INTELLIGENT COMPACTION DATA ANALYZING

FINAL REPORT ~ FHWA-OK-XX-XX

ODOT SP&R ITEM NUMBER 2160-18-03

Submitted to:
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DISCLAIMER

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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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)		
°C	Celsius	1.8C+32	Fahrenheit	°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

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16. ABSTRACT
Intelligent Compaction (IC) is becoming a useful tool for monitoring compaction quality of asphalt mixes during construction. The Oklahoma Department of Transportation (ODOT) has let nine projects using the IC technology for asphalt paving projects. For each project, ODOT paid the contractor to purchase the IC equipment and collect data. The collected IC data were submitted to the residencies associated with those projects. The IC data for three selected projects were analyzed by the OU research team in this Task Order using the VETA 5.1 software. The analysis was focused on data quality, missing data, data filtering, and compliance with ODOT IC Special Provision 411-18(a-e) and AASHTO PP 81. The VETA results were limited to percent coverage or number of roller pass, temperature, roller speed and roller frequency. Other quality indicators such as CMV and moduli were not analyzed. The target for the minimum number of roller passes was not specified. So, it was assumed as two for each project. Because of the lack of GPS data on actual pavement boundaries, custom boundaries were generated in VETA using a constant width of the pavement. A high degree of variability in the IC data was observed for the selected sites. For one project, the VETA software could not process the collected data for several files (corrupt files). Inconsistent file naming was another issue. In spite of variability, the VETA results were found very useful in checking ODOT and AASHTO requirements on coverage, number of roller pass, compaction temperature, roller speed and roller frequency. Point-wise temperature data are found to have some inherent weaknesses due to various factors that can influence surface temperature during compaction, including collecting data from outside of the paving zone. This was reflected in the minimum temperature results for all three sites. The VETA software was found to be a useful tool for analysis of IC data, irrespective of the IC provider used. For the sites studied, three different IC providers were used in collecting the IC data. Yet, the VETA software was able to process data for each site. An accurate layout of the project boundary is extremely important for the analysis of IC data. The Location Filter option in VETA allows user-defined project boundary. It is recommended that the future IC projects be encouraged to collect this data to enhance the accuracy of results. It is known that a thermal profile obtained from an IR bar/scan (MOBAR), mounted on the back of a paver, provides a much more useful data on paving quality than point-wise data from the temperature sensor mounted on the roller. Thus, it is recommended that future IC projects consider collecting MOBAR data and integrate such data with the IC data. IC data from only three sites were analyzed in this project. It is recommended that the IC data from the remaining sites be analyzed to realize the benefits of the agency investment.

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INTRODUCTION

Background

Long-term performance of flexible pavements is significantly influenced by the compaction quality achieved in different layers during construction (Commuri et al., 2011; Barman et. al., 2015; Yoon et al., 2018). The current compaction quality control techniques involve measuring density at selected locations during construction using density gauges and extracting cores from the constructed pavements. Consequently, these techniques do not adequately reflect the overall quality of the constructed pavement (Commuri, 2011). Many factors such as rolling pattern, coverage (number of passes), operational parameters (roller weight, frequency, speed, etc.), weather (temperature, wind, solar radiation, precipitation, etc.) can affect the density within a project, causing over- or under-compaction of asphalt mats (Von et al., 2010). To ensure uniform compaction throughout the asphalt pavement, several researchers have proposed different Intelligent Compaction (IC) technologies for monitoring compaction quality in real-time (Peterson, 2005; Camargo et.at., 2006; Commuri, 2011, Yoon et.al., 2018).

According to the Federal Highway Administration (FHWA), IC is defined as an advanced roller equipped compaction process that automatically records real-time parameters with an integrated measurement system including an accurate global positioning system (GPS), onboard computer reporting system, accelerometers, and infrared thermometers (Nieves, 2013). In recent years, efforts have been made to develop IC technologies based on vibrations and resistance force of instrumented rollers (Peterson, 2005; Camargo et.at., 2006; Peterson and Peterson, 2006; Barman et al., 2015). Various machine parameters such as amplitude and frequency of vibrations, harmonic ratio, energy ratio, and stiffness have been used as an indicator of uniform compaction. Over-compaction of pavements can also be avoided by controlling these parameters in real-time (Peterson, 2005; Peterson and Peterson, 2006). Several transportation agencies, including the Federal Highway Administration (FHWA) and some state DOTs (e.g., Minnesota, California, and Missouri), have evaluated the IC technologies in the field (Chang et al., 2011). Despite a lack of uniform specifications within the state DOTs and variations among manufacturers in quality control parameters, the IC technology is becoming a useful tool for monitoring compaction quality of asphalt pavements during construction. Minnesota DOT is planning to fully implement the IC technology on all asphalt pavement construction projects by 2020 (Chang et al., 2018).

Although different IC roller manufacturers are using different parameters as indicators of compaction quality and in-situ properties of the constructed pavement (e.g., density, modulus, stiffness, etc.), there is a need to analyze the IC data uniformly (Commuri, 2011; Mazari, 2017; Chang et al., 2018). To address this need, Transtec Group, Inc. and Minnesota DOT worked collaboratively in a FHWA project to develop a software, VETA, for analysis and management of IC data (Intelligent Compaction, 2018). Among many benefits, VETA is available free of cost and is becoming an effective intelligent construction data management (ICDM) and analysis tool (Chang, 2018). In VETA, compaction quality is evaluated in terms of coverage (number of pass), intelligent compaction measurement values (ICMV), roller speed, roller frequency, and temperature. The results are provided both in tabular and pictorial forms (e.g., pie charts), including statistical significance. VETA can analyze coverage in both vibratory and static modes.

Scope

Oklahoma Department of Transportation (ODOT) has developed Special Provision 411-18(a-e) for using the IC technology by paving contractors in Oklahoma. Also, AASHTO has developed guidelines and requirements (AASHTO PP 81, 2014) for using the IC technology for projects involving compaction of roadway embankments or asphalt pavements or both. To initiate implementation of IC, ODOT selected nine projects for using the IC technology by asphalt paving contractors in Oklahoma. For each project, ODOT paid the contractor to purchase the IC equipment and collect data. The collected IC data were submitted to the residencies associated with those projects.

The purpose of this Task Order was to analyze the collected data from three selected projects, using VETA. The data analyses were focused on data completeness, missing data, data quality, and data usefulness. Project location, construction time, file name, the IC platform used, and other pertinent information were identified from these data. Also, previous IC studies were reviewed selectively and reported in the monthly progress reports. In addition, a closeout meeting was held at ODOT to discuss the findings of this Task Order and to seek input from the Project Panel. The meeting covered the data analysis process, data filtering, and data usefulness, as noted above. This report provides a brief overview of selected previous studies, a description on data filtering, compliance, file naming, project boundary adjustment, data quality, and missing data. Findings from the VETA results are also discussed, followed by conclusions and recommendations.

IC TECHNOLOGIES AND OVERVIEW OF SELECTED PREVIOUS STUDIES

Intelligent compaction (IC) is becoming a useful tool to improve quality of compaction of asphalt pavements during construction. Its applications by FHWA, state DOTs and construction companies have primarily focused on the quality control (QC) aspects. Presently, the IC systems available commercially can be broadly divided into two categories: Original Engineering Manufacture (OEM) and after-market IC retrofit (Chang et al., 2018). The OEM comes directly from roller vendors factory. The IC retrofits, on the other hand, are usually placed on selected models of rollers. When a vibratory roller moves on an asphalt mat, a rebound force is generated from the compacted materials to the roller drums. Changes in this rebound force are used as an indicator of the compaction level and represented as the Intelligent Compaction Measurement Value (ICMV) (Chang et al., 2018).

A survey conducted by Yoon et al. (2018) found that state DOTs are currently using the IC technology primarily for Quality Control (QC) purposes. No state DOTs responding to this survey were using it as a Quality Assurance (QA) tool. Lack of specifications for compaction quality parameters (e.g., stiffness), lack of availability of IC equipment (e.g., retrofit) from manufacturers, and lack of training were cited as constraints for a broader adoption of the IC technology, among others. On the positive side, 13 out of 24 state DOTs that responded to this survey were planning to implement the IC technology in the future. Increased uniformity in compaction, less maintenance, and night-time paving were reported as the benefits of the IC technology by several DOTs. Also, several DOTs reported good correlations between non-nuclear gauge (NNG) density and pass counts.

The University of Oklahoma, under the leadership of Profs. Commuri and Zaman, has been working on developing IC technology, called Intelligent Compaction Analyzer (ICA), for more than a decade (Commuri et al., 2011; Barman et al., 2015; Imran et al., 2016; Barman et al., 2018). In ICA, coupled vibrations of an instrumented roller and the asphalt mat being compacted are collected using an accelerometer mounted on the roller drum. Dominant features from the vibration data are extracted using the Fast Fourier transform technique. A trained Artificial Neuron Network (ANN) is then used to predict density and stiffness of the asphalt mat as an indicator of compaction quality. The estimated ICA densities were found to correlate well with the core densities and with measured densities using a non-nuclear density gauge (NNDG).

Xu and Chang (2013) employed computer-aided methods to analyze IC data. It was reported that the compaction curves can be used to determine the optimum roller passes and to avoid over- or under-compaction during construction. Compaction Control Value (CCV) was suggested as an indicator of compaction level.

Hu et al. (2017) evaluated the effectiveness of Intelligent Compaction (IC) using two HMA resurfacing projects in Tennessee. Statistical analyses of IC parameters and in-situ densities of the HMA layer were conducted. The compaction curves were suggested as an indicator of compaction level and for determining the optimum number of roller pass. A detailed review of IC is given by Hu et al. (2017).

VETA Software

VETA is a map-based tool for viewing and analyzing geospatial data. IC machines monitor real-time asphalt or soil compaction progress, and thermal profilers collect temperatures of asphalt mats immediately behind pavers. VETA displays compaction information in easy-to-read formats, including graphs and maps (Chang et al., 2018). This software is increasingly used as a tool for intelligent construction data management (Intelligent Compaction, 2011).

VETA can import IC data from various rollers and perform data editing, data sorting, point verification, and data analysis. The raw IC data are stored by different machines as un-gridded data along the roller movement line. These raw data are then gridded in VETA by 1 ft X 1 ft area to better locate the roller coverage, as shown in Figure 1 (Chang et al., 2018). The IC data throughout the compaction process are recorded as “all passes” data, while the final coverage is represented as the final product of the IC data (Chang et al., 2018). Thus, a “final coverage diagram” reflects the “bird’s eye view” of the overall IC data. VETA generally imports the “all passes” data and provides the output as the “final coverage data” (Chang et al., 2018).

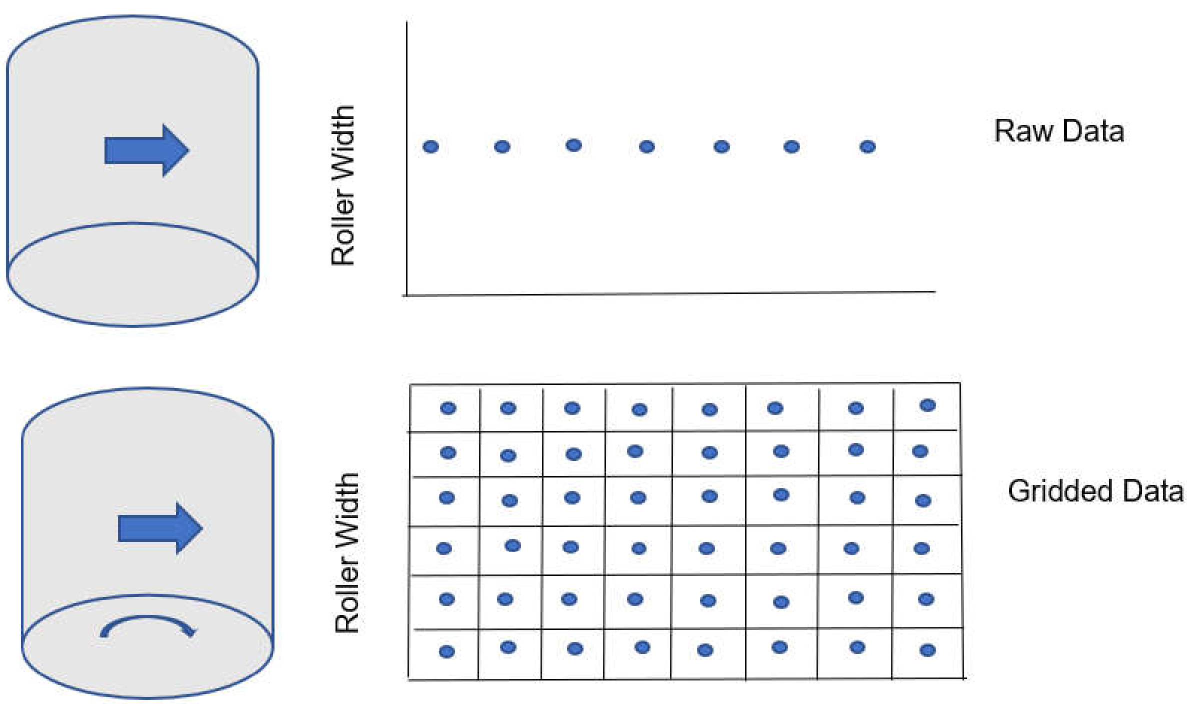


Figure 1 IC Raw and Gridded Data (after Chang et al., 2018)

METHODOLOGY

In this project, IC data from three projects were analyzed using the VETA 5.1 software. The data collection system does not always give a unique name to a file, which requires the user to rename the file using a unique identifier. Also, the IC data files are usually very large files (generally giga bites), making data sorting and filtering a challenging task. Project length is another important factor when lot-wise data analyses are involved. Technology platform (e.g., TOPCON, Bomag, Catterpillar, Hamm, Sakai, Volvo) is yet another variable because not all platforms record data in the same format or same order or record the same data. Thus, analysis time can vary significantly from one project to another.

Data Recording

The VETA software converts the raw IC data into gridded data, as shown in Figure 1. The IC data for two passes are shown in Table 1, as an example. Each grid point is identified uniquely by its latitude and longitude. As shown in Table 1, on September 30, 2016 the first roller pass (see last column called “Pass Number”) at grid point (36.66701, -98.1817) occurred at 12:55:32.739 pm. At the same grid point, the second roller pass occurred at 12:57:49.739 pm, about two minutes after the first roller pass. Table 1 also shows that the elevation of this grid point changes between roller passes. Although the elevation of a grid point is expected to decrease with roller passes due to compaction, the elevation of this grid point is found to increase during the second roller pass. Several factors might cause this variation including roller vibration and direction of roller movement (forward, backward). A vibratory roller creates an uneven surface. The peaks and valleys of the surface shift from one roller pass to another. Depending upon the location of a grid point, its elevation can, thus, increase temporarily during consecutive roller passes. Vertical gradient of a grid point can also influence the level of undulation of the surface. Viscosity of the asphalt mix during compaction influences the surface geometry as well. The recorded data for four passes at grid point (36.30419, -119.7288004) are shown in Table 2, where the time lapse between Pass 1 and Pass 4 is about 6 minutes. It is evident from Table 2 that the elevation of this grid point steadily decreases with the increase in roller pass due to compaction.

Table 1 Data Recording for Two Passes

Time	Latitude, °	Longitude, °	Elevation, ft	Pass Number
2016-Sep-30 12:55:32.739	36.66701	-98.1817	1247.425	1
2016-Sep-30 12:57:49.739	36.66701	-98.1817	1247.557	2

Table 2 Data Recording for Four Passes

Time	Latitude, °	Longitude, °	Elevation, ft	Pass Number
2015-Jun-15 13:12:41.436	36.30419	-119.7288004	119.124	1
2015-Jun-15 13:15:05.436	36.30419	-119.7288004	119.114	2
2015-Jun-15 13:17:22.436	36.30419	-119.7288004	119.111	3
2015-Jun-15 13:18:41.436	36.30419	-119.7288004	119.078	4

Data Formatting

Currently, different IC platforms are collecting IC data in different formats. For example, data files generated by SAKAI are in .pln (Polyline) format, whereas, Trimble's data files are in .csv (Comma-separated values) format. The TOPCON system also generates data files in .pln format (see Table 3). The VETA software uses different input files (Table 4) and creates a new file in .vetaproj (VETA project) format, as the output file. According to AASHTO PP 81 (2014), the data files should be named according to the date of collection of data using the following format: MMDDYY where MM indicates month, DD indicates data, and YY indicates year. A summary of input files generated by different IC platforms and the output files generated by VETA is given in Table 3.

Table 3 Files Format for Various Companies

Company	Generated Files Format	Output Files Format
SAKAI	.pln	.vetaproj
Trimble	.csv	.vetaproj
HAMM	.vexp	.vetaproj
MOBA	.log	.vetaproj
CAT	.csv	.vetaproj
TOPCON	.pln	.vetaproj
VOLVO	.csv	.vetaproj

As noted previously, IC data from three selected sites were analyzed in this Task Order. These data were collected using the IC technology provided by three different companies; namely Trimble, Bomag and Sakai. The formats of the generated files, manufacturer names, and the output file are summarized in Table 4.

Table 4 Files Format for Three ODOT Projects

Project	Company	Generated Files Format	Output Files Format
1	Trimble	.csv	.vetaproj
2	Bomag	.pln	.vetaproj
3	SAKAI	.pln	.vetaproj

Data Filtering and Cleaning

Data filtering and cleaning are an important step in IC data processing. Need for data filtering arises for different reasons. For example, a roller may occasionally move outside the pavement boundary (longitudinal joint, existing asphalt layer next to freshly laid asphalt, filling roller with water, etc.). The IC data outside of the paving boundary, as shown by extended rectangles outside the red line (paving boundary) in Figure 2, are not useful data. Such data should be taken out in the filtering process. Also, some regions may remain uncompacted for various reasons such as presence of concrete curb, utilities, fire hydrant, paving geometry, and human factors. An objective assessment of coverage requires that the IC data be filtered properly. The VETA software has several features for filtering or cleaning the raw data. An accurate layout of the paving boundary is important to the accuracy and efficiency of data filtering and cleaning. Some specifics are discussed below.

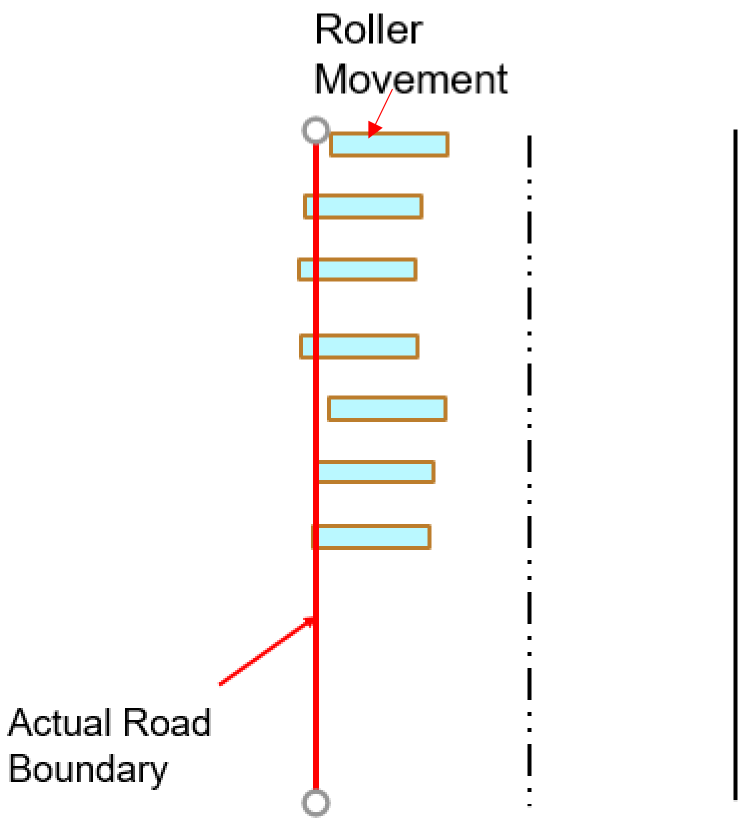


Figure 2 Data Filtering for Road Boundary

1. **Location Filter:** The location filter is used to encapsulate data within custom boundaries. Pass counts or coverage can be accurately analyzed only within a location filter, as it includes paving zones or area that did not receive any passes (indicated as “no pass” in tables) from the breakdown roller. As discussed later, boundary line or GPS coordinates of constructed pavements can be imported into VETA to obtain an accurate location filter that automates the filter location process, as shown in Figure 3. The dotted line indicates the GPS coordinates at every 3-ft interval of the project boundary.

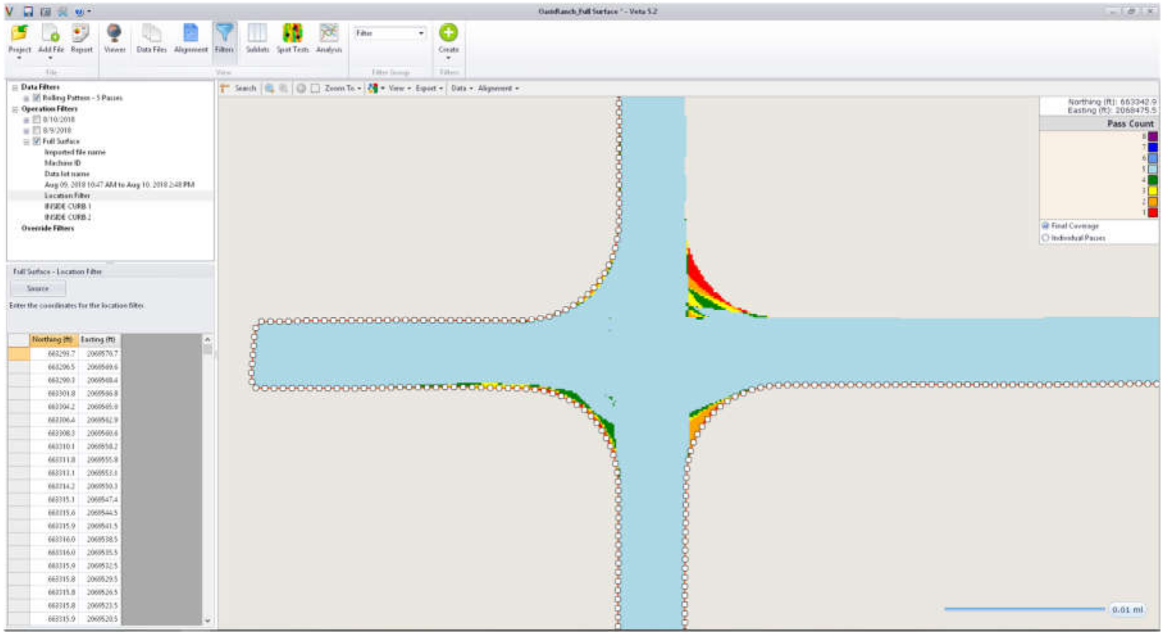


Figure 3 Location Filter Reflecting Actual Curb-Line.

1. **Time Filter:** The time filter is used to filter data by specific dates and times. Data can be organized sequentially according to "construction date," thereby allowing for the separate analysis of data for each day.
2. **Data Filters:** These features allow for direct filtering of data types such as Pass Count, Frequency, and Temperature. For example, the user has an option of setting a minimum temperature (e.g., 176°F) and thereby excluding all temperature data that may have been collected from a previously paved asphalt mat. Chang et. al. (2018) suggested data cleaning based on a threshold temperature value, as shown in Figure 4. In case of Figure 4, data having a temperature of lower than 176°C were excluded from the analysis. The discontinuity of IC data observed in Figure 4 (elliptical area shown in red) was caused by the filtering of data based on the temperature. In reality, the roller was passing over a concrete bridge without any paving of that segment, although the temperature data collection continued for that segment. Thus, data filtering using temperature is a useful feature of VETA.

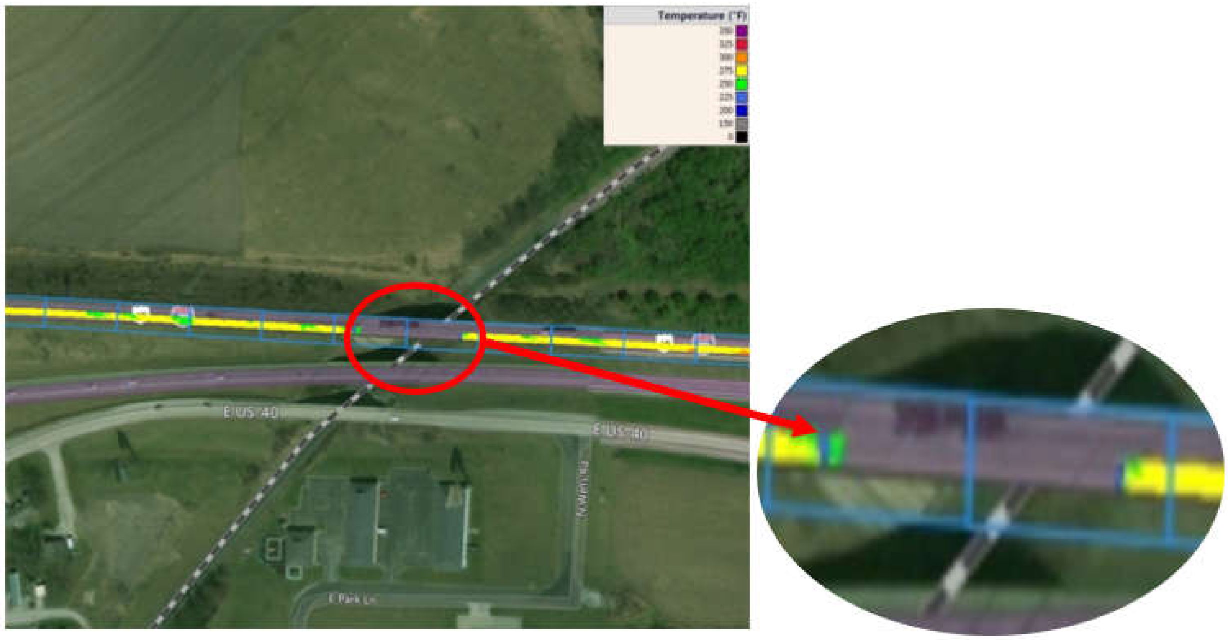


Figure 4 Data Cleaning Based on Threshold Temperature (Chang et al., 2018)

3. **Vibration Filter:** This filter in VETA can be used for screening the IC data according to compaction modes (vibratory mode vs static mode) (Intelligent Compaction, 2011). Figure 5 shows the vibratory compaction mode. This filter can be used to determine coverage for vibratory mode only, static mode only or for both vibratory and static modes. This is also an important filtering feature in VETA (Figure 5).

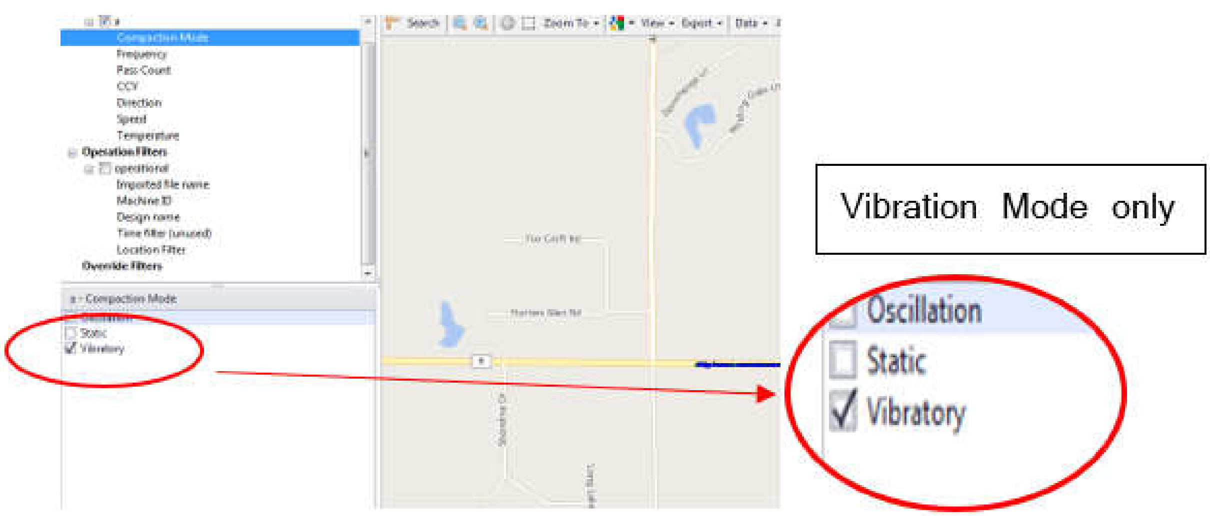


Figure 5 Data Filtering in VETA Analysis by Using Compaction Mode

RESULTS AND DISCUSSION

As noted previously, in this Task Order, the OU team analyzed the IC data for three selected projects obtained from ODOT. A summary of the results for all three projects is given in this section.

Project 1: Highway 38

Project 1 was a resurfacing project in Alfalfa County. About 11,160 tons of S4 mix were used in this project. The overall IC data consisted of 12 files. The VETA software was able to process each file. Thus, the IC data in this project did not have any corrupt file. The location of this project and a typical cross-section of the pavement are shown in Figure 6 and Figure 7, respectively. No data for the paving boundary was available in the data file. Based on the typical cross-section in Figure 6, the width of the lane was considered as 16-ft. The coverage data or the number of roller passes was determined based on this boundary. Other general information of this project is given below:

Project 1: Highway 38
County: Alfalfa
Number of segments analyzed: 12
(based on the number of files)
Number of corrupt files: None
Contract ID: 160001
Call order: 20
Asphalt tonnage: 11,160 tons (S4 mix)
Type of work: Resurfacing or overlay
Typical lane width (with shoulder): 16-ft
Construction period: Oct. 4 – Oct. 22, 2016

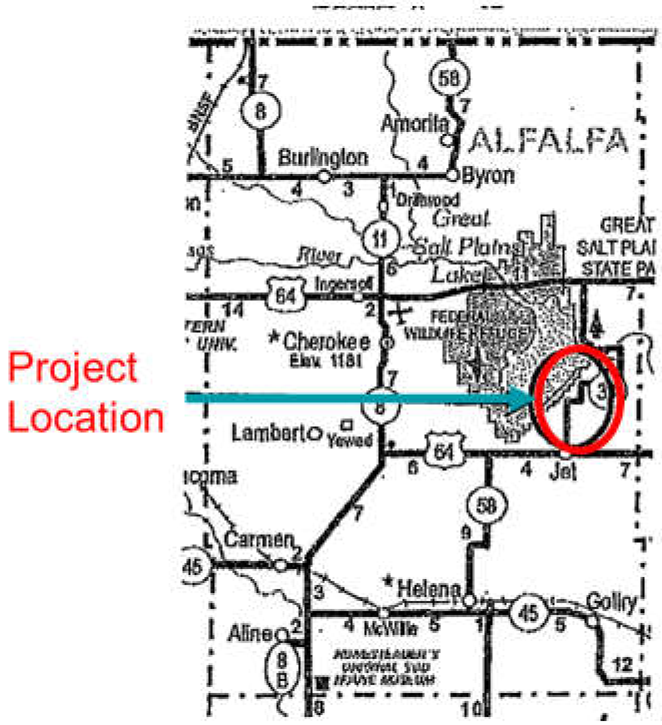


Figure 6 Location of Project 1

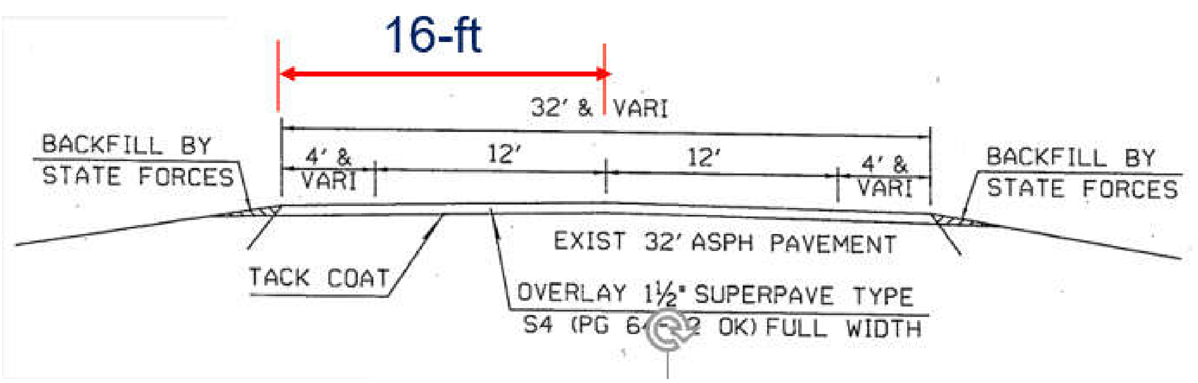


Figure 7 Typical Cross-Section of Project 1

Percent Coverage or Number of Passes:

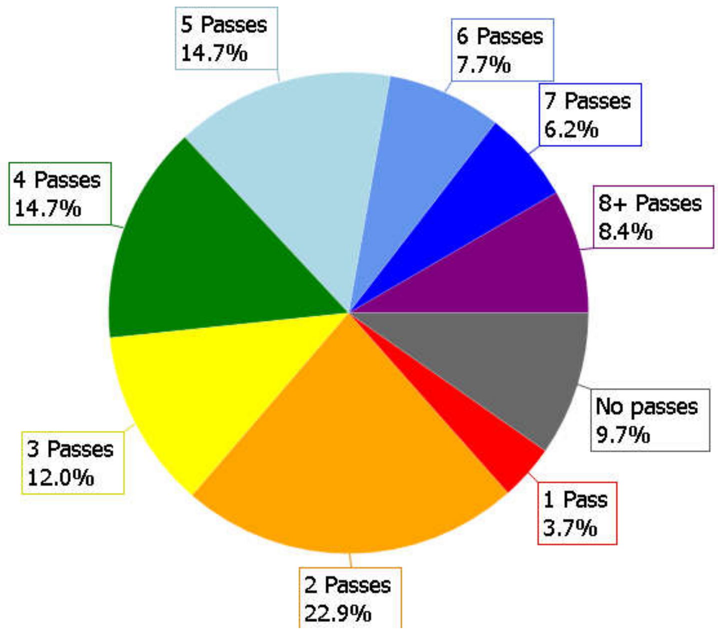
The percent coverage or number of passes as a percent of the project area obtained from the VETA is summarized in Table 5, while the statistical distributions (mean and standard deviation) are given in Table 6. In Table 5, the coverage varies from zero pass or no pass to eight or more passes. Typical pie charts of the coverage for different number of roller passes are shown in Figure 8 to Figure 10.

Table 5 Summary of Percent Coverage for Project 1

Date	Total Area (ft^2)	Optimum Pass (OP)	No pass	1 pass	2 passes	3 passes	4 passes	5 passes	6 passes	7 passes	8+ passes	% Covered with OP
4-Oct-2016	17547.0	2	5.5	52.1	30.9	11.0	0.5	0.0	0.0	0.0	0.0	42.4
6-Oct-2016	145232.8	2	11.8	2.1	25.0	11.7	13.4	13.6	6.0	5.5	10.8	86.0
8-Oct-2016	183275.0	2	12.3	2.0	20.8	9.0	11.8	15.8	7.4	6.7	14.2	85.7
12-Oct-2016	78962.0	2	4.5	1.8	22.0	9.6	14.5	16.3	6.9	6.5	17.9	93.7
13-Oct-2016	58414.0	2	3.6	1.6	21.7	11.1	13.1	20.3	7.8	7.3	13.5	94.8
13-Oct-2016	15539.0	2	0.0	2.1	21.6	13.0	14.9	21.3	7.8	6.6	12.7	97.9
17-Oct-2016	89944.0	2	9.7	3.7	22.9	12.0	14.7	14.7	7.7	6.2	8.4	86.6
18-Oct-2016	150821.0	2	7.9	2.8	22.6	10.3	13.3	17.7	7.8	6.4	11.2	89.3
19-Oct-2016	171861.0	2	9.3	2.6	24.9	9.1	11.5	17.7	7.0	5.8	12.1	88.1
20-Oct-2016	177467.0	2	7.7	3.3	21.3	10.5	12.8	17.4	7.4	6.3	13.4	89.1
21-Oct-2016	127291.0	2	7.7	2.8	23.2	10.4	14.6	15.4	7.6	5.8	12.6	89.6
22-Oct-2016	34058.0	2	0.0	3.7	29.0	10.5	15.3	24.4	5.4	4.5	7.1	96.2

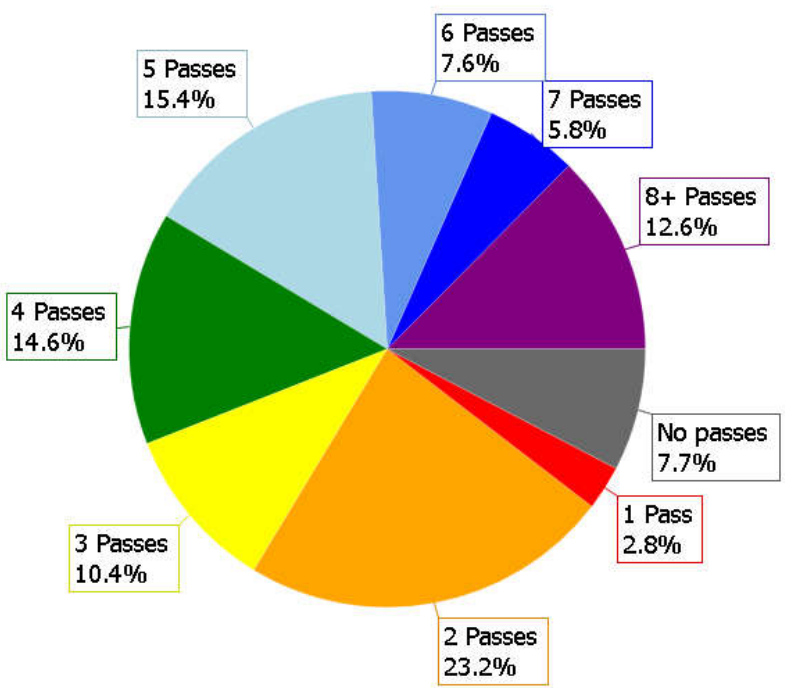
Table 6 Mean and Standard Deviation Values for All Passes Project 1

	No pass (%)	1 pass (%)	2 passes (%)	3 passes (%)	4 passes (%)	5 passes (%)	6 passes (%)	7 passes (%)	8+ passes (%)
Mean	6.7	6.7	23.8	10.7	12.5	16.2	6.6	5.6	11.2
Standard Dev	4.1	14.3	3.2	1.2	4.0	5.9	2.2	1.9	4.5



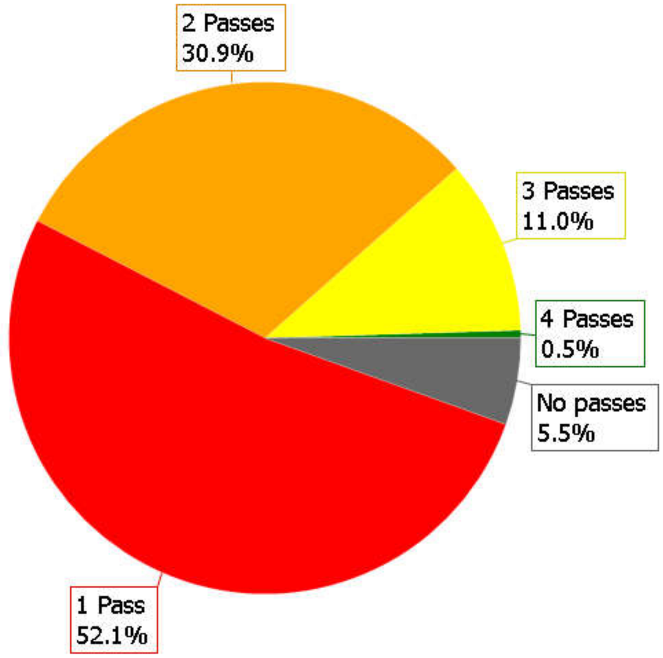
Best Case: Oct 13, 2016

Figure 8 Best Case Coverage Pie Chart for Project 1 (Contract ID: 160001)



Average Case: Oct 21, 2016

Figure 9 Average Case Coverage Pie Chart for Project 1 (Contract ID: 160001)



Worst Case: Oct 4, 2016

Figure 10 Worst Case Coverage Pie Chart for Project 1 (Contract ID: 160001)

According to ODOT Special Provision 411-18(a-e) for IC (ODOT, 2015), at least 90% of the total compaction area should be covered with the optimum number of passes. Because no data was provided for the optimum number of passes, it was assumed as two. It is evident from Table 5 that the percent coverage varied throughout the project. For example, on October 8, 12.3% of the constructed overlay did not have any coverage (no roller pass). On October 22, on the other hand, the entire overlay received at least one roller pass. ODOT's requirement for the optimum number of passes (two) was met only on October 12, 13 and 22. On October 12, 17.9% of the area had eight or more roller passes, followed by October 8 and 13. The mean and standard deviation values varied between 6.6 and 23.8 and between 1.2 and 14.3, respectively. Consideration of actual project boundary would likely provide more objective results.

Temperature

Table 7 provides a summary of the temperature results for Project 1. According to ODOT Provision 411-04(K(1)) (ODOT, 2009), a Hot Mix Asphalt (HMA) layer should be compacted by the break-down roller before the temperature drops below 180°F. Generally, IC system is installed on the break-down roller only. However, there was no information about IC system on secondary or finish roller. So, in this report only the break-down roller with IC was considered. From Table 7 it is seen that this temperature requirement was met only partly. For example, on October 20, most (99%) of the construction zone met the minimum temperature requirement, while on October 4 only 78% zone did so. Since surface temperature can be influenced by various factors such as spraying of water by the roller, ambient moisture, wind, and solar radiation, the results in Table 7 would need to be interpreted accordingly. Since no base data were provided, consideration of these factors was not possible. The standard deviations are seen to vary between 20.4% (October 19) and 47.8% (October 4).

Table 7 Summary of Temperature Results for Project 1

Date	Temp.≥ 180°F (% of constructed area)	Maximum Temp.(°F)	Minimum Temp. (°F)	Mean Temp. (°F)	Standard Dev. (°F)
4-Oct-2016	78.0	254.7	84.6	191.0	47.8
6-Oct-2016	89.0	284.9	76.5	213.6	26.3
8-Oct-2016	80.0	286.0	56.7	194.4	26.6
12-Oct-2016	93.0	280.9	63.9	210.6	24.4
13-Oct-2016	81.0	273.4	60.8	194.1	25.4
13-Oct-2016	85.0	279.9	55.2	206.5	24.1
17-Oct-2016	96.0	272.8	68.9	219.3	23.6
18-Oct-2016	95.0	272.8	93.7	218.3	21.5
19-Oct-2016	97.0	277.9	58.3	218.4	20.4
20-Oct-2016	99.0	293.5	60.3	221.8	21.8
21-Oct-2016	94.0	279.3	55.2	218.0	24.1
22-Oct-2016	78.0	272.8	51.1	200.1	34.9

Frequency and Speed

Table 8 provides a summary of the mean speed and frequency values for Project 1. According to NAPA (2001), a good “rule of thumb” is to adjust the rolling speed (feet per minute or fpm) to provide about ten impacts of the drum per foot of pavement. This level of impact can be achieved by a typical vibratory roller operating at 3,800 VPM and traveling at 4.3 MPH. From Table 8, it is evident that the range of operational frequency of the roller in this project varied between 3,790 VPM and 3,815 VPM. The mean speed varied between 3.6 MPH and 4.2 MPH. So, the speed and frequency of the vibratory roller satisfied the NAPA (2001) requirements approximately. For some reason, the standard deviation of mean frequency on October 4 (162 VPM) was much higher than the standard deviations for other days.

Table 8 Summary of Mean Speed and Frequency Values for Project 1

Date	Mean Speed (MPH)	Standard Dev. (MPH)	Mean Frequency (VPM)	Standard Dev. (VPM)
4-Oct-2016	3.9	0.8	3794	162
6-Oct-2016	3.8	0.8	3811	50
8-Oct-2016	3.5	0.9	3813	41
12-Oct-2016	3.6	0.9	3815	30
13-Oct-2016	4.0	1.1	3811	53
13-Oct-2016	3.7	1.0	3810	54
17-Oct-2016	3.8	0.9	3811	48
18-Oct-2016	4.0	1.0	3812	47
19-Oct-2016	3.9	0.9	3811	48
20-Oct-2016	3.8	1.0	3812	43
21-Oct-2016	3.7	1.0	3812	42
22-Oct-2016	4.2	1.3	3811	49

Inconsistent Project Boundary

As noted previously, an accurate paving boundary is important to the analysis of IC data. The VETA-generated project boundary may not match the actual project boundary for various reasons including GPS calibration, GPS accuracy, and interference. A significant offset between the VETA-generated boundary (in white) and the GPS-based project boundary (in violet) can be seen from Figure 11. For the purpose of analysis, the VETA-generated map is not necessarily important, as the relative locations of data are sufficient (e.g., if all data are offset in the same way the discrepancy should not be an issue). For more accurate analyses, a custom Location Filter would be manually drawn by placing points on the map to enclose the data with respect to actual paving width. In order to reduce this inherent inaccuracy, VETA software has provision for inserting the actual project boundary, or end-of-asphalt line, within a Location Filter using GPS coordinates at selected points (e.g., every 3 ft.). This is discussed further in the “Curb-Line Boundary” section of this report.

Figure 11 Inconsistent Boundary Problem for Project 1

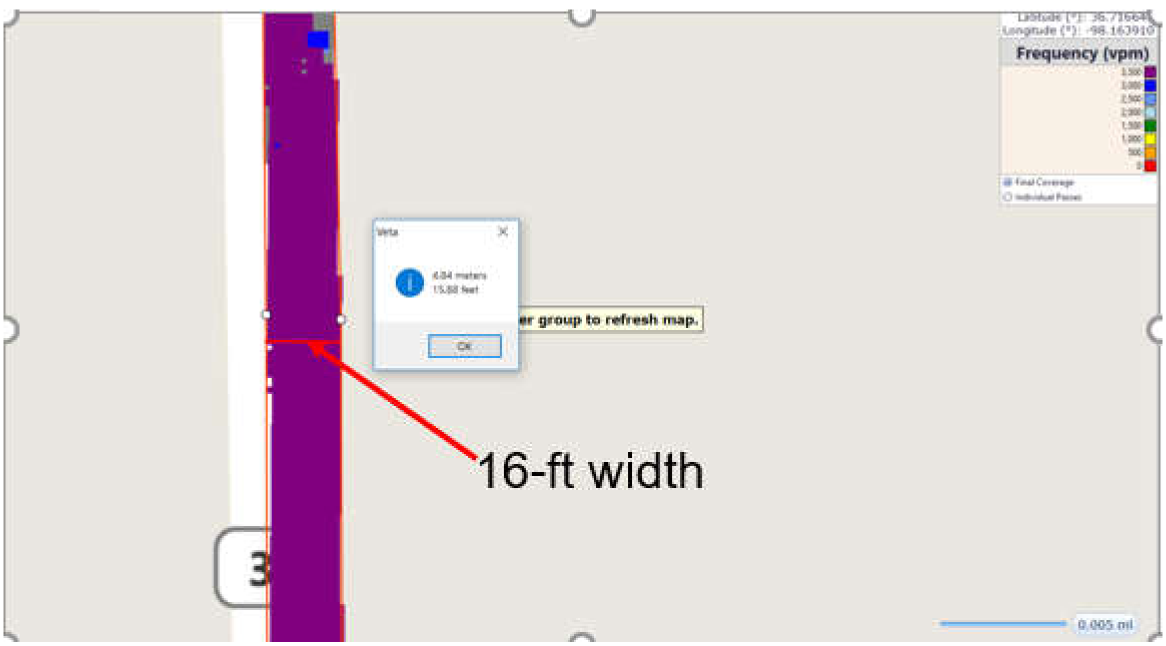


Figure 12 Boundary Setup in VETA Software (16-ft (assumed))

File Naming Inconsistency

Consistent file names are important to the success of IC projects. It is evident from Figure 13 that two data files were recorded for the same date -- October 13, 2016. Inconsistent file names can lead to problems such as data override, identification and cataloging. A consistent file naming convention is proposed in this report. It is intended to avoid any discrepancies in file naming in future IC projects.

Figure 13 Inconsistent File Naming

Project 2: Highway 9

A summary of the results for Project 2 (Contract ID: 160040) is given in Tables 9 through 12. This project was also a resurfacing project in McIntosh County, with a typical lane width of 16-ft including shoulder. It used 17,700 tons of S4 mix. The overall IC data were recorded in 16 files. Unlike Project 1, seven data files for Project 2 could not be processed by VETA. Consequently, the coverage data for the period June 30 through July 9, 2016 could not be obtained from VETA (see Table 9). Also, the temperature data (Table 11) and the roller operational data (Table 12) were missing for the same period. Moreover, larger variations in the results were seen for this project compared to Project 1. Only nine out of sixteen data files could be processed by the VETA 5.1 software. A summary of the results obtained from these nine files is discussed next. The general information on Project 2 is given below:

County: McIntosh
Analyzed Segments: 9 (based on the number of files)
Corrupt Files: 7 (based on the number of files)
Contract ID: 160040
Call Order: 480
Asphalt Tonnage: 17,700 tons (S4 mix)
Type of work: Resurfacing
Typical lane width (with shoulder): 16-ft (see Figure 13)
Construction period: May 24 – July 9, 2016

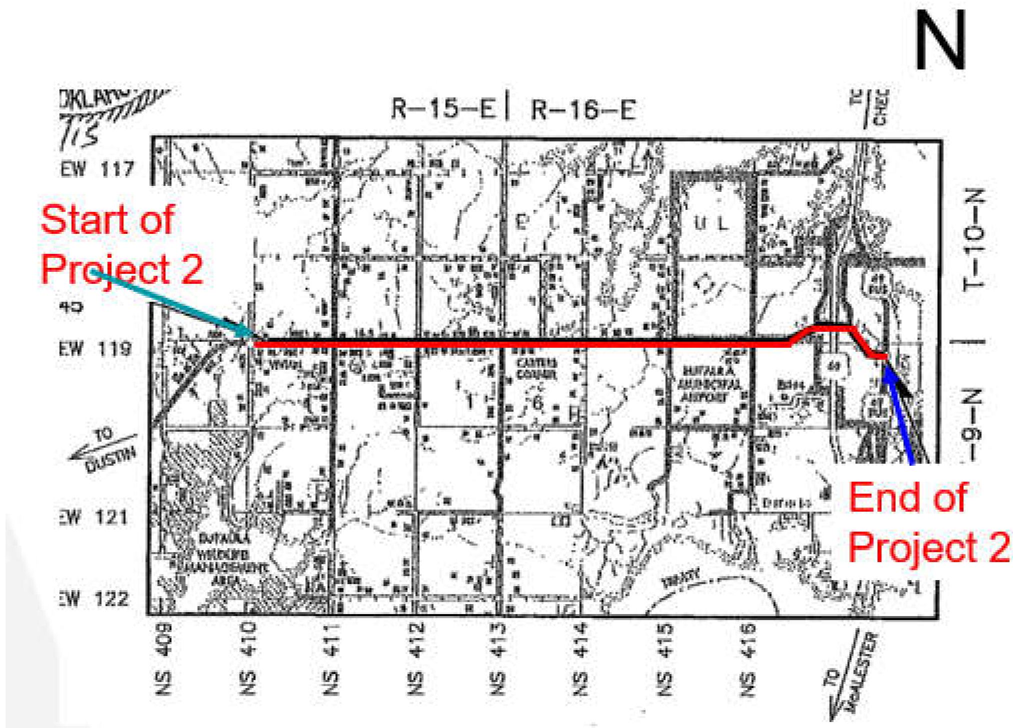


Figure 14 Project 2 Location

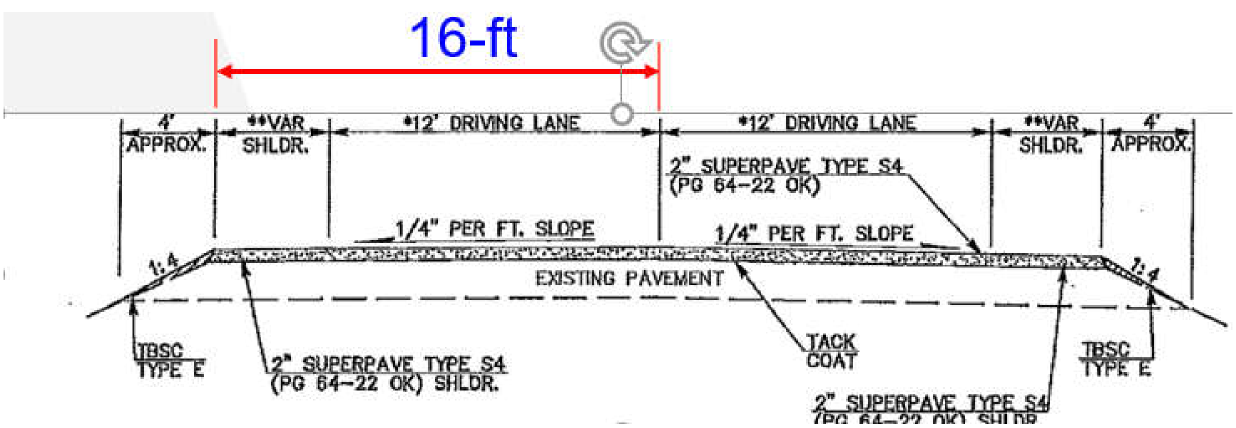


Figure 15 Typical Cross Section for Project 2

Percent Coverage or Number of Passes

The percent coverage data for this project is summarized in Tables 9 and 10, and these results are presented as pie charts in Figure 14. Because no optimum pass count was specified, it was assumed as two. Also, the lane width (16-ft) was assumed constant and used in defining the project boundary.

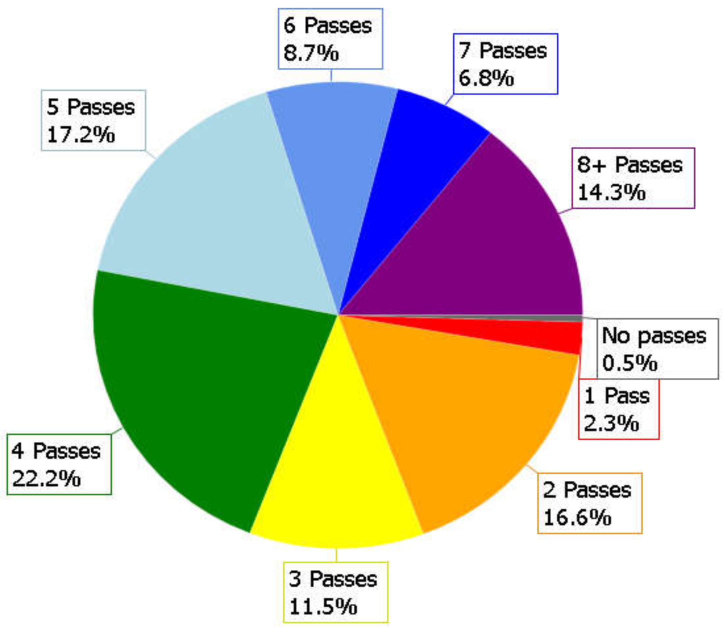
Table 9 Summary of Percent Coverage for Project 2

Date	Total Area (ft^2)	Optimum Pass (OP)	No pass	1 pass	2 passes	3 passes	4 passes	5 passes	6 passes	7 passes	8+ passes	% Covered with OP
24-May-2016	30,176	2	1.1	7.5	32.3	15.3	15.2	11.4	5.4	3.8	8.1	91.5
25-May-2016	52,069.0	2	1.0	2.6	27.1	20.8	18.4	15.3	4.8	2.6	7.2	96.2
6-Jun-2016	20,318	2	2.2	2.9	9.8	18.5	23.1	17.2	8.7	6.8	14.3	97.3
3-Jun-2016	37,113	2	0.5	2.3	16.6	11.5	22.2	16.4	8.5	5.9	13.6	96.6
4-Jun-2016	38,799	2	0.6	2.8	14.5	14.9	22.8	14.5	10.2	3.9	15.2	97.0
5-Jun-2016	46,723	2	0.6	2.3	14.2	20.1	18.9	18.4	10.1	4.4	10.7	95.0
7-Jun-2016	179,897	2	0.6	2.5	14.5	14.8	23.1	17.3	10.2	5.5	11.5	96.9
8-Jun-2016	223,055	2	1.8	3.3	16.3	16.9	23.4	15.6	7.7	4.2	10.7	94.8
9-Jun-2016	168,594	2	1.1	3.1	15.9	18.2	20.0	15.3	10.5	5.5	10.4	95.8
30-Jun-2016	VETA error	2										
1-Jul-2016	VETA error	2										
5-Jul-2016	VETA error	2										
6-Jul-2016	VETA error	2										
7-Jul-2016	VETA error	2										
8-Jul-2016	VETA error	2										
9-Jul-2016	VETA error	2										

Table 10 Mean and Standard Deviation Values for All Passes Project 2

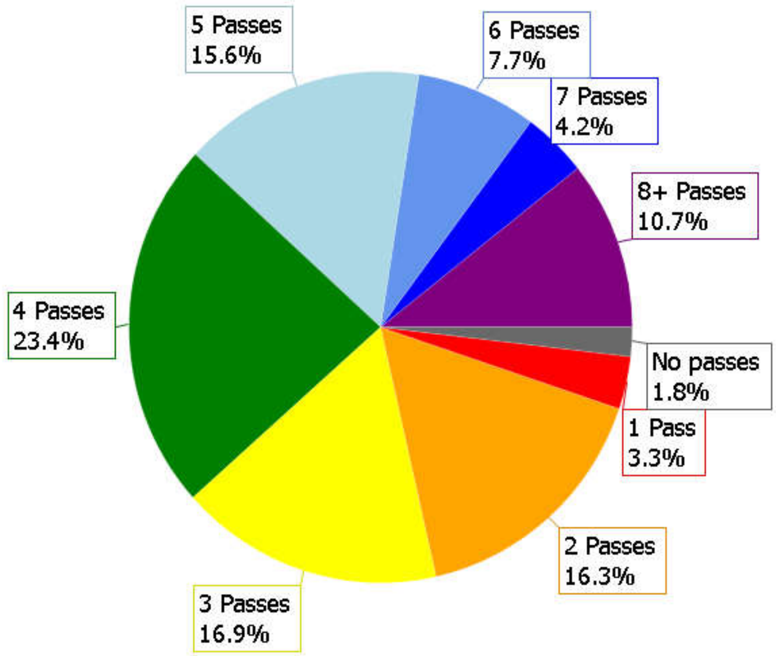
	No pass (%)	1 pass (%)	2 passes (%)	3 passes (%)	4 passes (%)	5 passes (%)	6 passes (%)	7 passes (%)	8+ passes (%)
Mean	1.1	3.3	17.9	16.8	20.8	15.7	8.5	4.7	11.3
Standard Dev	0.6	1.6	7.1	3.0	2.8	2.0	2.1	1.3	2.7

Unlike Project 1, it is evident from Table 9 that more than 90% areas received at least two roller passes. The coverage requirement of 90% was thus met for all analyzed days. Only a small percentage of the paving area (less than 4.5 percent) did not meet the coverage requirement. Comparatively, for Project 1, the percent coverage with less than two passes was much larger. As noted previously, with actual paving boundaries, these percentages will likely change. The percent coverage with eight or more passes was similar (11.2 and 11.3) in both projects. From Figure 16 to Figure 18, it is evident that pie charts provide an effective way of depicting rolling-pattern and coverage.



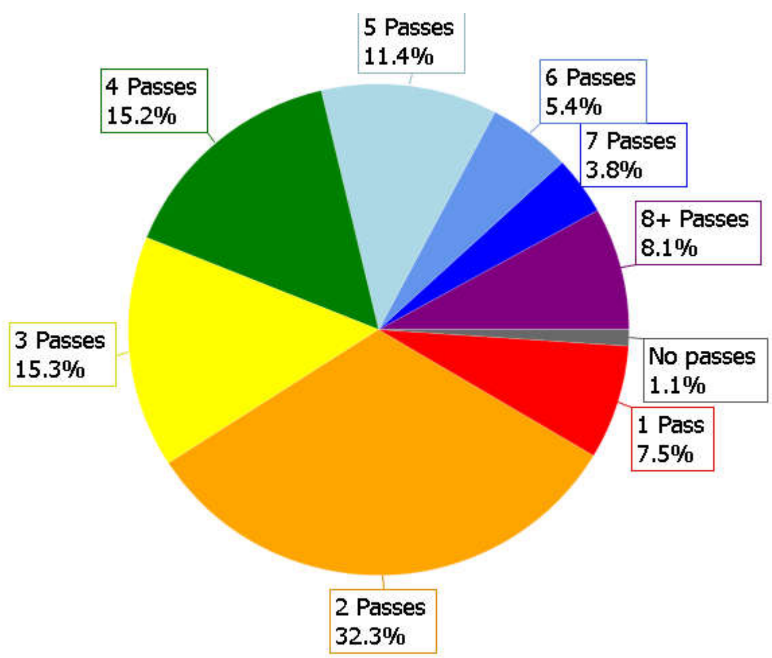
Best Case: June 3, 2016

Figure 16 Best Case Coverage Pie Chart for Project 2 (Contract ID: 160040)



Average Case: June 8, 2016

Figure 17 Average Case Coverage Pie Chart for Project 2 (Contract ID: 160040)



Worst Case: May 24, 2016

Figure 18 Worst Case Coverage Pie Chart for Project 2 (Contract ID: 160040)

Temperature

A summary of the temperature results is given in Table 11. Although this project had better coverage (Table 9), the temperature data show lower values and larger standard deviations (19.6% to 51%). The mean temperature values generally ranged from 180.5°F to 203.1°F, except on May 25 (170.4°F) and June 4 (138.5°F). On an average, only 64.8% of the constructed overlay met the temperature requirement (temperature ≥ 180°F, considering IC system on the break-down roller only). The overall range varied between 24.2% (June 4) and 86.2% (June 8). Overall, the maximum temperatures were all within a good range, but the minimum temperatures were much lower. It is possible that the minimum temperature data were collected on a previously constructed pavement (i.e., temperature sensor recorded data not from the asphalt mat being compacted, but from the previously constructed lane). Also, wind speed, moisture, solar radiation, air temperature, and other factors can influence pavement surface temperature data. Since no base data were provided, consideration of these factors was not possible. Also, it is known that a thermal profile obtained from an IR bar/scan (MOBAR), mounted on the back of a paver, provides a much more useful data on paving quality than point-wise data from the temperature sensor mounted on the roller. Future IC projects may consider collecting MOBAR data and integrate such data with the IC data. Recently, Missouri DOT has done several projects in which both IC data and thermal profile data from MOBAR have been used to evaluate the overall quality of compaction (Chang et al., 2018).

Table 11 Summary of Temperature Results for Project 2

Date	Temp.≥ 180°F (% of constructed area)	Maximum Temp.(°F)	Minimum Temp. (°F)	Mean Temp . (°F)	Standard Dev. (°F)
24-May-2016	74.6	300.2	32.0	192.5	51.0
25-May-2016	38.5	271.4	74.4	170.4	25.1
3-Jun-2016	54.7	298.4	32.0	180.5	47.6
4-Jun-2016	24.2	239	75.2	138.5	47.4
5-Jun-2016	75.3	258.8	64.4	194.1	25.5
6-Jun-2016	83.4	282.2	68.0	196.5	19.6
7-Jun-2016	73.5	278.6	66.2	189.5	31.6
8-Jun-2016	86.2	285.8	66.2	203.1	21.9
9-Jun-2016	73.0	300.2	75.2	190.0	33.3
30-Jun-2016	–	–	–	–	–
1-Jul-2016	–	–	–	–	–
5-Jul-2016	–	–	–	–	–
6-Jul-2016	–	–	–	–	–
7-Jul-2016	–	–	–	–	–
8-Jul-2016	–	–	–	–	–
9-Jul-2016	–	–	–	–	–

Frequency and Speed

A summary of the roller speed and vibration frequency data for Project 2 is reported in Table 12. It is seen that the mean roller frequency is reported by VETA as zero, which means either these data represent the operation of the roller in a static mode or the vibration data were not measured/recorded properly. It is also possible that the accelerometer was not functioning properly. Field notes from construction sites would be helpful in rationalizing such data. The average roller speed during compaction varied between 2.7 MPH and 4.5 MPH. The overall average roller speed was 3.6 MPH.

Table 12 Summary of Mean Speed and Frequency Values for Project 2

Date	Mean Speed (MPH)	Standard Dev. (MPH)	Mean Frequency (VPM)	Standard Dev. (VPM)
24-May-2016	3.2	7.8	0	0
25-May-2016	2.7	0.4	0	0
6-Jun-2016	3.4	0.5	0	0
3-Jun-2016	3.5	1.1	0	0
4-Jun-2016	4.2	1.3	0	0
5-Jun-2016	2.9	0.3	0	0
7-Jun-2016	4.1	0.6	0	0
8-Jun-2016	3.8	0.5	0	0
9-Jun-2016	4.5	1.0	0	0
30-Jun-2016	–	–	–	–
1-Jul-2016	–	–	–	–
5-Jul-2016	–	–	–	–
6-Jul-2016	–	–	–	–
7-Jul-2016	–	–	–	–
8-Jul-2016	–	–	–	–
9-Jul-2016	–	–	–	–

Data Filtering

Two project boundaries are shown in Figure 19. The white boundary is generated by VETA. The blue boundary is also generated by VETA from the recorded GPS data. In addition to shifting between the boundaries, some abnormalities are seen in the blue boundary in the form of extra area, outside of the paving area. It may have been caused by the departure of the roller from the paving area (e.g., filling roller with water), while still collecting data. It may also be caused by change in roller operator or some other issues. Such abnormalities can be avoided by switching off data collection while the roller is outside of the paving area. Again, filed notes from the construction site will be helpful in sorting out such abnormalities. VETA is capable of filtering data outside of the project boundary. The research team used this filtering option to take out data from outside of the paving area (Figure 20). The filtered data was used to determine coverage, temperature, roller speed, and roller frequency. It is noted that a uniform width (16-ft) of the paving lane was used here in defining the project boundary, as in other projects. Having actual boundary of the constructed overlay will certainly make the analysis of the IC data more objective and accurate. As discussed previously, discrepancy between the VETA and GPS boundaries can be adjusted by proper calibration of GPS and using a GPS of better accuracy.

Figure 19 Variability in Road Width

Figure 20 Exclusion of Data

Project 3: Highway 58

Project 3 in Alfalfa County was a relatively small project involving laying of only 2,594 tons of S3 mix and 1,126 tons of S4 mix. This project was related to bridge approach and shoulder works. One major difference between this project and the other two projects (Project 1 and Project 2) is that relatively small areas (hundreds of square feet compared to thousands of square feet) were compacted in this project. Also, the lane width (20-ft, including shoulder) of this project was much larger than the other two projects (16-ft). Moreover, no corrupt data files were found for this project. The roller vibration frequency could not be obtained from the VETA analysis for some days, as discussed subsequently. The general information of Project 3 is given below:

County: Alfalfa

Analyzed Segments: 10 (based on the number of files)

Corrupted Files: 0

Contract ID: 160069

Call Order: 20

Asphalt Tonnage: 2,594 tons (S3 mix); 1,126 tons (S4 mix)

Type of work: Bridge approach and shoulder

Typical lane width (with shoulder): 20-ft

Construction period: Not mentioned

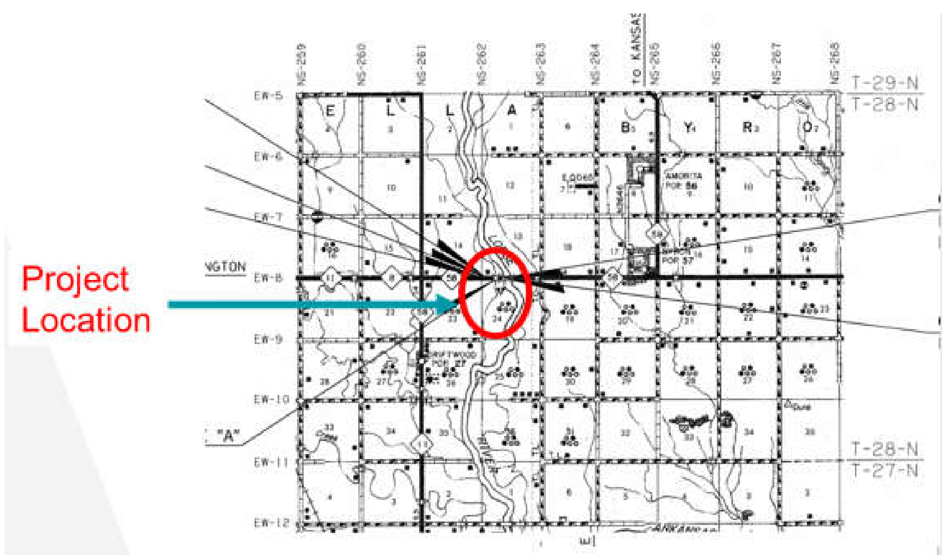


Figure 21 Project 3 Location

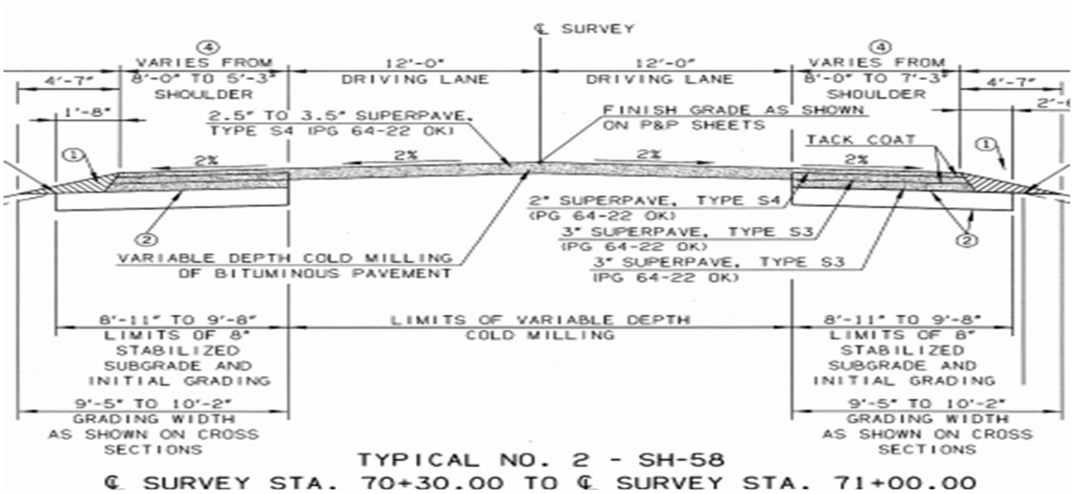


Figure 22 Typical Cross Section for Project 3

Percent Coverage or Number of Roller Passes

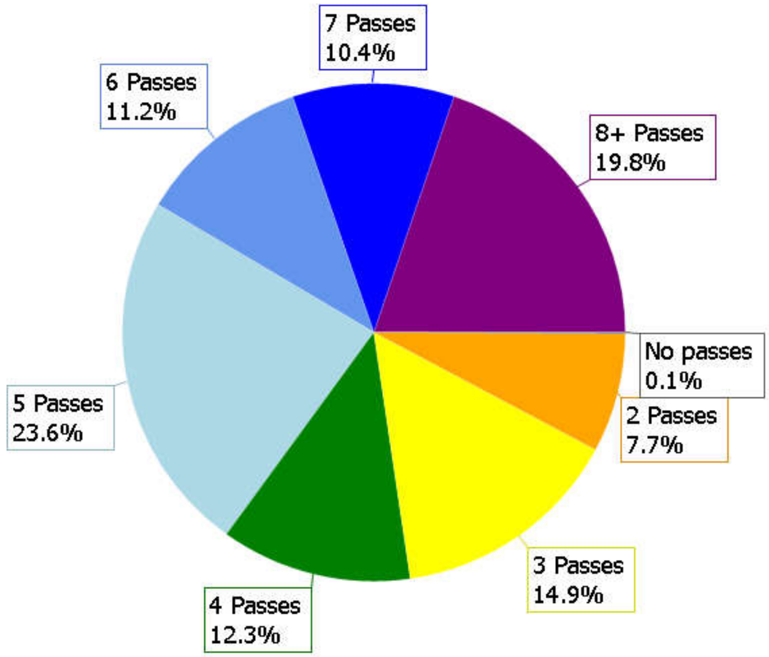
Overall, the coverage data for Project 3 show high coverage (i.e., most areas having optimum roller passes or more). Because the optimum roller pass was not specified, it was assumed as two. Unlike Project 2, all ten data files for this project were analyzed by VETA. Naming of some data files was found inconsistent. These files are highlighted in red in Table 13. Also, the file naming convention did not include any date, making sorting of the files according to construction sequence difficult. For this project, there were two data files with abnormally small compaction areas (WBML_L2_1312017_CMV with 181 ft^2 and EBML_L3_1312017_CMV with 344 ft^2) and relatively low high pass coverage. The rolling pattern obtained for these files shows dissimilarities with other data files. The percent area covered with at least six roller passes was zero for both data files. However, for other data files a higher coverage area was observed for six or more roller passes. It is possible that the data contained in these files might be incomplete. Overall, ODOT's coverage requirement was met on all days except EB_SHLDR_L2_CMV and WBML_L2_1312017_CMV (Table 13). The coverage was particularly low (27.6%) on WBML_L2_1312017_CMV.

Table 13 Summary of Percent Coverage for Project 3

File Name	Date	Total Area (ft^2)	Optimum Pass	No pass	1 pass	2 passes	3 passes	4 passes	5 passes	6 passes	7 passes	8+ passes	% Covered with OP
EB_SHLDER_ L1_CMV	Missing	5,230	2	0.1	0.0	7.7	14.9	12.3	23.6	11.2	10.4	19.8	99.9
EB_SHLDR_ L2_CMV	Missing	6,680	2	3.8	6.8	8.2	16.1	18.1	23.0	7.8	6.7	9.6	89.5
EB_SHLDR_ L3_CMV	Missing	6,646	2	0.8	4.6	9.5	16.0	17.3	21.2	12.8	9.3	8.5	94.6
EBML_L2_ 1312017_CMV	Missing	12,879	2	0.1	1.3	14.1	24.9	18.1	17.1	7.8	6.7	9.9	98.6
EBML_L3_ 1312017_CMV	Missing	344	2	0.0	0.0	10.6	37.4	47.9	4.0	0.0	0.0	0.0	99.9
EBML_LIFT1_ 1302017_CMV	Missing	5,612	2	1.2	1.3	4.7	22.2	28.9	14.0	19.9	5.6	2.2	97.5
SML_L3_CMV	Missing	7,673	2	1.0	9.1	26.7	30.8	14.8	8.8	5.4	2.5	0.9	89.9
WBML_L2_ 1312017_CMV	Missing	181	2	2.1	70.3	24.7	2.9	0.0	0.0	0.0	0.0	0.0	27.6
WBML_L3_ 1312017_CMV	Missing	17,652	2	0.8	2.4	19.5	25.6	17.5	15.3	6.3	5.1	7.4	96.7
WBML_LIFT1_ 1302017_CMV	Missing	17,810	2	0.3	1.7	21.7	28.4	14.7	17.1	7.4	4.7	3.9	97.9

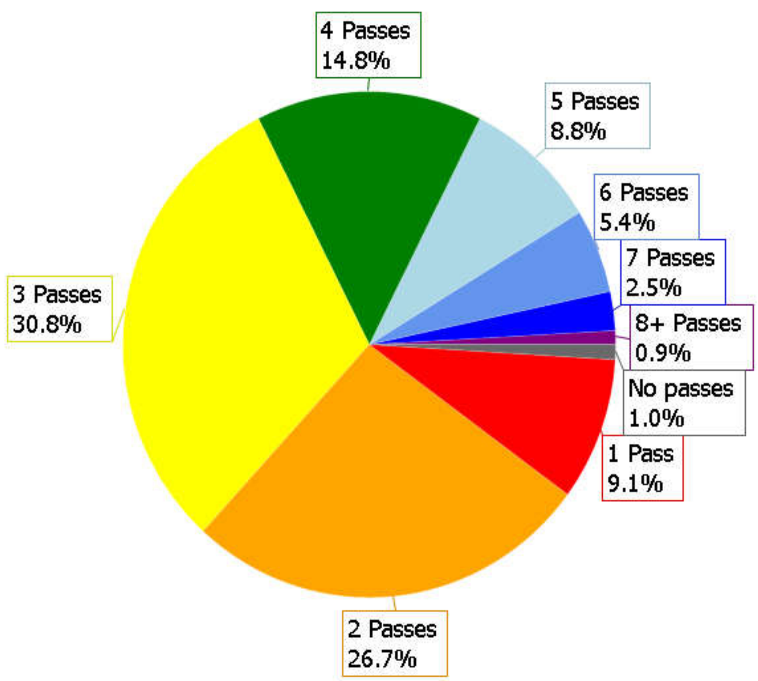
Table 14 Mean and Standard Deviation Values for All Passes Project 3

	No pass (%)	1 pass (%)	2 passes (%)	3 passes (%)	4 passes (%)	5 passes (%)	6 passes (%)	7 passes (%)	8+ passes (%)
Mean	1.0	9.8	14.7	21.9	19.0	14.4	7.9	5.1	6.2
Standard Dev	1.2	21.5	7.8	9.8	12.4	7.9	5.9	3.5	6.2



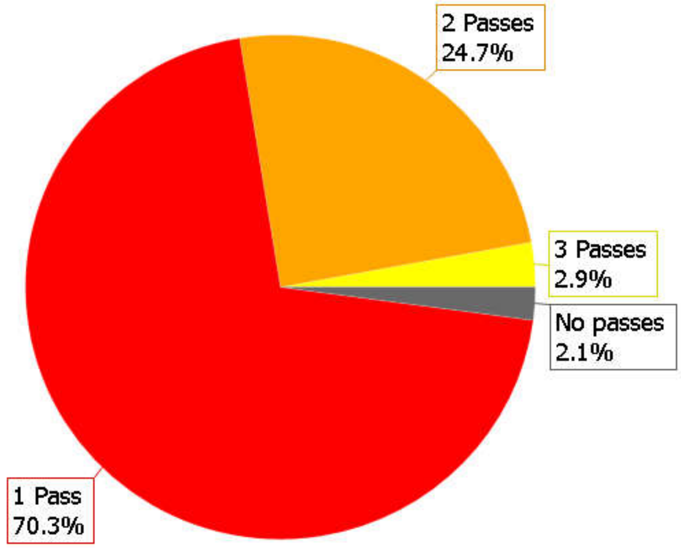
Best Case: EB_SHLDER_L1_CMV

Figure 23 Best Case Coverage Pie Chart for Project 3 (Contract ID: 160069)



Average Case: SML_L3_CMV

Figure 24 Average Case Coverage Pie Chart for Project 3 (Contract ID: 160069)



Worst Case: WBML_L2_1312017

Figure 25 Worst Case Coverage Pie Chart for Project 3 (Contract ID: 160069)

Temperature

A summary of compaction temperature results is presented in Table 15. It is evident that the maximum temperatures and mean temperatures were lower than those in Project 1 and Project 2 (considering IC system installed at break-down roller only). The percent of paving area meeting the compaction temperature requirement varied significantly throughout the project from 29.9% on EB_SHLDR_L3_CMV to 100% on WBML_L2_1312017_CMV. Although the maximum temperatures were generally lower than those in Project 2, but they were still within an acceptable range for compaction. As in previous projects, the minimum temperatures might have been recorded on previously-compacted mats. Smaller paving areas generally show larger variability because of difficulty in using consistent rolling patterns and maneuvering of roller, among other factors.

Table 15 Summary of Temperature Results for Project 3

Date	Temp.≥ 180°F (% of constructed area)	Maximum Temp.(°F)	Minimum Temp. (°F)	Mean Temp. (°F)	Standard Dev. (°F)
EB_SHLDER_L1_CMV	49.6	264.2	69.8	172.5	41.1
EB_SHLDR_L2_CMV	87.2	294.8	53.6	202.5	45.2
EB_SHLDR_L3_CMV	29.9	237.2	60.8	131.3	52.1
EBML_L2_1312017_CMV	60.5	249.8	48.2	180.6	30.8
EBML_L3_1312017_CMV	69.3	242.6	51.8	188.4	17.5
EBML_LIFT1_1302017_CMV	35.8	233.6	50.0	171.0	26.7
SML_L3_CMV	61.0	262.4	60.8	188.8	33.2
WBML_L2_1312017_CMV	100.0	217.4	194.0	210.3	7.3
WBML_L3_1312017_CMV	66.1	249.8	46.4	184.6	29.4
WBML_LIFT1_1302017_CMV	78.5	264.2	41.0	196.3	23.9

Frequency and Speed

From the mean roller speeds in Table 16 it is seen that it varied from 1.6 MPH to 4.0 MPH. In general, these values were lower than the speeds in the other projects. This was likely due to small paving areas. Also, the roller frequency was much lower than the frequency used in the other two projects. The overall average frequency was 2,593 VPM, which is much smaller than the suggested frequency.

Table 16 Summary of Mean Speed and Frequency Values for Project 3

Date	Mean Speed (MPH)	Standard Dev. (MPH)	Mean Frequency (VPM)	Standard Dev. (VPM)
EB_SHLDER_L1_CMV	2.5	0.5	2575	275
EB_SHLDR_L2_CMV	2.2	0.5	2599	206
EB_SHLDR_L3_CMV	2.8	1.8	2597	195
EBML_L2_1312017_CMV	2.2	0.5	--	--
EBML_L3_1312017_CMV	1.6	0.3	--	--
EBML_LIFT1_1302017_CMV	1.8	0.3	2578	235
SML_L3_CMV	2.4	0.8	2569	243
WBML_L2_1312017_CMV	1.2	0.0	--	--
WBML_L3_1312017_CMV	4.0	2.0	--	--
WBML_LIFT1_1302017_CMV	2.1	1.7	2639	183

Data Filtering

The VETA-generated site map is compared with the location of the collected data in Figure 26. A larger offset between the two maps is seen compared to the offsets in Project 1 and Project 2. Smaller construction area is a likely contributor to this difference. These results demonstrate the need for accurately specifying the project boundary.

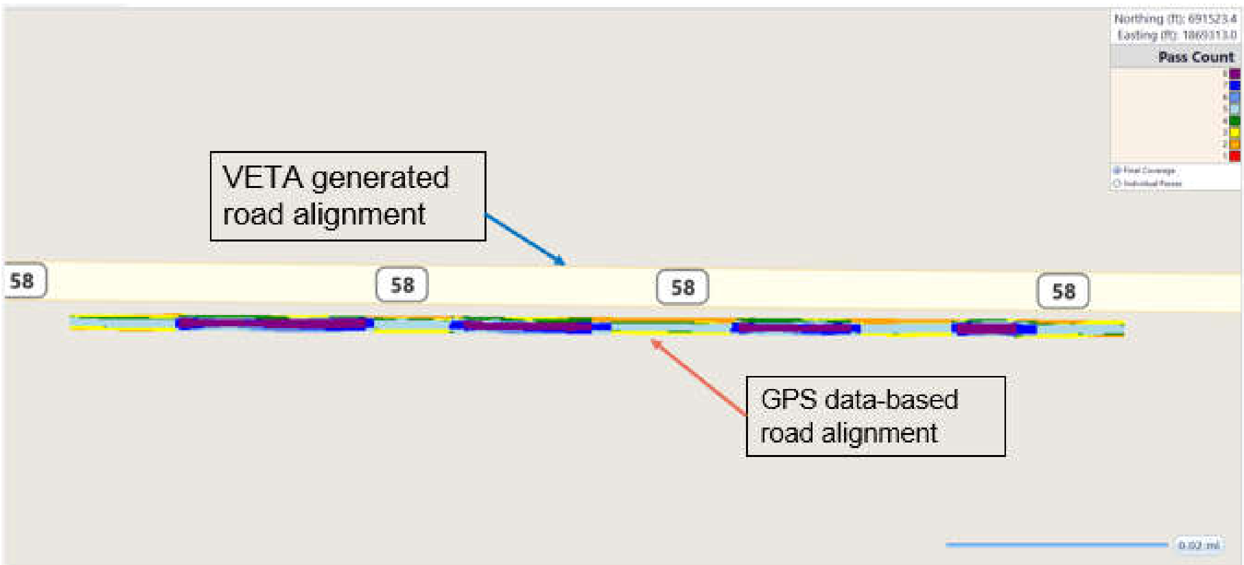


Figure 26 Inconsistent Boundary Problem for Project 3

Overall Comparison of Three Sites

An overall comparison of the three sites analyzed in this Task Order is presented in this section. On an average, Project 2 and Project 3 met ODOT's specification of 90% coverage (Figure 27). Project 1, however, did not to meet ODOT's specification, but only by a small percentage.

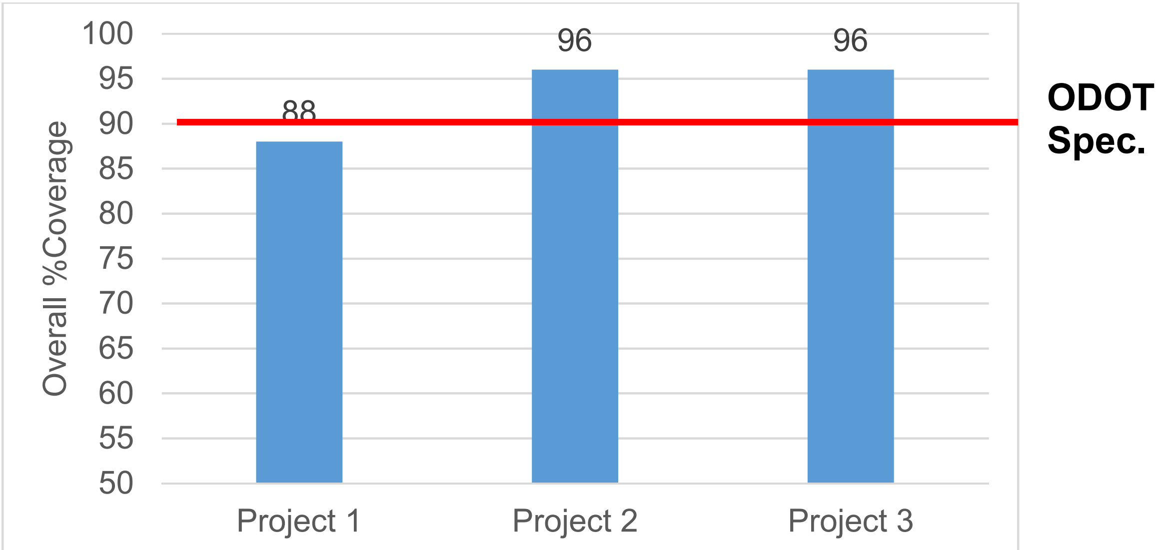


Figure 27 Overall Percent Coverage Comparison among Three Projects

Generally, it is presumed that a site with better temperature control provides better compaction quality in the field. However, from Figure 28 it is evident that Project 1 had much better control of temperature than the other two projects. Also, a lower percent coverage with target pass is observed for Project 1 compared to other projects. The assumption in target pass number, project boundary and types of work might cause this variation. On an average, only 8.7% of overlay in Project 1 was compacted at a temperature lower than the 180°F requirement (assuming IC system on break-down roller only), whereas for the other two projects these values were much higher (30-40%). As noted previously, wind speed, moisture, solar radiation, air temperature, and other factors can influence pavement surface temperature data. Since no base data were provided, consideration of these factors was not possible.

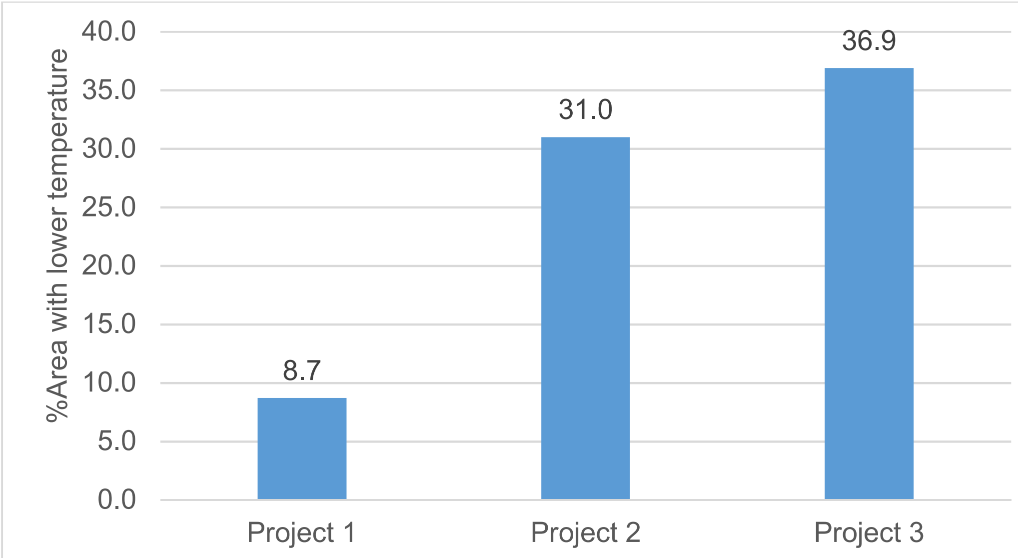


Figure 28 Lower Temperature Coverage Comparison among Three Projects

Compliance and Missing Data

Oklahoma Department of Transportation (ODOT) has developed Special Provision 411-18(a-e) for the implementation of IC technology (ODOT, 2015). Also, AASHTO PP 81 has specified requirements for projects using the IC technology (AASHTO, 2014). The AASHTO requirements cover compaction of both roadway embankments and asphalt pavements. The data compliance and missing data for the three projects analyzed herein are summarized in Table 17. The compliance is checked for both specifications (ODOT and AASHTO). It is seen that some requirements were met, while the other requirements were not met. The conclusions and recommendations of this Task Order are partly guided by Table 17.

Table 17 Compliance and Missing Data for all Three Projects

Items	Standards	Recommendations	Project 1	Project 2	Project 3
GPS Coordinate System	ODOT Special Provision	Universal Transverse Mercator (UTM) or Oklahoma State Plane	Met	Met	Met
File Naming	AASHTO PP 81	MDDYY(Month-Date-Year) format	Met	Met	Did not meet
Optimal Pass Number	ODOT Special Provision	At least 90% of the total area should be covered with optimum number of passes	Did not meet	Met	Met
Survey Markers Location	AASHTO PP 81	At least two survey markers at the start and at the end (in total four) and one survey marker in every 2.5 KM	Missing Data	Missing Data	Missing Data
Survey Markers Accuracy	AASHTO PP 81	less than or equal to 30 mm in X, Y, and Z directions	Missing Data	Missing Data	Missing Data
GPS accuracy	AASHTO PP 81	Should be checked daily	Missing Data	Missing Data	Missing Data
Temperature sensor calibration	AASHTO PP 81	Should be performed periodically	Missing Data	Missing Data	Missing Data
Brief Description of Compacted layers	AASHTO PP 81	Should be provided	Missing Data	Missing Data	Missing Data

Boundary Adjustment

When VETA performs calculations on data, it only considers zones where compaction data is present. Areas that did not receive any roller passes are excluded from the analysis, thereby producing inaccurate results. To remedy this problem, one must use the Location Filter that considers "no pass" zones as "no passes" rather than lack of data. Therefore, use of custom Location Filters is extremely important to analyze the IC data. In this Task Order, the custom Location Filters were used by manually drawing the project boundary by keeping the paving width constant. However, this is inherently inaccurate, as the research team could not be sure which data to include or exclude based on relative location of the data alone. This issue can be resolved by importing the GPS coordinates of the post-construction edge-of-asphalt line into VETA to generate a custom Location Filter- based project boundary (Figure 29 and Figure 30).

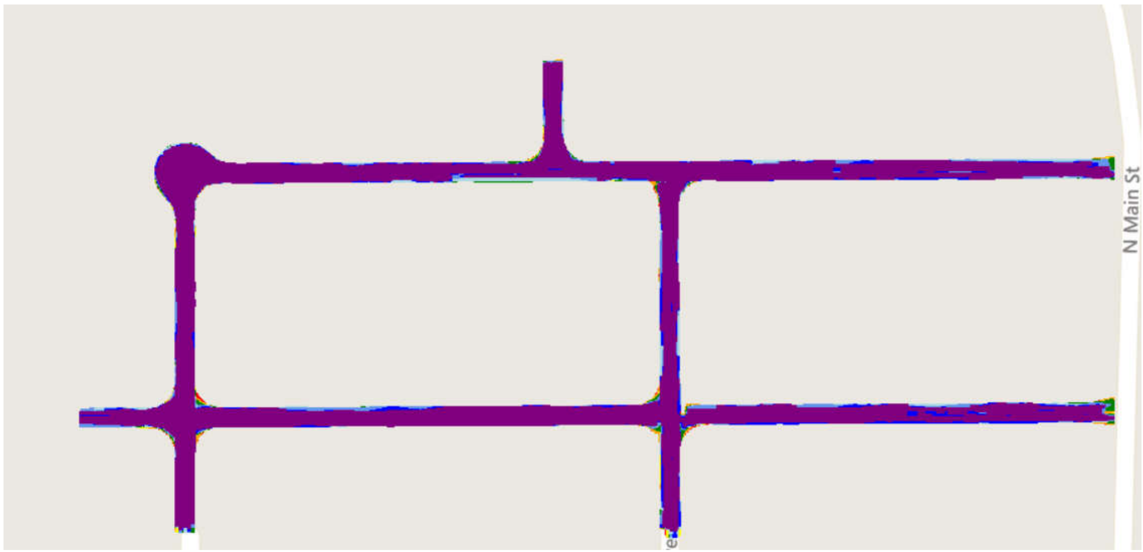


Figure 29 Typical Recorded IC Data

Figure 30 Filtering the IC Data Based on Road Boundary GPS Data

An illustration of the post-construction GPS coordinates is given in Figure 29. In this case the post-construction GPS coordinates were taken using the TOPCON Pocket3D device. The device was set to take GPS coordinates (in State Plane format) every three feet (measured using a calibrated wheel), along the entire outside curb (constructed pavement). About 1,200 GPS points were taken and imported into VETA, resulting in an accurate Location Filter-based project boundary (Figure 30). This process was repeated two more times for the curb lines that define the two islands of the project. GPS coordinates for the island-defining curb lines were imported into VETA as Exclusion Filters, which work exactly like Location Filters, but they *exclude* all data within their boundaries from analysis.

With the outside curb Location Filter *including* all areas within its boundary for analysis and the two exclusion filters for the island-defining curb lines *excluding* the "no pass" island zones, an accurate project boundary was generated for analysis.

File Naming

To use the IC technology effectively, the IC data files should be named properly. As noted in AASHTO PP 81, the file name should include date of work, optimal pass number, mix type, lane or shoulder identification number. Based on these guidelines, the following file naming convention is proposed:

MonthDateYear_Mix Type_Shoulder/Lane ID_Optimal pass

As an example, the following file name may be used for the IC data collected for Project 1 on October 13, 2016.This naming convention eliminates the discrepancies noted earlier.

October_13_2016_S4_Shoulder_North_Bound_East_2

CONCLUSIONS AND RECOMMENDATIONS

In this Task Order, IC data from three selected projects were analyzed using the VETA software. In addition to percent coverage (number of roller pass), attention was given to temperature, roller speed and roller frequency because of influence of these parameters on compaction quality. Special attention was given to project boundary and file naming because of their importance. Attention was also given to data quality and missing data. The analyzed results were checked for compliance with the ODOT and AASHTO requirements. The following conclusions can be drawn from the results presented in the preceding sections:

Conclusions

- Although the IC technology shows promise as a useful tool for monitoring of compaction quality during construction of asphalt pavements, an effective use of this technology (irrespective of the platform) requires attention to collection of data. Incomplete and inconsistent data often lead to inconsistent, inaccurate and misleading results. An accurate layout of the project boundary is extremely important to the analysis of results. No project specific boundary data was available for the three projects analyzed in this study. Also, no weather data and notes from the construction sites were available that made the analysis and interpretation of VETA results challenging.
- A high degree of variability in data among the selected projects was evident from the VETA results. For one project, the VETA software was not able to process the collected IC data for several files (corrupt files). In another project, the mean roller frequency was reported as zero. Inconsistent file naming was another issue. Lack of exposure to the IC technology and training was a likely factor for such variability. These issues should be taken into consideration in future IC projects.
- In spite of the aforementioned variability, the VETA results (see Table 17) show the benefit of the technology relative to coverage and operational parameters of the roller (speed and frequency). With operator training and understanding of the IC technology, the quality of IC data can be improved significantly.
- Point-wise temperature data are found to have some inherent weaknesses due to various factors that can influence surface temperature during compaction, including collecting data from outside of the paving area. This was reflected in the minimum temperature results for all three sites.
- A data file covering a relatively small area (e.g., hundreds of square feet instead of thousands of square feet in Project 3) may not be a suitable candidate for IC

analysis because of difficulty in setting consistent rolling patterns and consistent operational parameters of the roller.

- The VETA software was found to be a great tool for analysis of IC data, irrespective of the IC platform used. In this study, three different IC platforms were used in collecting the IC data. Yet, the VETA software was able to process data for all of these IC platforms.
- The Location Filter in VETA was found to be a particularly useful tool for user-defined project boundary. Also, time and data filters are useful features. The statistical and graphical outputs were also found extremely useful.
- The accuracy of the VETA results could be verified by comparing them with the results from cores extracted from under-compacted and adequately-compacted zones.
- A successful implementation of the IC technology has real potential to improve compaction quality and increase pavement life. Operator training, calibration, rolling pattern, GPS accuracy, data filtering, and data analysis experience should be taken into account to realize the benefit of the IC technology.

Recommendations

- Accurate layout of project boundary is extremely important for the analysis of IC data. The Location Filter option in VETA allows for a user-defined project boundary. Some IC technology such as TOPCON's Pocket3D device provides a user-friendly option of collecting post-construction boundary at a desired interval. It is recommended that the future IC projects be encouraged to collect this data to enhance the accuracy of results and to realize the benefits of the IC technology.
- Calibration of the GPS with the available benchmarks in the vicinity of the project can significantly reduce the offset between VETA-generated and the GPS-based project boundaries. It is recommended that the future IC projects perform such calibration.
- Wind speed, moisture, solar radiation, ambient air temperature, and other factors can influence pavement surface temperature data. Since no base data were

provided and the scope of this Task Order was limited, consideration of these factors was not possible. It is recommended that future IC projects consider pertinent weather data as part of the data reporting process. Nearby weather stations could be great resource in this regard.

- It is known that a thermal profile obtained from an IR bar/scan (MOBAR), mounted on the back of a paver, provides a much more useful data on paving quality than point-wise data from the temperature sensor mounted on the roller. Equally important, these temperature data can be analyzed using the VETA software. Thus, it is recommended that future IC projects consider collecting MOBAR data and integrate such data with the IC data.
- Because of limited scope, no effort was made in this Task Order to study stiffness-related parameters such as CMV. Also, no efforts were made to compare any performance properties (density, dynamic modulus, IFIT value, rut potential) of the extracted cores with the CMV or modulus or other performance indicators obtained from the analysis of IC data. Correlations among and between these field performance parameters and the CMV or modulus or other performance indicators can be pursued in future projects. Therefore, it is recommended that, in addition to coverage, the future IC projects address performance-related parameters.
- Appropriate file naming is important to data processing and cataloging. It is recommended that the future IC projects use a logical and consistent convention in naming data files. A naming format is suggested in this report.
- Several studies and specifications (AASHTO PP81, 2014; Chang, 2018) as well workshops have identified the need and benefits of paving crew's training and exposure to the IC technology. AASHTO PP 81 (2014) suggests certification frequency (one time per calendar year). Certifications are routine for less evolving areas such as materials testing and mix designs. IC certification may involve system troubleshooting, IC setup and operation, daily checking of GPS and temperature sensors, creation and use of layer IDs, and other elements of IC. It is recommended that the agency provide assistance for IC training to enhance its use and subsequently require certification.

- IC data should be processed in a timely manner. According to ODOT IC provision 411-18(a-e), the Engineer should get access to raw data and results from the analysis software within 24 hours of obtaining the data.
- IC data from only three sites were analyzed in this project. It is recommended that the IC from the remaining sites be analyzed to realize the benefits of the agency investment.

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APPENDIX A: LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
ICA	Intelligent Compaction Analyzer
ICMV	International Compaction Measurement Value
MPH	Miles Per Hour
NN	Neuron Network
ODOT	Oklahoma Department of Transportation
OEM	Original Engineering Manufacture
QA	Quality Assurance
QC	Quality Control
VPM	Vibration Per Minute