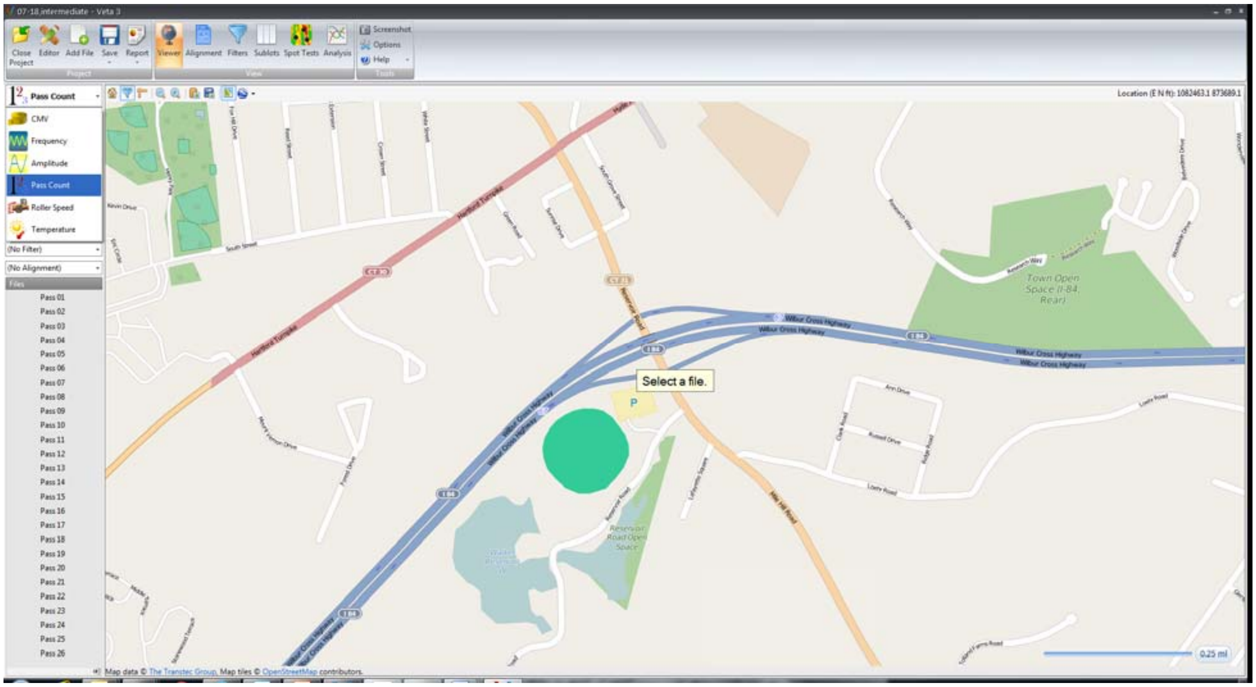
Figure 5. Veta Generating Map



Importing Data...

Importing 07-18,intermediate.csv

Figure 6. Generated Map



Select a file.

Once the map is generated, the user has the option of viewing a graphic of any of the collected data including CMV, roller frequency, roller amplitude, pass count, roller speed or temperature. This option is shown in the menu on the upper left of the image in Figure 6. Any of these graphics can be viewed for any of the roller passes by selecting the pass number in the lower left menu shown in Figure 6. Figures 7 and 8 show pass count coverage for the 1st and then 2nd pass for this particular roller.

Figure 7. Pass Count Map - Pass Number 1

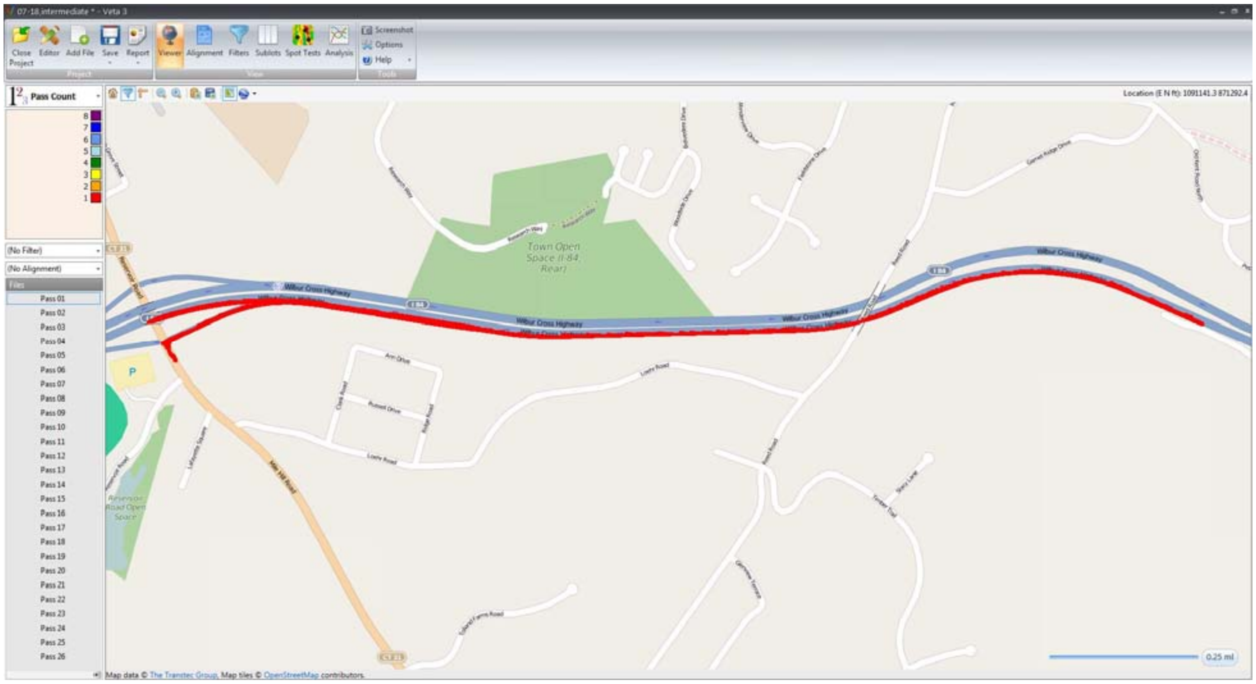
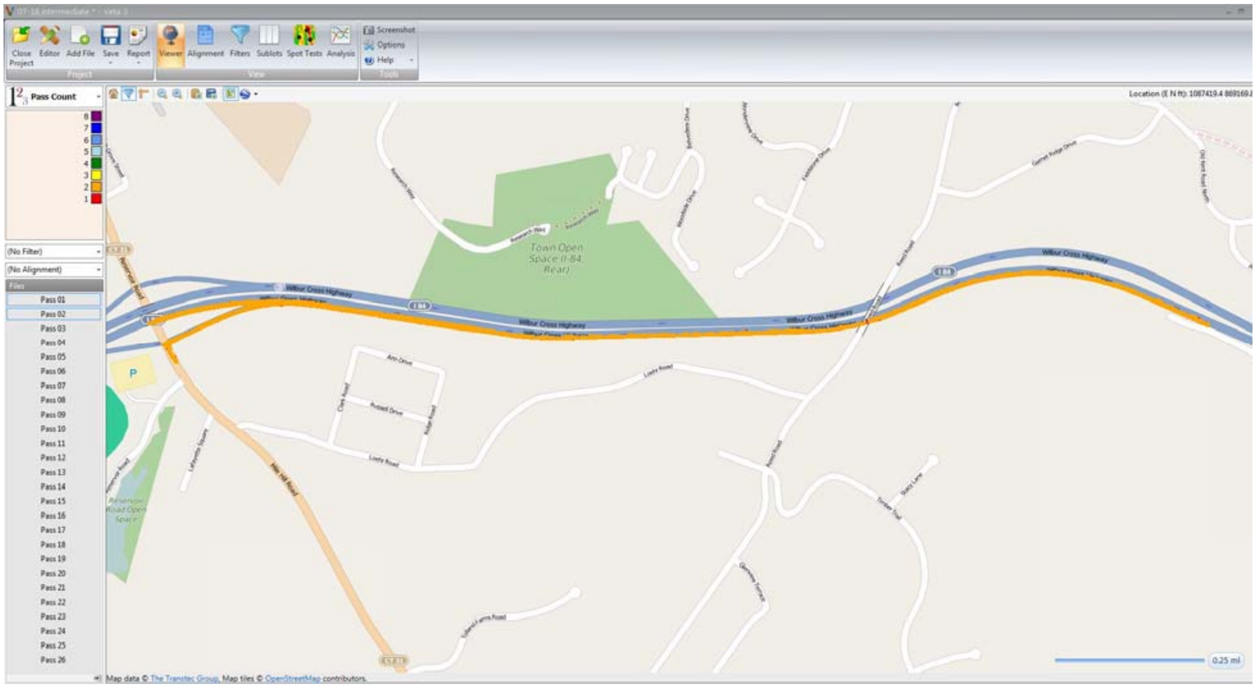


Figure 8. Pass Count Map - Pass Number 2



To this point, from a UC standpoint, the pass count, speed and temperature mapping functions appear useful to the point of making sure all areas were covered. There are some issues that occur in many of the maps where the coverage does not align exactly over the travel way, but adjacent to it. This limits the usefulness of the software by not allowing the user to determine if all areas shown as covered on the map actually received the same treatment.

Compaction Uniformity Analysis

The uniformity of the pavement compacted with the UC equipment was determined by examining the spread or variation in core density data on the pilot projects and comparing those values to the same values on other projects from the 2014 construction season that did not use IC or UC equipment. The projects that were selected for comparison were typical CT DOT limited access resurfacing projects that took place at night. The projects that were selected for comparison purposes consisted of two projects on the same Interstate route by two different contractors and one project on a CT DOT limited access route. The projects that were selected for comparison were constructed using a CT DOT Traffic Level 3 and PMA. All were constructed at night. In order to make sure the comparisons were equitable, the research team selected non-bridge cores on limited access highway projects only. Mat cores were grouped together for analysis, and joint cores were grouped separately for the analysis. A summary of the descriptive statistics are shown in Table 1 and Table 2.

Table 1. Mat Cores Descriptive Statistics

Core Group	# of Cores	Mean Density (%MTD)	Standard Deviation*	Variance	C.V.*
UC	147	94.1	1.6	2.5	1.7
Non-UC	84	92.0	2.2	4.9	2.4

***Coefficient of Variation as a percentage of the mean**

Table 2. Joint Cores Descriptive Statistics

Core Group	# of Cores	Mean Density (%MTD)	Standard Deviation*	Variance	C.V.*
UC	148	91.7	1.6	2.5	1.7
Non-UC	71	89.6	1.7	2.8	1.9

***Coefficient of Variation as a percentage of the mean**

From Table 1, it is evident that there was a marked improvement in both density and uniformity when viewing the descriptive statistics for the UC mat cores. The improvement in density is 2.1 % of MTD, and the variance is half that of the non-UC mat cores.

The joint cores (Table 2) show an improvement in overall density; however, the uniformity is not improved to the same degree as the mat cores. In order to determine if these improvements were statistically significant, a Levene's F-test was conducted on the core density values. This analysis compared the variance of the UC cores to that of the non-UC cores. A Levene's F-test is conducted using the absolute value of the difference between each observation and the mean. An analysis of variance (ANOVA) is then conducted between the UC differences and the non-UC differences. An F-statistic is then generated and compared to the critical value for the test. The results of the Levene's test comparisons are shown in Tables 3 and 4.

Table 3. Levene's F-test for Variances on Mat Cores

Groups	*Count*	*Sum*	*Average*	*Variance*
Non-UC Difference	84.0	142.2	1.7	2.0
UC Difference	147.0	187.3	1.3	0.9

ANOVA

Source of Variation	*SS*	*df*	*MS*	***F***	*P-value*	***F crit***
Between Groups	9.4	1.0	9.4	**7.3**	0.0	**3.9**
Within Groups	295.7	229.0	1.3			
Total	305.1	230.0				

Table 4. Levene's F-test for Variances on Joint Cores

Groups	*Count*	*Sum*	*Average*	*Variance*
Non-UC Difference	71.0	88.8	1.3	1.2
UC Difference	148.0	182.3	1.2	1.0

ANOVA

Source of Variation	*SS*	*df*	*MS*	***F***	*P-value*	***F crit***
Between Groups	0.0	1.0	0.0	**0.0**	0.9	**3.9**
Within Groups	234.8	217.0	1.1			
Total	234.9	218.0				

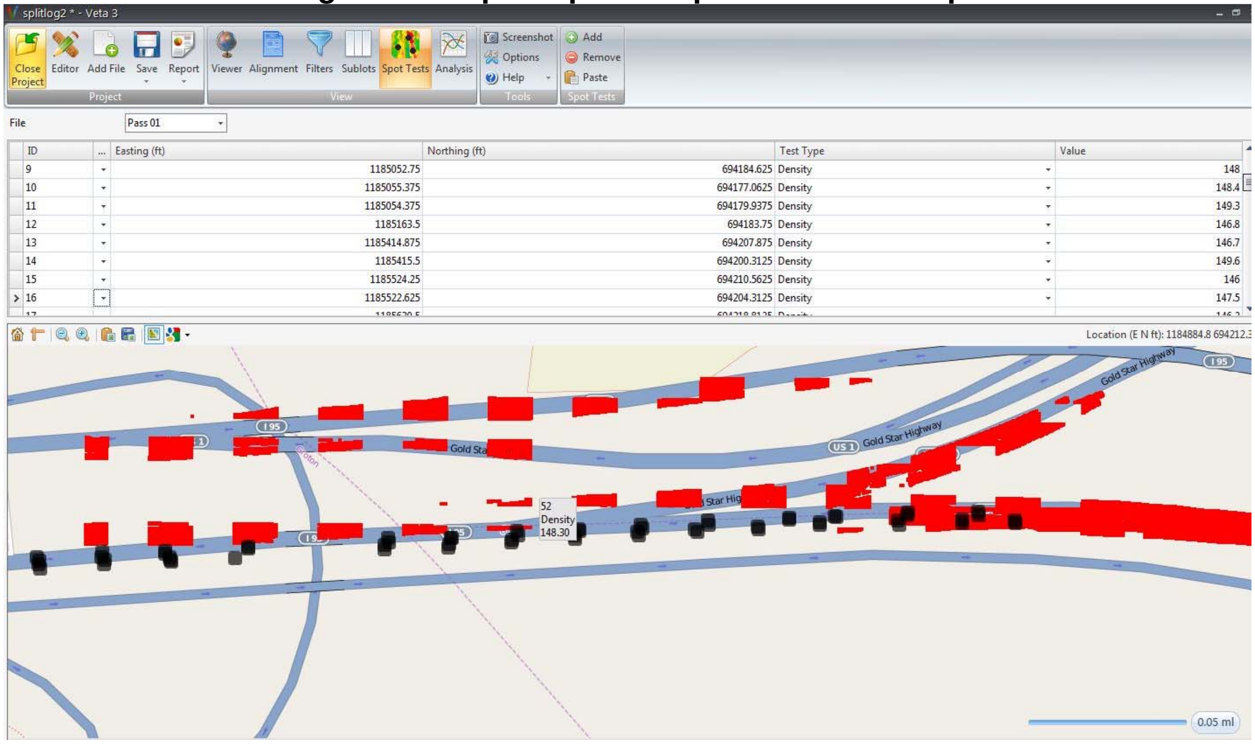
Table 3 gives convincing evidence that the UC and non-UC mat density cores have much different levels of variation. The F-statistic is nearly twice the critical value. The UC equipment appears to have not only improved overall density, as discussed, previously, but also significantly improves the uniformity of the mat.

Table 4 shows the comparison for the joint cores. The F-statistic is so low that, when rounded to one decimal point, it is 0.0. This, combined with the high p-value, is enough to accept the null hypothesis that the averages (in this case average variations) are not statistically different. This is not proof that they are the same; there is just no compelling evidence that they differ. This is consistent with conclusions that can be drawn from the descriptive values in Table 2. It can be stated that use of the UC equipment had a more profound impact on mat uniformity than joint uniformity.

Nuclear Density Measurements

CAP Lab personnel were on hand for a few nights of paving on each project to witness the process as well as conduct a series of nuclear density measurements. The intent was to correlate these measurements with the acceptance cores and conduct a uniformity analysis on the correlated values. This would lend insight to the uniformity of the pavement on a tighter scale because the nuclear density measurements were taken approximately 100 feet apart from each other. Another goal of this effort was to see what value there was in superimposing this data on the Veta map from the rollers on those respective nights of paving. CAP Lab rented a GPS rover (Trimble® SPS985) to track the exact location of the nuclear measurements. The nuclear density values were input into the rover system manually immediately after each test. This data was then loaded manually into the Veta file for that night using the Spot Tests option. A screen shot of the superimposed information is shown in Figure 9.

Figure 9. Superimposed Spot Test Veta Map



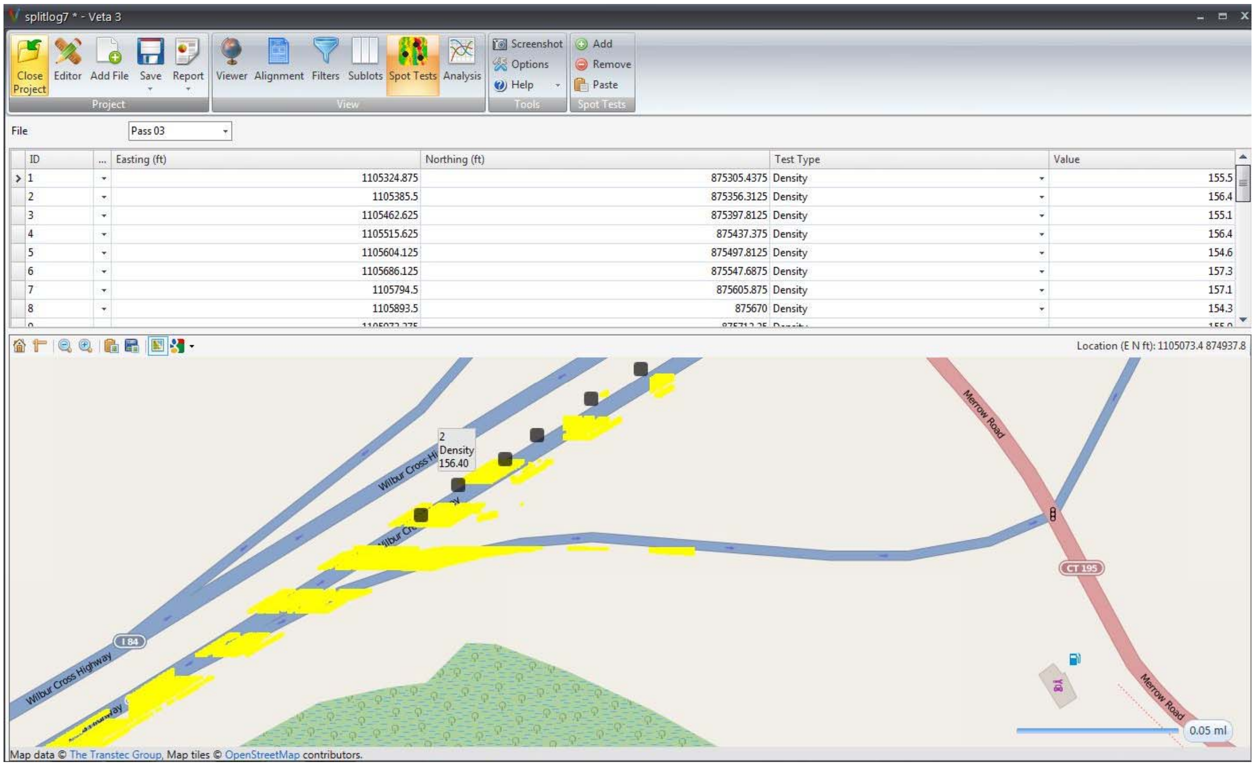
File: Pass 01

ID	...	Easting (ft)	Northing (ft)	Test Type	Value
9		1185052.75	694184.625	Density	148
10		1185055.375	694177.0625	Density	148.4
11		1185054.375	694179.9375	Density	149.3
12		1185163.5	694183.75	Density	146.8
13		1185414.875	694207.875	Density	146.7
14		1185415.5	694200.3125	Density	149.6
15		1185524.25	694210.5625	Density	146
16		1185522.625	694204.3125	Density	147.5

***Black Squares indicate Superimposed Spot Test Locations**

The usefulness of the spot tests being overlaid on the Veta maps lies in the ability to view the actual property of the material at that given location. The black dots on the map indicate the spot locations where NDG measurements took place. Unfortunately, it was found that there are shortcomings in the mapping coverage graphics as well as the location of both machine coverage and spot tests. As seen in Figure 9, it appears that the roller was operating adjacent to the highway in some instances. It also appears that the roller missed covering several spots, as seen in between the red areas. This is also the case in Figure 10 where it appears the roller was rolling, intermittently, off of the roadway, and some of the spot test locations also did not locate in the roadway, but adjacent to it.

Figure 10. Roller and Spot Test Veta Map



File: Pass 03

ID	...	Easting (ft)	Northing (ft)	Test Type	Value
1		1105324.875	875305.4375	Density	155.5
2		1105385.5	875356.3125	Density	156.4
3		1105462.625	875397.8125	Density	155.1
4		1105515.625	875437.375	Density	156.4
5		1105604.125	875497.8125	Density	154.6
6		1105686.125	875547.6875	Density	157.3
7		1105794.5	875605.875	Density	157.1
8		1105893.5	875670	Density	154.3

Location (E N ft): 1105073.4 874937.8

Map data © The Transtec Group, Map tiles © OpenStreetMap contributors.

Unfortunately, the GPS coordinates were not taken at the acceptance coring locations; so, correlation with nuclear density values was not conducted. Basic descriptive statistics of the nuclear density values are shown in Tables 5 and 6 for the two different projects.

Table 5. Nuclear Density Descriptive Statistics

Project	Number of Measurements	Mean Density (PCF)	Standard Deviation	Variance	C.V.*
I-95	175	146.8	2.1	4.4	1.4
I-84	118	155.2	2.2	5.0	1.4

***Coefficient of Variation as a percentage of the mean**

The descriptive values in Table 5 indicate that both projects were similar in terms of uniformity at least for the three nights per project in which the research team was conducting nuclear density measurements.

Conclusions and Recommendations

Based upon the literature contained in the reviewed FHWA IC reports, as well as what was found with use of UC equipment on two pilot projects in Connecticut, it is quite clear that IC/UC is capable of collecting many different types of data at a very high rate. This includes roller settings, stiffness, speed, material surface temperature and ground coverage. These data are displayed real-time, which can be a significant benefit to contractors as informed decisions can be made as to when to start/continue/discontinue compactive effort. The benefit to agencies (such as CT DOT) is evident from the improvement in density and uniformity of the pavement that was demonstrated on pilot projects on I-84 and I-95 during 2014. Mapping of the data, via Veta software, may prove useful in identifying areas of distress in support layers if the ICMV can eventually be correlated with density and if the mapping itself is improved. Based upon the research conducted for this study, the research team makes the following recommendations:

- The IC/UC equipment should not be used as an acceptance tool at this time.
- The IC/UC equipment should not be used for identifying areas of distress on HMA surfaces at this time, as there is no conclusive evidence of good correlation between the ICMV values and pavement density.
- The source of the mapping issues identified (superimposed coverage not aligning over the roadway) during this study should be investigated and identified.
- An alternate coordinate system should be trialed in an effort to improve mapping issues as suggested by the FHWA report [3]. UTM is the recommended system and it is stated to use caution when using the State Plane system.
- IC/UC lends itself well as a Quality Control tool and contractors should be encouraged to use the equipment.
- Contractors who choose to employ this technology should take advantage of the ability to develop compaction curves on long term projects that last

for multiple days in order to optimize compactive effort and ultimately project density.

- The IC/UC equipment may be useful in identifying problems with support layers if used to map granular bases prior to paving.
- Use of the equipment for UC purposes was successful in improving overall density and uniformity, and should be promoted moving forward.
- When use of UC/IC equipment is required, transfer of the data files should take place daily to ensure continuity of the data. This is the case when only the UC data is required, and also when all IC data is required. The reason for this is the extraordinarily large volume of data.
- Transfer of the UC data files should be managed by uploading to a cloud-based system for easy downloading and to ensure data files are not lost. Email transfer of data files is not recommended.

References

1. *Intelligent Compaction: One-Stop Shop for IC*, The Transtec Group, Copyright 2008-2015. http://www.intelligentcompaction.com/

2. "Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials", Report No. FHWA-IF-12-002, Federal Highway Administration, Office of Pavement Technology, July, 2011.

3. "A Study on Intelligent Compaction and In-Place Asphalt Density", Report No. FHWA-HIF-14-017, Federal Highway Administration, Office of Pavement Technology, December 2014.

4. "Veta User's Guide, Version 3.0", The Transtec Group, Incorporated, and Minnesota Department of Transportation, Copyright 2011 – 2015.