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IMPLEMENTATION OF INTELLIGENT COMPACTION (IC) FOR PAVEMENT CONSTRUCTION IN VERMONT

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16. Abstract

Compaction is one of the most important operations in pavement construction. Poor compaction of different pavement layers (i.e. subgrade, sub-base, base, and wearing course) can lead to various types of deterioration/failure, which consequently increases the cost of maintenance and rehabilitation. Therefore, it is crucial to control the compaction quality at different stages of road construction. Since the density-based Quality Control (QC) and Quality Assurance (QA) methods relying on spot-test measurements and retrieved-core testing can only cover less than 1% of the compacted area, it is difficult to ensure the uniformity and consistency of the compaction process. As a result, it is highly desired to transition from the current point-wise to a system-wide inspection practice.

Intelligent Compaction (IC) is considered to be an innovative technology intended to address some of the problems associated with conventional compaction methods of earthwork (e.g. stiffness-based measurements instead of density-based measurements). The main objective of this project was to evaluate the performance of IC technology in the state of Vermont. At the initial stage of the project, the IC data from Bethel-Stockbridge project were analyzed to gain a better insight into IC performance. Then, a reclaimed asphalt pavement project (Route 117) was selected for field testing and data collection. During the first construction season, the field test plan and data analysis were focused on understanding the IC roller measurements (i.e. ICMVs) and their association with the point-wise measurements (Dynamic Cone Penetration, Nuclear Gauge Density, Pavement Quality Indicator). Then, during the second construction season, the field test plan was focused on evaluating the consistency of compaction operation using the IC roller. In addition, feasibility of using target ICMV, optimum number of passes and roller temperature data as QC tool were investigated.

The results from field tests indicated a very weak correlation between the ICMVs and point-wise density measurements. Changing the underlying material and using inconsistent roller parameters were identified as the potential causes of this poor correlation. However, calibration of the roller parameters at the initial stage of the second construction season testing improved the correlations between ICMV and spot density measurements. Target ICMV and optimum number of passes determined at this stage were successfully used as QC tool. In addition, geo-spatial analysis indicated that using IC roller live monitoring system can potentially improve the consistency and uniformity of the compaction process. Finally, the temperature data recorded by IC roller were found to be reliable for utilization as a QC tool in the course of laying the HMA layer.

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ORGANIZATION OF THE REPORT

The results and analysis presented in this report is based on the data provided by VTrans and also the data collected from the Essex-Jericho (Route 117) project. This report is structured as follows: Chapter 1 gives an introduction about IC. Chapter 2 includes the research methodology and field test plan used at different phases of the project. Chapter 3 provides the results of data analysis at different stages of the project. The conclusions are provided in Chapter 4. Finally, Chapter 5 includes recommendations on IC implementation in the State of Vermont.

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CHAPTER 1 –INTRODUCTION

1.1 Introduction

Effective compaction of embankments, subgrades, and base materials is critical to the performance of pavements and other earth structures (e.g. Corriea et al., 2016; Kumar et al., 2016). Current quality-control (QC) and quality-assurance (QA) methods use in-situ testing devices (e.g. nuclear density tests), assess less than 1% of the actual compacted area (Mooney et al., 2010), provide only spot checks and are unable to provide a wide measure of adequate compaction (Barman et al., 2016; White et al., 2019). In addition, from the QA-QC perspective, it is highly desirable to transition from the current density-based acceptance practice to stiffness-based inspection practice.

To ensure long lasting performance of pavement materials and avoid significant maintenance and rehabilitation costs, it is necessary to achieve high quality and uniformly compacted materials. It is well known that slight reduction in air voids during pavement compaction can lead to few years of extended life service of pavement (Montoya et al., 2108). The limitations of conventional compaction techniques and current density-based acceptance practice in roadway construction has led to non-uniform and unsatisfactory compaction of the pavement materials, which in turn has resulted in premature failure and short life-time performance of the pavement in many cases (Chang et al., 2014). A significant portion of the roadway maintenance cost is the result of poor compaction of the sub-base and pavement (e.g. Zumrawi and Margani, 2017; Kamali-Asl et al., 2016).

IC is an innovative technology intended to address some of the problems associated with conventional compaction methods (e.g. Mooney et al., 2010). IC refers to an improved compaction process using rollers equipped with an integrated measurement system that consists of a GPS (global positioning system), accelerometers, onboard computer reporting system, and infrared thermometers for hot mix asphalt (HMA)/warm mix asphalt (WMA) feedback control (e.g. Chang et al., 2011) as depicted in Figure 1. GPS system records the coordinates (i.e. Easting and Northing) of various roller measurements (e.g. ICMVs, pass counts, frequency, and amplitude) and accelerometers measures the frequency and amplitude of the vibratory rollers (e.g. Barman et al., 2106; Zhong et al., 2018). Then, the processing unit translates the accelerometer's data into stiffness (ICMVs) for a specific coordinate (Mooney et al., 2010).

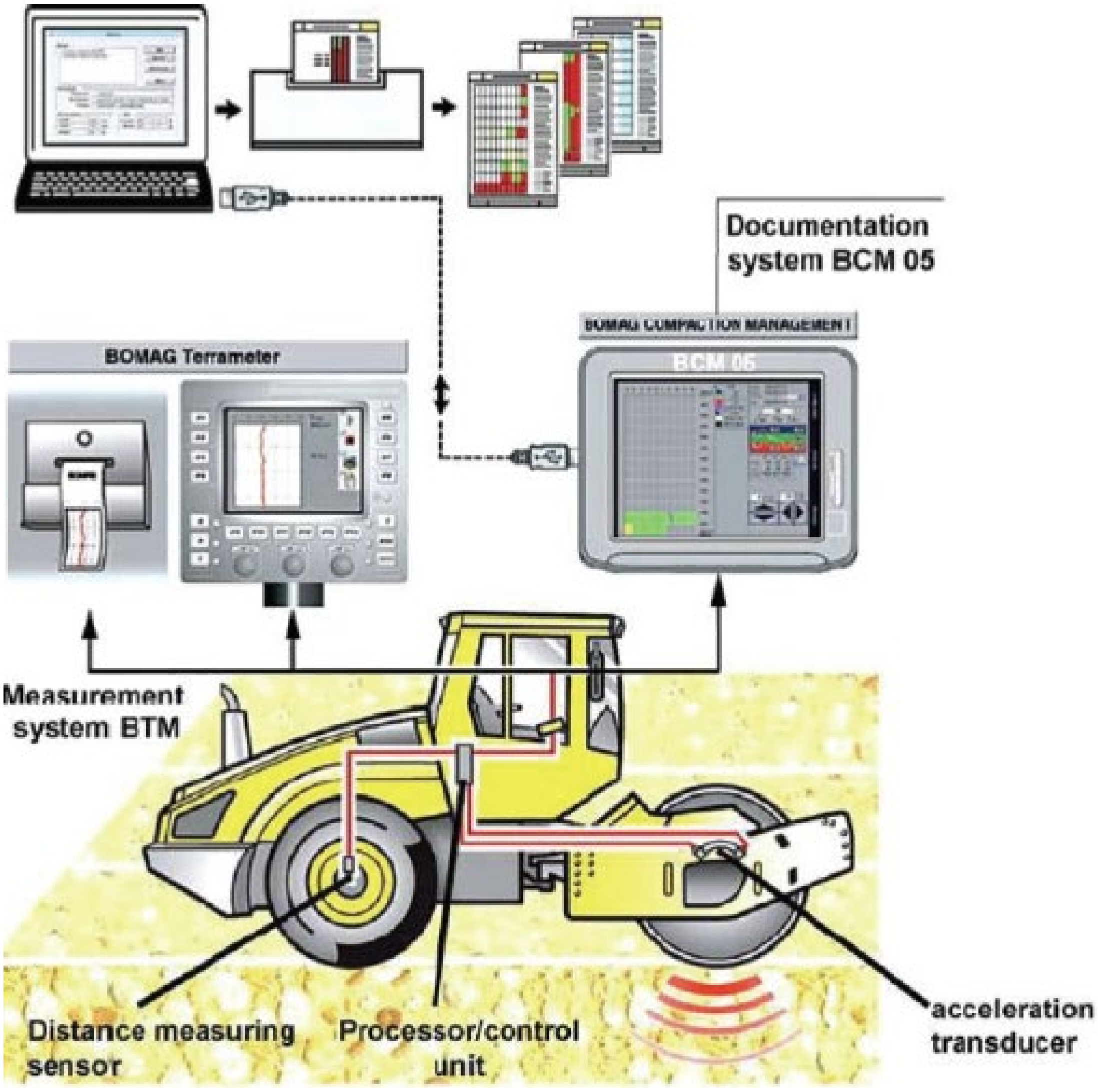


Figure 1. Schematic of the IC roller (Source: BOMAG Catalog)

The use of IC rollers (i) increases the compaction uniformity; (ii) provides a system wide (i.e. global) stiffness-based inspection practice; (iii) allows for real-time monitoring, identification of weak areas, and making informed decisions on proper course of action during compaction; (iv) optimizes construction time; (v) generates IC base map and enables maintaining construction records; and (vi) leads to potential savings in maintenance costs and extended service life (e.g. e.g. Mooney et al., 2005, Arasteh and Nieves, 2013).

In order to implement IC technology, the roller operators should be trained, and the officials must have adequate experience on using this technology. Although the long-term benefits of using IC can potentially compensate the extra expenses associate with IC implementation, it might limit implementation of IC in small scale projects (Savan et al., 2016). Prior to IC implementation, one of the main issues to be addressed is that whether intelligent compaction measurement values (ICMVs) in terms of stiffness can be directly correlated to in-situ measurements (e.g., moduli, density, and California bearing ratio) using conventional methods (Mooney et al., 2010). According to Mazzari et al. (2017), the correlation between ICMVs and the traditional stiffness/density based compaction measurement tools such as light-weight deflectometer (LWD), dynamic cone penetration (DCP), and nuclear gauge (NG) can vary through different sections and different layers of the pavement, which can be due to different material properties.

Difference between depth of IC measurement and in-situ spot tests impacts the correlation between ICMVs and in-situ density measurements (Fathi et al., 2017). Mooney et al. (2010) found that the depth of ICMV measurements and vibration amplitude are positively correlated, where 0.1 mm increase in the vibration amplitude can followed by 3 cm increase in depth of measurement. Other parameters such as layer interaction, drum/soil contact mechanics, and stress-dependent soil modulus contribute to the amplitude dependence of ICMVs (Chang et al., 2011). Therefore, to avoid the inconsistency between the roller measurements, it is recommended not to change the frequency and amplitude during the compaction operation.

Since IC roller measurements vary based on the properties of underlying material, (Kamali-Asl et al., 2016), and the depth of IC roller stiffness measurements is relatively higher than the depth of point-wise density/stiffness based measurements (Hu et al., 2017), the resulted discrepancy is a source of uncertainty for IC roller measurements and more importantly the success of its implementation. In addition, other factors including unfamiliarity of the local contractors with the IC can adversely affect the success of IC implementation. Table 1 summarizes the benefits and limitations of IC implementation in pavement projects (Kamali-Asl et al., 2016).

Table 1. Benefits and limitations of IC implementation

Advantages	Disadvantages
• Optimal number of passes • 100% possible coverage of the roadway • Cost-effective • Provides better QA/QC* • Longer performance of pavements *Provided that communication service is available	• High capital cost • Unfamiliarity of contractors and state officials with the method • Uncertainty in correlation between ICMVs and spot-test measurements • Inappropriate for layered structures with high base-to-subbase stiffness ratio • Not very appropriate for asphalt compaction

1.2 Objectives of the Project

The focus of this project was to address the uncertainties associated with the implementation of IC technology in Vermont. The main objectives of the project were to:

- Analyze the existing data from a previous IC project conducted by the Agency, learn from the data and plan details of IC implementation for field tests
- Conduct IC field tests and supplementary spot tests to validate and establish correlations with the indices obtained from IC at the test sections
- Assess feasibility of using IC as a QC tool
- Evaluate the consistency of IC Operation
- Develop recommendations on IC implementation
- Monitor pavement performance to evaluate the improved performance

CHAPTER 2 – METHODOLOGY AND FIELD TEST PLAN

The research methodology followed during different phases of the project included:

- Preliminary analysis of existing IC data and planning IC field tests
- Field tests (IC and spot tests) and data analysis during first construction season
- Field tests (IC and spot tests) and data analysis during second construction season

The summary of activities and field tests are detailed in the following section.

2.1 Preliminary Analysis on Bethel-Stockbridge Project IC Data

At the initial stage of the project, in order to gain a better insight on interpreting the IC data, available portions of the IC data from a previous project (i.e. Bethel-Stockbridge project) provided by Mark Woolaver from VTrans were analyzed. The Bethel-Stockbridge project was completed on August 2014. The main objective of this project was compacting the natural sub-grade of the Bethel-Stockbridge road (River Street) to the desired level. Figure 2 demonstrates the location of the road which is highlighted in purple color. The compaction was achieved using a single drum vibratory roller Caterpillar CS54B compactor, equipped with an in-situ measurement system and feedback control to record the IC data. The accelerometers installed on the drum were used to record the vibration frequency and amplitude, and the response of the compacted subgrade soil. The Real Time Kinematic-Global Positioning System (RTK-GPS) recorded the exact location and speed of the roller and the number of time that the roller passed over a specific location. The values from this positioning system were recorded in SI units and The UTM (Universal Transverse Mercator) coordinate system. Although it was desired to examine the correlations between the ICMVs and the spot density measurements, the analysis was limited to explanatory data analysis of IC data (e.g. stiffness, pass and roller parameters) since the location of point-wise density measurements (i.e. spot-tests) were not provided. All-pass data were used to evaluate the compaction quality through different roller passes, where the target ICMV and optimum number of passes can be determined based on the compaction curve. In addition, RMV data was used to evaluate the roller performance through the compaction operation.

Figure 2. The Location of the Bethel-Stockbridge road

2.2 Field Tests During First Construction Season

This stage of the project involved collecting data from first and second reclaimed phase, and first asphalt layer in Route 117 reclaimed based pavement project. The main objective was to examine the performance of IC in a reclaimed base project and construct the regression models between the ICMVs and in-situ spot density test. Therefore, the field tests were designed to collect spot test measurements along with extracting the IC roller data. The field tests performed at this stage included:

- Dynamic cone penetration (DCP): to measure the in-situ stiffness of the reclaimed layers.
- Nuclear gauge density: to measure the in-situ density and moisture content of the reclaimed layers.
- Pavement quality indicator (PQI): to measure the density of asphalt layer.
- Extracted asphalt cores: to measure density and moisture content.
- IC data collected, extracted, and converted to .CSV files using Veta software.

2.3 Field Tests and Data Analysis During Second Construction Season

This stage (i.e. second construction season) of the project involved a more sophisticated field test plan and data analysis. Based on the data analysis and results obtained from the first construction season, the field test plan during second construction season started with calibration of the roller parameters (e.g. target ICMV at optimal number of passes, frequency, and amplitude). The main focus of this stage of the project was to examine the consistency of IC process and feasibility and reliability of using IC feedback data (especially stiffness and temperature) as a QC tool. The field tests performed during this stage of the project included:

- IC roller parameters were calibrated to determine target ICMV, number of passes, frequency and amplitude in the test section.
- Target ICMV determined from the first step was used to compact the road and feasibility of using target ICMV as a QC tool was examined.
- Several NG and PQI density tests were performed on a grid to examine the consistency of IC roller measurements through a spatial analysis on density data. Subsequently, the consistency and compaction quality of an IC compacted section was compared to a non-IC compacted section.
- A geo-statistical analysis was performed on PQI density measurements to investigate the spatial uniformity of a section of first hot mix asphalt (HMA) layer.
- Spot temperature measurements were performed using handgun infrared in order to examine the correlation between the IC measured temperature and in-situ temperature measurements. Then, the feasibility and reliability of using IC temperature sensors as a QC tool was evaluated.
- The correlation between the temperature in the course of HMA paving and the resulted density was examined to highlight the important role of temperature during paving HMA layer.

CHAPTER 3 –RESULTS AND DISCUSSIONS

3.1 Results of IC Data Analysis from Bethel-Stockbridge Project

The result of the analysis of the IC data collected by the Caterpillar CS54B compactor during the compaction of the Bethel-Stockbridge road is represented in this section. The explanatory data analysis was performed using R-Studio platform. R is a statistical package, which provides wide variety of statistical and graphical analysis including histograms and normal Q-Q probability plots of different types of IC data (e.g. pass counts, compaction measurement value (CMV), amplitude (mm), vibration frequency (vpm), and speed of roller (mph)). In addition, the Veda 2.1 software was used to perform the spatial geo-statistics analysis. Semivariogram graphs were generated to evaluate the spatial uniformity of the compacted material during the compaction process. In addition, the compaction curve, which can be used to evaluate the efficiency of the compaction, was generated using the mean CMV measurements and the corresponding number of passes in the All-Pass data. The compaction plot is also generated by Veda 2.1 software.

3.1.1 Speed of Roller (mph)

The summary of statistical analysis of the "Roller Speed" data, extracted form IC data, representing the measurements from the last passes is provided in Table 2. As it can be seen in Table 2, the maximum speed of roller during the compaction period was 44.80 (mi/hr) and the minimum speed was 2.6 (mi/hr). Moreover, 75 percent of the recorded roller speeds are below 6.5 mph.

Table 2. Summary of Statistics for Speed Roller Data (mi/hr)

Minimum	2.6
1st Quartile	4.9
Median	5.9
Mean	6.39
3rd Quartile	6.5
Maximum	44.80

Figure 3 demonstrates the histogram plot of the "Speed Roller" data. The occurrence frequency of each dataset (i.e. each Roller Speed (mph)) in the measurements from the last passes can be observed in this histogram. As evident from Figure 3, during collection of the final coverage data, more than 90% of time the speed of the roller was less than 10 mph.

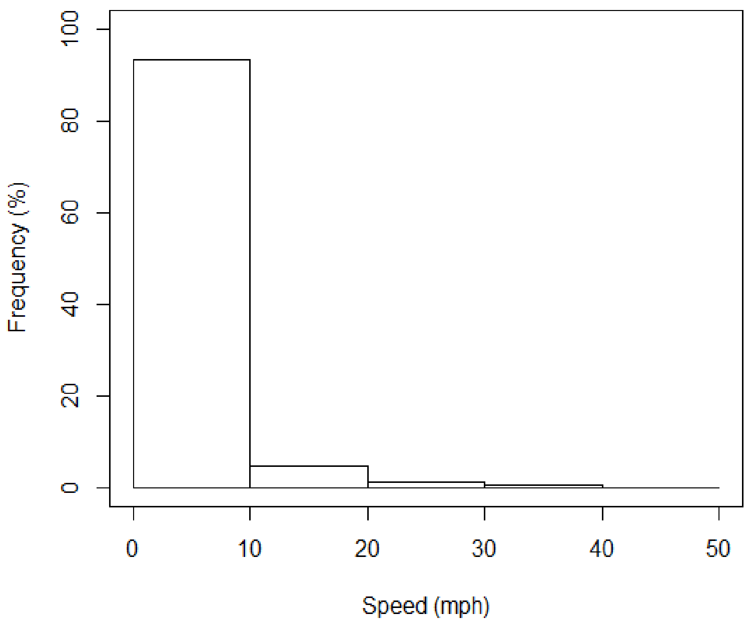


Figure 3. Histogram of Roller Speed (mi/hr)

3.1.2 Pass Count

The “Pass Count” data represents the number of roller’s passes in a given area, which was recorded in the last pass measurements. The analysis of “Pass Count” data can be used to optimize the IC process. Moreover, the number of roller passes can be used for generating a compaction curve using the “CMV” values and “Pass count” data. The summary of statistics of the “Pass Count” data is presented in Table 3. The maximum number of roller passes was 33 times, and the minimum number of pass counts was recorded as 1 time. The third quartile data reveals that more than 75% of “Pass Count” data were less than 5 pass counts.

Table 3. Summary of Statistics Pass Count Data

Minimum	1
1st Quartile	1
Median	3
Mean	3.715
3rd Quartile	5.00
Maximum	33

In addition, as evident from the histogram plot of the "Pass Count" data shown in Figure 4, more than 90% of times the number of "Pass Counts" was less than 10 times.

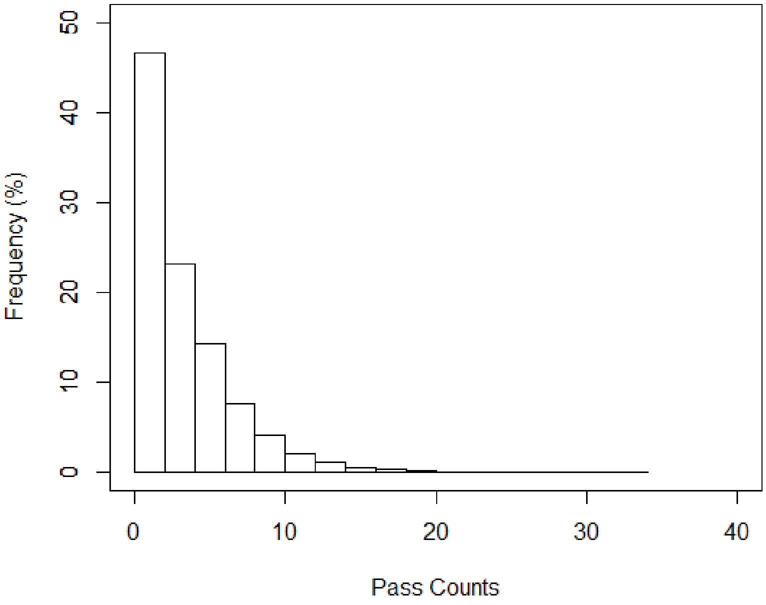


Figure 4. Histogram of Pass Counts

3.1.3 Amplitude and Frequency Data

Amplitude (mm) and frequency (vibration per meter: vpm) of vibration are among the most important parameters that determine the intelligent compaction values. The amplitude (mm) and frequency (vpm) of the roller is automatically optimized by the IC rollers and the operator should select the roller speed based on them. Therefore, evaluation and analysis of the amplitude and frequency data provided by the roller can help improve the understanding of the compaction process. The statistical analysis results on amplitude and frequency data is represented in Table 4. Although the maximum of the amplitude is 10 mm, more than 75% of amplitude data are lower than 2.77 mm.

Table 4. Summary of statistics for Amplitude data (mm)

Minimum	0.34
1st Quartile	2.31
Median	2.55
Mean	2.56
3rd Quartile	2.77
Maximum	10

Figure 5 indicates the histogram of amplitude (mm) data, where the majority of data are between 2 to 4 mm.

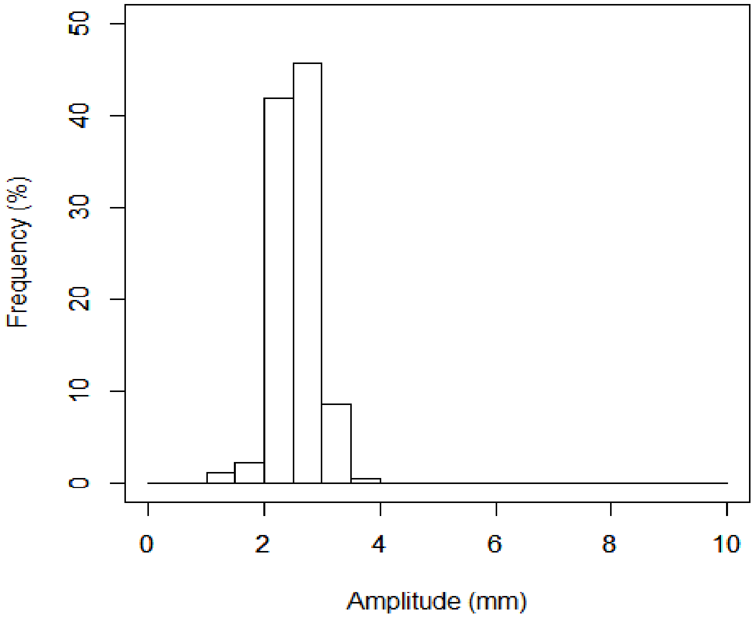


Figure 5. The Histogram of Amplitude (mm) data

Furthermore, the vibration frequency data recorded by compaction meters or accelerometers mounted on the rollers drum, can be analyzed to investigate the influence of this roller parameter on CMV data (Hu et al., 2108). The vibration frequency data were analyzed and the summary of this statistical analysis is provided in Table 5. Although there is a gap between the maximum and minimum vibration frequency, other statistics reveals that the frequency was fluctuating in a very small range. This can be confirmed by the small range of variation that was observed in amplitude data.

Table 5. Summary of Statistics for Vibration Freq. Data (vpm)

Minimum	15
1st Quartile	30.40
Median	30.50
Mean	30.62
3rd Quartile	30.60
Maximum	34.90

The histogram plot of the vibration frequency data is demonstrated in Figure 6, where more than 90 percent of the data were in the order of 30 vpm.

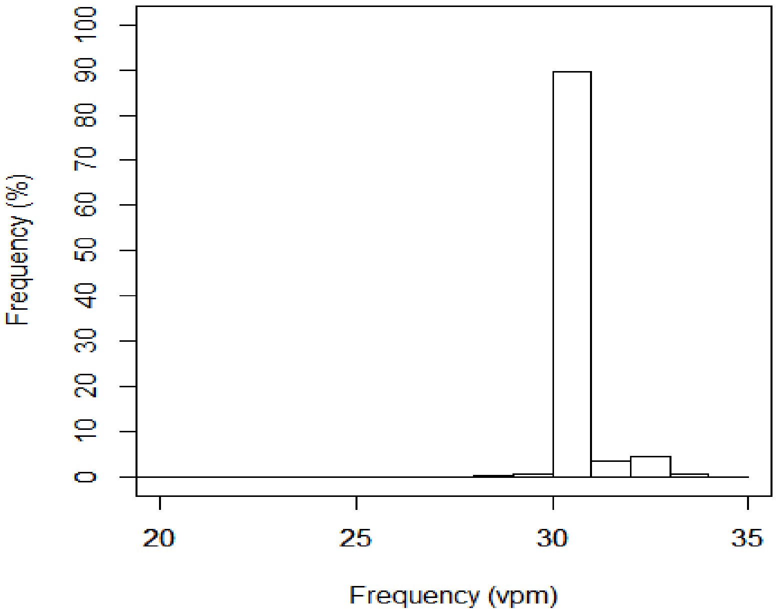


Figure 6. Histogram of Vibration Frequency (vpm) data

3.1.4 CMV Data

CMV is a dimensionless compaction parameter, which is the function of the roller configuration (e.g. the weight and diameter of the drum) and roller operation parameters such as speed, frequency, and amplitude (Vennapusa, 2009; Hu, et al., 2017). Since the dynamic roller response is used to determine this value (Adam, 1997), CMV would change from roller to roller. Therefore, it is necessary to perform statistical analysis on CMV data which can help with optimizing the intelligent compaction process. CMV can be calculated as (Adam, 1997; Vennapusa, 2009):

$$CMV = C \times \frac{A_1}{A_0}$$

Where:

C = Constant (300 in Caterpillar rollers)

A_0 = Acceleration amplitude of the fundamental component of the vibration

A_1 = Acceleration amplitude of the first harmonic component of the vibration

The summary of the statistical analysis on CMV data is provided in Table 6. The maximum number of CMV is recorded as 196.20, where 1.40 is the minimum value recorded for CMV. Based on the statistics, 25% of the CMV data are less than 31.40, 50% of the CMV data are less than 47.90, and 75% of them are less than 67. Moreover, the average number of the CMV is determined to be 50.55.

Table 6. Summary of Statistics for CMV Data

Minimum	1.40
1st Quartile	31.10
Median	47.90
Mean	50.55
3rd Quartile	67
Maximum	196.20

The histogram of the CMV data (see Figure 7) illustrating the distribution of the CMV data indicates that most of the CMV data are in the range of 20 to 80 (around 90%). As can be seen in Figure 7, the visual observation of CMV data distribution suggests that the data distribution is close to normal condition. In addition, Shapiro-Wilks test revealed a p-value of 0.11 that confirmed the CMV data distribution is not significantly different from normal distribution. However, a huge range of variation is observed in the CMV data, where the standard deviation of this parameter was 24.07. Based on the huge range of variation and relatively high standard deviation value, it can be inferred that the CMV measurements were not consistent and a considerable number of outliers exist in the data.

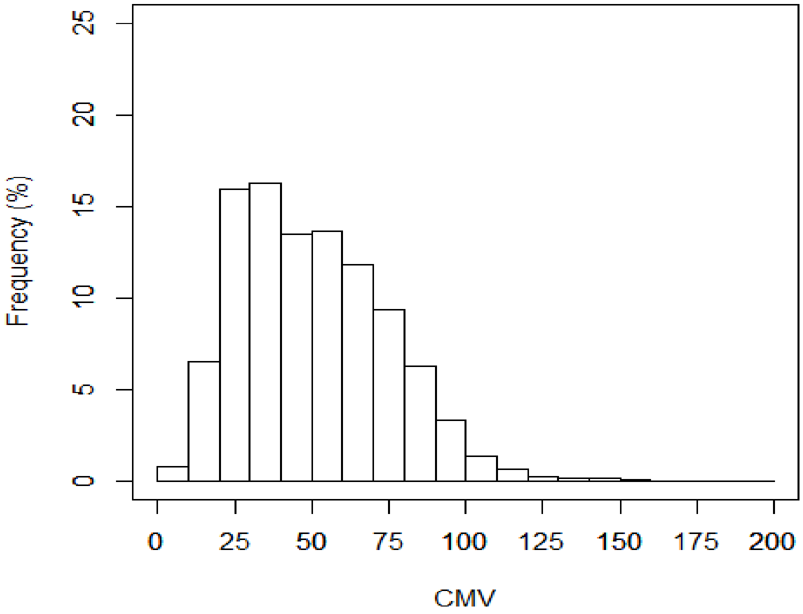


Figure 7. Histogram of the CMV data

One of the most important tasks in IC is to optimize the compaction process, which can in part be accomplished by generating the compaction curve: the plot of mean CMV versus the number of pass counts provided by "All Passes" data. In order to optimize the compaction, the CMV value can be plotted against the target number of pass counts. Compaction curve generated based on the CMV value indicated that the target CMV and the target number of pass counts should be 50 and 3, respectively. Figure 8 indicates the compaction curve generated based on the IC data.

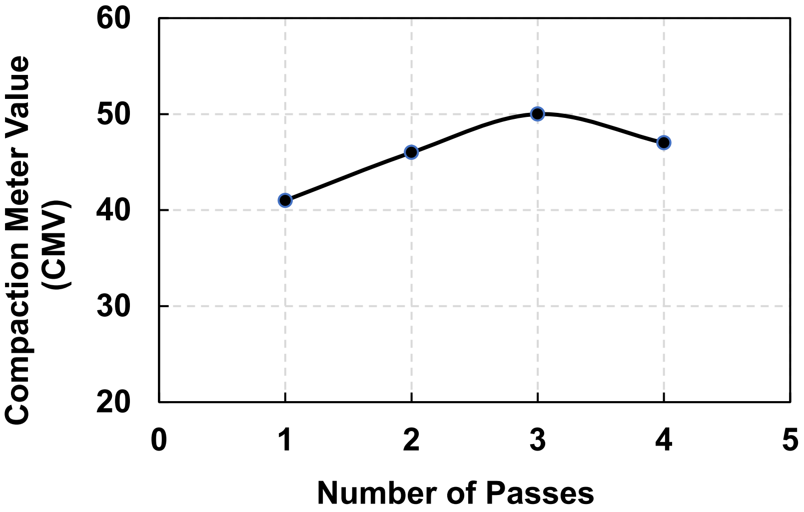


Figure 8. Compaction curve based on CMV values and pass counts

3.1.5 RMV Data

Resonant Meter Value (RMV) is a measure that explains the changes in the behavior of the drum (e.g. rocking motion, partial uplift, double jump, and chaotic motion) during the compaction period (Vennapusa et al., 2009; Hu et al., 2018). RMV can be determined using the following formula (Vennapusa et al., 2009; Hu et al., 2018):

$$RMV = C \times \frac{A_{0.5}}{A_1}$$

Where:

C = Constant (300)

A_0 = Acceleration amplitude of the fundamental component of the vibration

$A_{0.5}$ = Subharmonic acceleration amplitude

When RMV is close to zero, it shows that the drum is continuously compacting the underlain material. On the other hand, when the values are dramatically above zero, the roller is transitioning to the rocking mode, double jump or chaotic mode (Thurner & Sandstrom, 2000). This would directly affect the CMV values and quality of compaction in the compacted area (Adam & Kopf, 2004; White et al., 2011). Furthermore, undesirable RMVs can influence the areas that are already well compacted (Thurner & Sandstrom, 2000). Therefore, analyzing the RMV data helps the pavement engineers to improve their interpretation from the CMV data (Vennapusa et al., 2009).

The statistical analysis of the RMV data was performed using the RStudio program. Table 7 represents the summary of statistics for RMV data. Based on the statistical analysis, more than 50 percent of the RMVs are higher than 80.36, and only 25 percent of the RMV data is lower than 13.20, which is still considered as a high number for RMVs.

Table 7. Summary of Statistics for RMV Data

Minimum	0.00
1st Quartile	13.20
Median	71.6
Mean	80.36
3rd Quartile	140.7
Maximum	200

The histogram plot of the RMV data is demonstrated in the Figure 9. The plot confirms that there are lots of significantly large RMVs in this IC dataset. These significantly large RMV numbers indicates that the roller was not performing well and probably CMV values may not show the actual stiffness of the material.

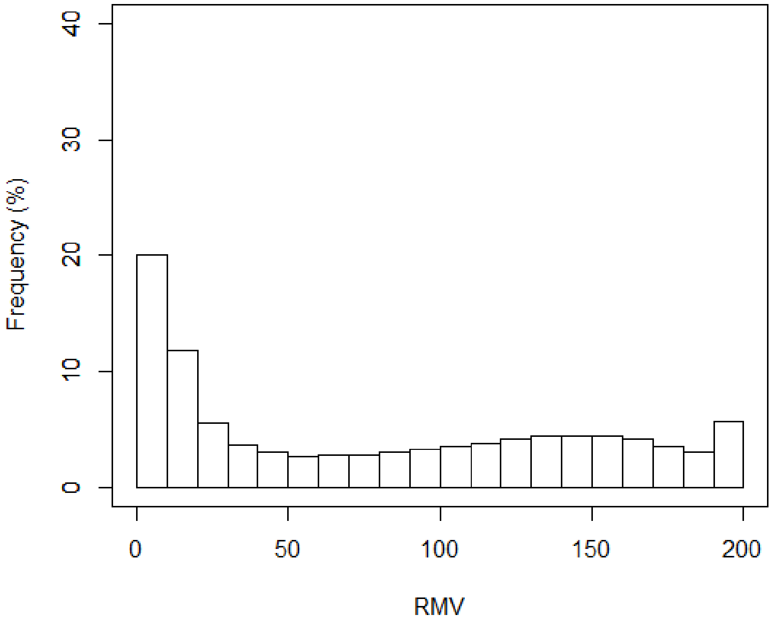


Figure 9. The histogram of RMV data

3.1.6 Summary of the Key Points on Data Analysis

In this section the summary of the key points about data analysis is presented:

- The processed IC data files necessarily include the information about: Speed of Roller (mph), Number of Pass Counts, Amplitude (mm) and Frequency (vpm) of Roller Vibration, Compaction Meter Value (CMV), Resonant Meter Value (RMV), the Location of the Data Point in UTM (Universal Transverse Mercator) system.

- Before performing the data analysis, the Intelligent Compaction (IC) data must be evaluated to detect and refine any potential outliers through the data. This is necessary to have a realistic data analysis.

- Statistical analysis of the roller parameters, such as speed (mph), amplitude (mm), and frequency (vpm), can provide important information about the compaction process. In addition, these parameters can directly influence the roller measurements and specially ICMVs.

- Since ICMVs are the function of roller configuration (e.g. the weight and diameter of the drum) and vary based on the roller brand, these values should be interpreted based on the spot density measurements and also the number roller passes.

- The efficiency of the compaction process can be investigated through the evaluation of the compaction curve, in which the mean ICMVs are plotted against the corresponding number of pass counts. Evaluation of the compaction curve can help with optimizing the compaction process by determining the target ICMV and target number of passes.

- Resonant Meter Value (RMV) is the numerical explanation of the roller behavior, where the values close to zero are favorable. Since RMVs directly influence the compaction quality and CMVs, statistical analysis should be performed to investigate the distribution of this parameter. A huge number of RMVs far greater than zero indicated that the drum entered a chaotic or rocking mode.

3.2 Field Testing Results During First Construction Season

This section contains the evaluation of IC compaction performance during the first construction season in Route 117 project, where the results of spot test measurements (NGD and DCP) and the regression models of IC data and point-wise measurements are represented. The regression models were generated at different layers to evaluate the correlation between spot measurements and ICMVs.

3.2.1 Background on Project and Data Collection Process

IC field tests were conducted in Route 117 project, a reclaimed asphalt pavement (RAP) project. Prior to implementation of IC, 4 inches of the existing distressed asphalt pavement was removed. Then, the remaining amount of asphalt and a portion of underlying base was pulverized through a reclaiming process to the depth of 10 inches. After completion of the first reclaiming phase, the road was graded and compacted using the IC roller, CS56B Caterpillar. DCP and NGD tests were performed to investigate the correlation between the spot measurements and the CMVs acquired from IC roller. The second reclaiming phase involved placing a 6 inches layer of the injected emulsion mixed with reclaimed base material. Then, the whole layer was compacted using the IC rollers in order to achieve the desired level of compaction. In addition, spot test measurements were performed using DCP and NGD tests. Figure 10 illustrates the construction and data collection process.

Figure 10. The photos of (a) reclaiming, (b) shaping, (c) IC compaction, and (d) DCP test

In the next construction stage, a 3 inches layer of cold mix material (a mixture of unheated aggregate and emulsion) was placed above the second reclaimed surface. However, no IC roller compaction was involved during paving the cold mix layer. The last stage of the construction involved paving two layers of hot mix asphalt (HMA) material. The first layer was 3.5 inches of Type II hot mix and the second layer was 1.5 inches of Type IV hot mix. For both layers, the compaction was performed using the IC roller. In addition, PQI and core extraction were used to evaluate the compaction quality at random spots. Figure 11 illustrates the process of density measurements and core extraction.

Figure 11. The process of (a) Pavement Quality Indicator and (b) Core extraction

3.2.2 Results from First Reclaim Phase

In the course of first phase of reclaiming, spot tests including 102 DCP and 27 NGD measurements were performed on two separate segments of River Rd. pavement. The IC roller compacted area and the locations where DCP and NGD tests were performed are indicated in Figure 12. As can be seen, the spot test measurements (highlighted in black color) were performed at two separate segments of the road. The number of DCP and NGD measurements were limited due to the restrictions (e.g. traffic jams) imposed by road closure.

Figure 12. The location of spot test measurements and IC compacted area during first reclaim phase

3.2.2.1 Correlation Between CMV and DCPI

DCP and IC data were analyzed to obtain the dynamic cone penetration index (DCPI) and intelligent compaction measure value (ICMV/CMV). Then, the correlation between ICMVs and DCPI was investigated at each segment and the results are presented in Figures 13a and 13b. In addition, the correlation between all DCPI measured at both segments and the ICMVs is demonstrated in Figure 13c. The R-squared value resulted from the linear regression model of the CMVs and the DCPIs relative to the first segment of the road is found to be 0.14 (R^2 = 0.14), which is slightly lower than the R-squared value obtained from the second segment data (R^2 = 0.17). These low R-squared values indicate that only 14 to 16 percent of the variability of DCPIs can be explained by regression model. On the other hand, the results from regression model that represents both segments of the road is more promising since the R-squared value is found to be approximately 0.22 (R^2 = 0.22). This suggests that the regression model could have potentially improved if more spot test measurements were available.

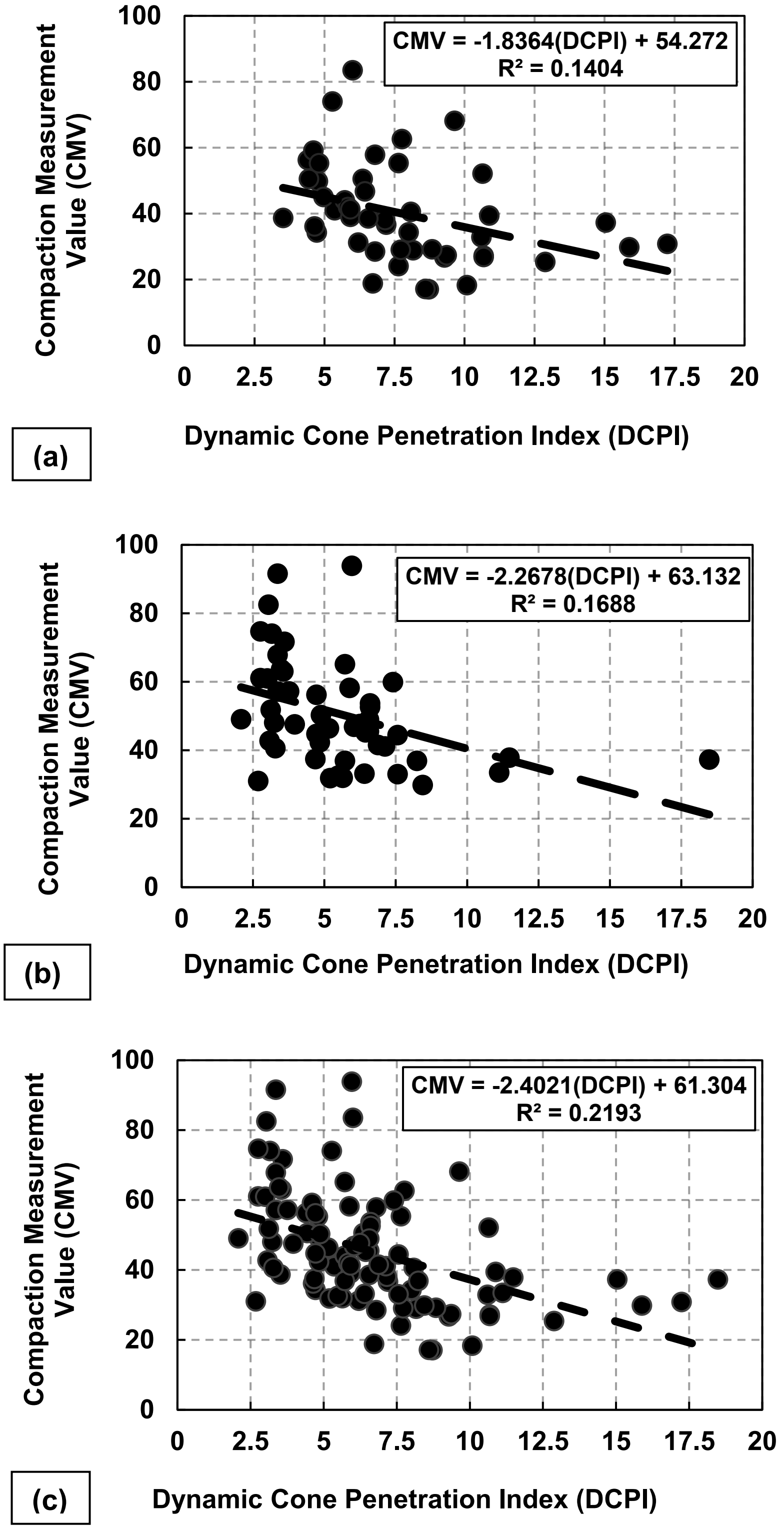


Figure 13. The correlation between the spot test measurements and IC data related to (a) first segment, (b) second segment, (c) both segments

3.2.2.2 Correlation Between CMV and NGD

NGD measurements were performed less frequently than DCP measurements due to limited periods of road closure. Therefore, NGD measurements were limited to the first segment of the road. A total of 27 dry density (lb/ft^3) and moisture content measurements were performed on the first segment of the road. Then, the correlation between the dry density (lb/ft^3) and CMVs was investigated. Figure 14 demonstrates the regression model based on the relationship between CMVs and NGD measurements. As can be seen, the very low R-squared value of the regression model ($R^2 \sim 0.03$) implies a significantly weak correlation between variation of dry density measurements resulted from NGD test and CMV.

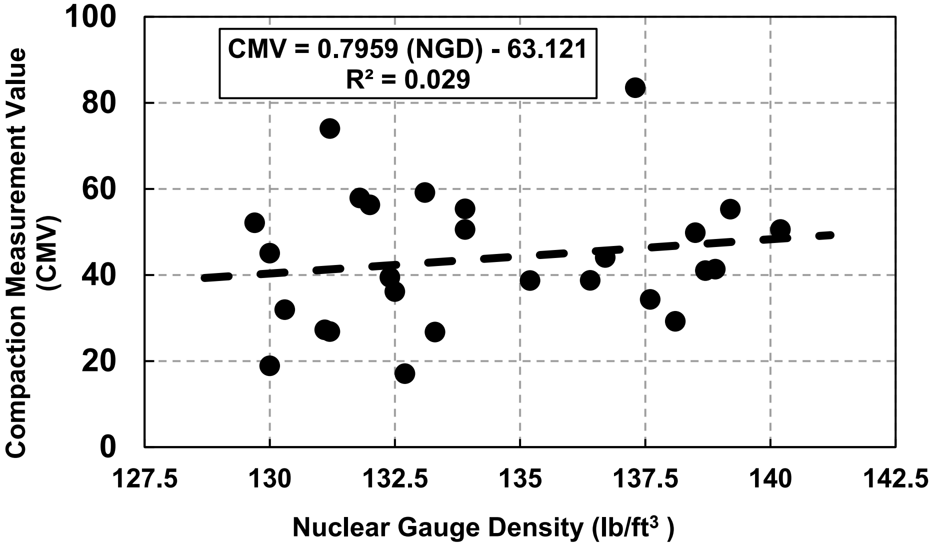


Figure 14. The correlation between CMV and NGD values during first reclaim phase

3.2.3 Results from Second Reclaim Phase

The IC data were collected during the second phase of reclaiming, where a 6 inches layer of emulsion injected reclaimed material was placed and the road was compacted with the roller. In addition, spot density measurements were performed to compare the compaction values resulted from the IC with the traditional density measurements. A total of 78 DCP and 20 NGD measurements were performed, with locations identified on the map in Figure 15.

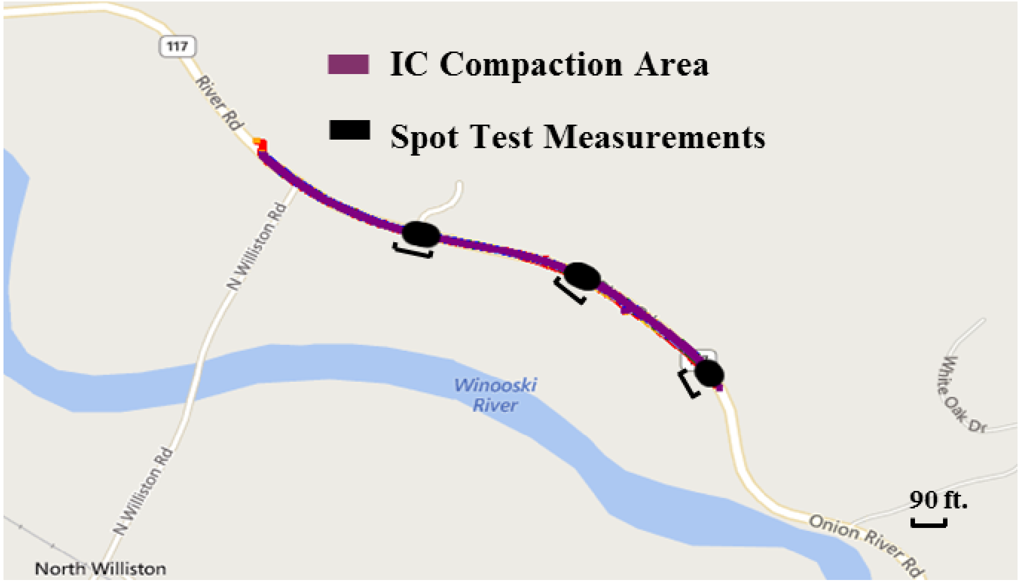


Figure 15. The location of spot test measurements during second reclaim phase

3.2.3.1 Correlation Between CMV and DCPI

Figure 16 illustrates the correlation between the CMVs and DCPIs (78 measurements). As can be seen, the R-squared value resulted from the regression model is very low (R2 = 0.037), indicating a weak correlation between the IC data and spot test results. Compared to the initial reclaim phase, this regression value is significantly lower.

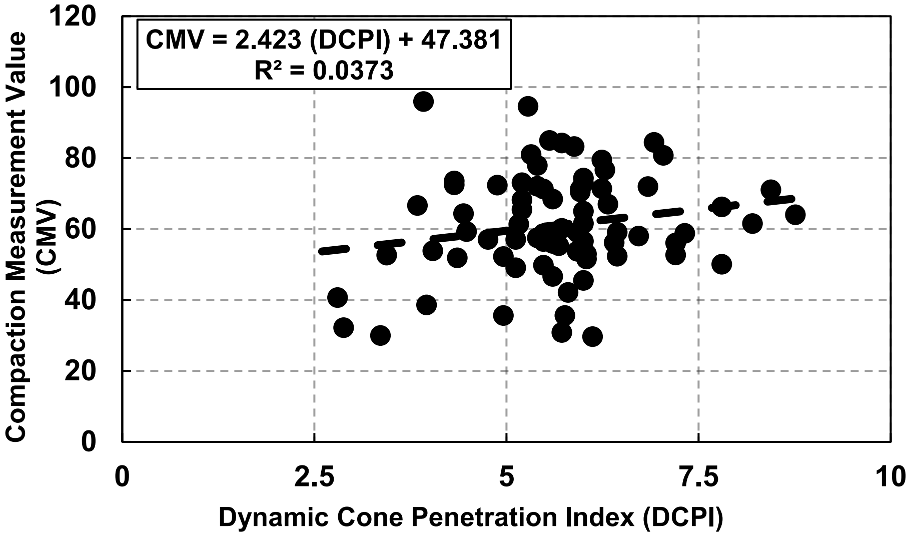


Figure 16. The correlation between CMVs and DCPI for second reclaim phase

3.2.3.1 Correlation Between CMV and NGD Measurements

The correlation between CMV and NGD (20 measurements) is presented in Figure 17. The R-squared value is approximately 0.11, indicating a very weak correlation. Although this value is still larger than the regression value between CMVs and dry densities achieved through the initial reclaiming phase, the model can only capture 11% of variability in data.

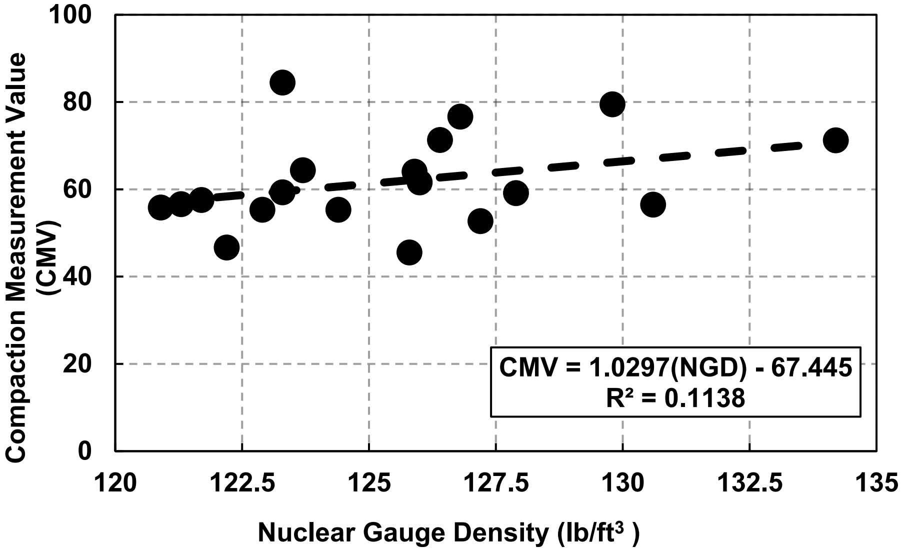


Figure 17. The Correlation between CMVs and dry densities for second reclaim phase

3.2.4 Type II Hot-mix Paving

At this stage of the construction, a layer of 3.5 inches of hot mix Type II was placed on top of a 3 inches cold mix layer. Then, the road was compacted using the IC roller and spot measurements were performed using PQI device, which is used to measure the density (lbs/ft^3) and moisture content (%) during construction of hot-mix asphalt pavements. A total of 118 PQI measurements were performed to monitor the roller operation and to ensure the desired level of compaction. In addition, a total of 20 cores were drilled to measure the density of the hot-mix layer.

3.2.4.1 Correlation Between the CMVs PQI Measurements

Different segments of the hot mix paved road were compacted at different days and the IC data were collected and analyzed at the end of each day. The pavement quality indicator (PQI) was used to determine density at different spots during each day of compaction operation. The entire IC and spot test data collected from different segments of the road were used to investigate the correlation between the CMVs and density measurements obtained from PQI device, as presented in Figure 18. According to the regression model, the R-squared value is very small (approximately 0.04) indicating a very weak correlation. Furthermore, this correlation is significantly lower than the one between CMVs and dry densities measured using nuclear gauge density during the second phase of reclaiming.

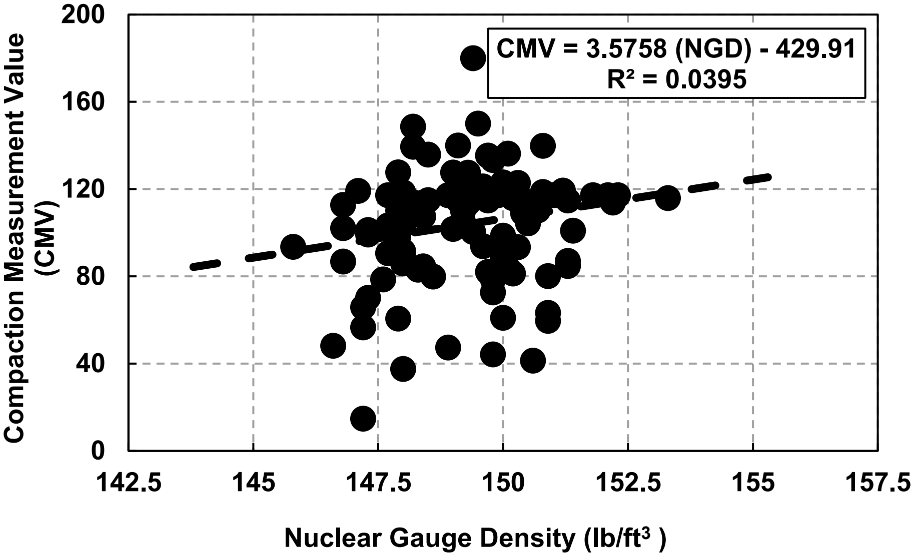


Figure 18. The correlation between CMVs and NGD for Type II hot-mix layer

3.2.4.1 Correlation Between the CMVs and Core-density Measurements

A total of 20 cores were drilled at different depths, ranging from 2.81 to 3.9 inches, in order to measure density, void ratio, and water content. The density values were plotted against the CMV values to investigate the correlation between these two parameters, as presented in Figure 19. The correlation between core densities and the CMVs is very weak due to very small R-squared value ($R^2 \sim 0.06$).

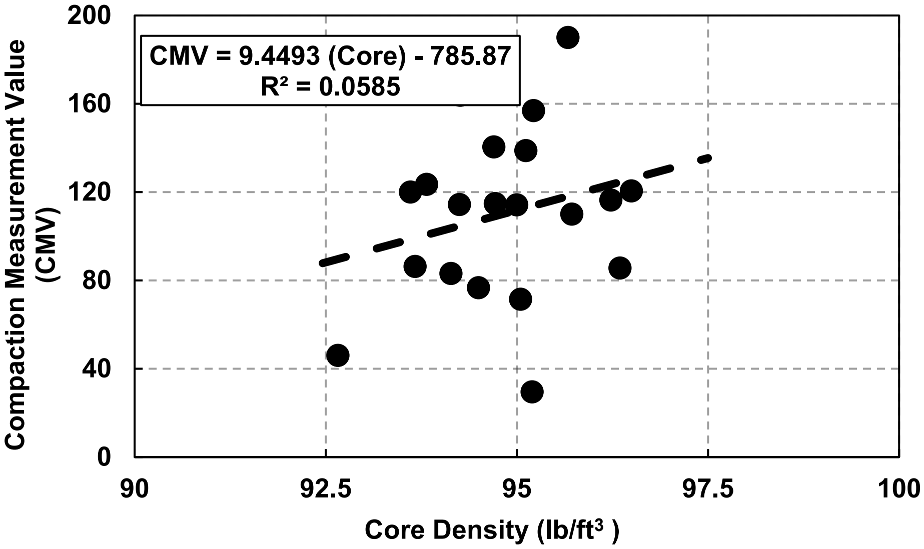


Figure 19. The Correlation between CMVs and Core-Density results

3.2.5 Feasibility of Using Live GPS Data as QC Tool

The feasibility of using live GPS data during IC as a suitable quality control (QC) tool was investigated. The coordinates and ICMVs were recorded for all roller passes including the final coverage, and were used to evaluate the final results of compaction. The IC technology offers the real-time monitoring of the compaction process using the color-coded maps that illustrates the ICMVs during the compaction process. The areas that are poorly compacted or do not meet the target ICMV can be easily identified during the compaction process by monitoring the color-coded maps. To investigate the reliability of this IC feature (real-time monitoring) as a QC tool, the spot measurement results (e.g. pavement quality indicator, core density testing) can be compared with the ICMVs illustrated in the color-coded maps. Good agreement between the two can confirm the reliability of using IC generated color-coded map as a QC tool.

The IC data from the first hot mix layer (3.5 inches of Type II hot mix) were selected to examine this hypothesis. The color-coded maps of different sections of the road were generated using the Veta 5.2 software. Then, the corresponding core density testing results were compared to the ICMVs from the color-coded maps. Figure 20 illustrates the color-coded map of ICMVs and the gray spots indicate the location of cores extracted upon the completion of the compaction process. According to IC final coverage map (Figure 20), the target ICMV is achieved almost over the entire compacted area. The core density test results are represented in Table 8. According to the core test results, provided by Pike Industries (the contractor of the project), the upper specification limit (USL) for compaction was 96.5 % and the lower specification limit (USL) was 92.5 %. According to the core density test results (Table 8), the cores, illustrated in Figure 20, were compacted to the density values within the acceptable compaction range (between 92.5% and 96.5%). In addition, Figures 21 and 22 indicate the color-coded map of the other two sections of the road and Tables 9 and 10 represent the corresponding compaction results. Similarly, evaluation of the core density testing results at these sections of the road indicated that there is a meaningful relationship between the color-coded map results and the spot measurements.

Table 8. The core density testing results (cores 1-5)

Core No.	Core depth (in.)	Weight (grams)			Compaction (%)
		Air	Water	Surf. Dry	
1	3.29	3472.7	2042.2	3478.7	95.3
2	3.22	3385.1	1990.0	3390.3	95.3
3	2.95	3158.4	1869.3	3164.2	96.2
4	3.56	3694.6	2156.2	3712.3	93.6
5	3.08	3286.7	1950.0	3294.4	96.4

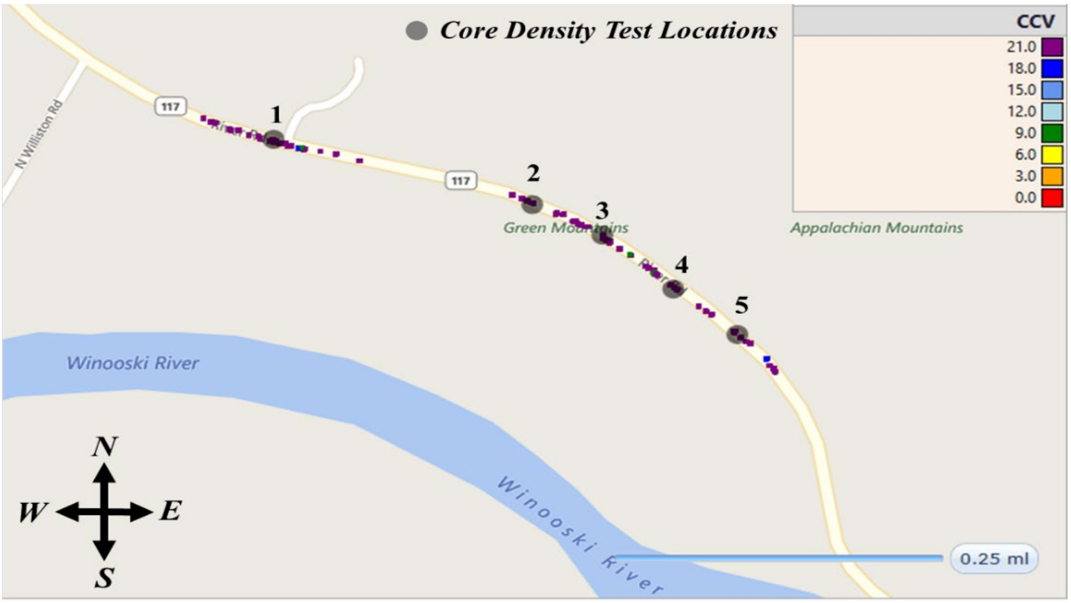


Figure 20. The color-coded map of ICMVs and the core density test locations (cores 1-5)

Table 9. The core density testing results (cores 19-24)

Core No.	Core depth (in.)	Weight (grams)			Compaction (%)
		Air	Water	Surf. Dry	
19	3.52	3762.1	2226.4	3478.7	96
20	3.74	3971.8	2334.3	3390.3	95.1
23	3.52	3675.0	2152.1	3164.2	94.3
24	3.69	3857.3	2267.3	3865.9	95.1

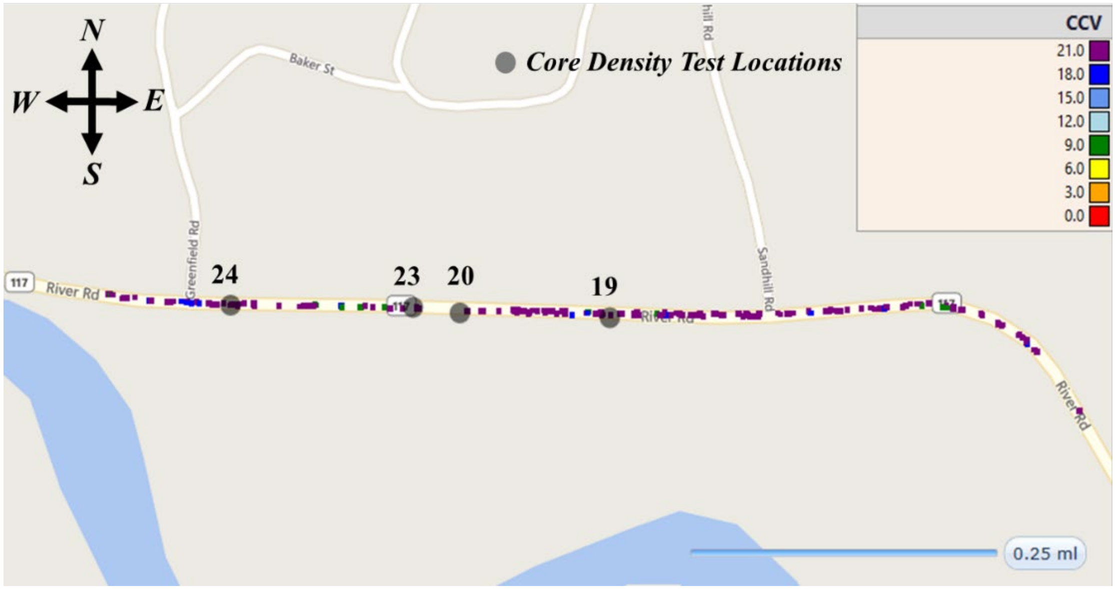


Figure 21. The color-coded map of ICMVs and the core density test locations (cores 19-24)

Table 10. The core density testing results (cores 32-36)

Core No.	Core depth (in.)	Weight (grams)			Compaction (%)
		Air	Water	Surf. Dry	
32	3.69	3872.6	2266.0	3875.8	94.7
33	3.62	3843.4	2259.9	3875.8	95.2
34	3.31	3506.4	2055.5	3511.5	94.8
35	3.39	3575.4	2094.0	3581.3	94.6
36	3.90	4007.8	2332.3	4016.6	93.6

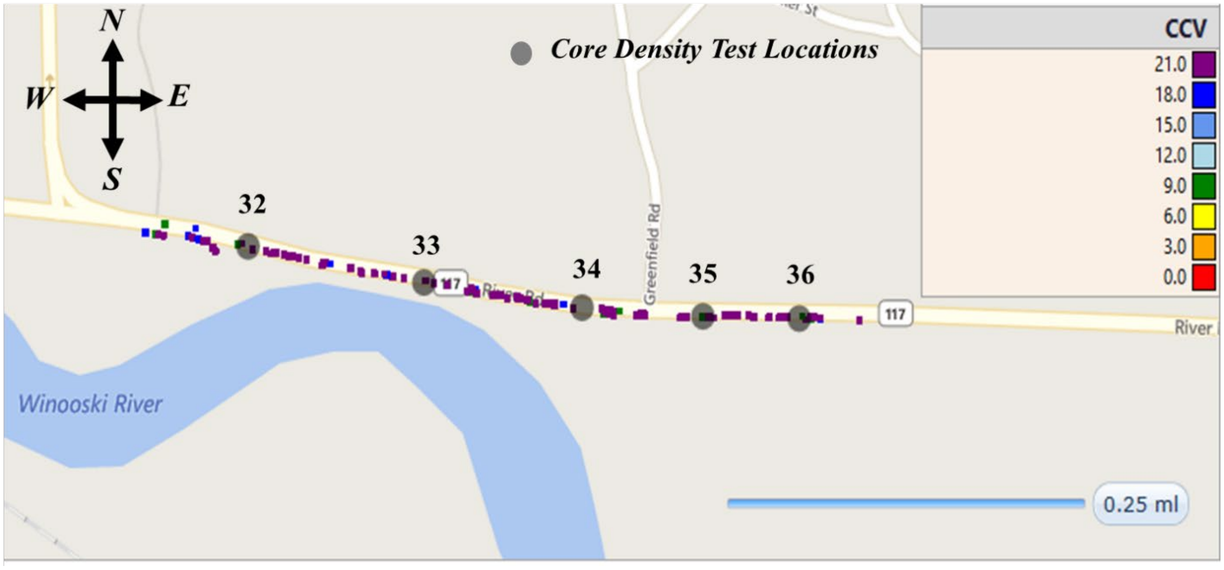


Figure 22. The color-coded map of ICMVs and the core density test locations (cores 32-36)

3.2.6 Discussion on the Results from First Construction Season

The correlations between CMVs and DCP, NGD, and density from core data were in general weak. Based on the collected data used in the analysis, DCPI seems to have much stronger association with the CMVs compared to NGD and core density. However, it should be noted that the correlations tend to improve as the size of the dataset increases. The frequentist statistical analysis indicated that the regression model between DCPIs and CMVs is the only meaningful regression model and the rest of the regression models are not significant. The summary of statistical analysis is represented in Table 11. Using inconsistent roller parameters (e.g. target CMV, frequency, and amplitude) and variation of underlying material through different sections of the road are the potential sources of weak correlation between the spot measurements and IC roller measurements. However, one should bear in mind that the discrepancies between the depth of IC roller measurements and spot measurements (e.g. NGD and DCP) also impact the correlation between these two measurements. Calibration of the roller parameters according to the change in type of material and using consistent parameters throughout the same section might improve the correlation between spot measurements and CMVs.

Comparing the color-coded maps generated in the course of the IC process with the core density testing results suggests that monitoring the live GPS data can be potentially used as a QC tool to evaluate the compaction quality of the pavement. The density results from PQI and NGD can be used to investigate the reliability of using real-time monitoring of compaction using IC generated color-coded map during IC process.

Table 11. The summary of frequentist analysis on regression models

Pavement Layer	Regression Models	R-Squared	P-value
First Reclaim	CMVs and DCPI	0.2193	1.08×10^{-6}
	CMVs and NGD	0.029	0.3956
Second Reclaim	CMVs and DCPI	0.0373	0.0902
	CMVs and NGD	0.1138	0.1577
Type II Hot Mix	CMVs and PQI	0.0080	0.656
	CMVs and Core Results	0.0584	0.3044

3.3 Field Testing Results During Second Construction Season

3.3.1 Description of Project During Second Construction Season

The second construction season of Essex-Jericho-Richmond pavement project initiated with cutting 4 inches of the distressed pavement. The first phase of reclaiming (reclaimed stabilized base) involved pulverizing the pavement together with underlying base course material to the depth of 10 inches. Then, during the second reclaim phase, a 6 inches layer of emulsion injected reclaimed material was placed on the road (full depth reclaiming) and, then the pavement was cut/filled to grade and compacted using the single drum IC roller, BOMAG BW 211D-50. The spot density measurements were performed using nuclear gauge. Figure 23 illustrates different equipment used during different stages of construction.

Figure 23. Picture of different road construction equipment (a) Reclaimer, (b) grader, (c) IC roller, and (d) Nuclear Gauge Density

3.3.2 Calibration of Roller Parameters and Investigation of Using IC as a QC Tool

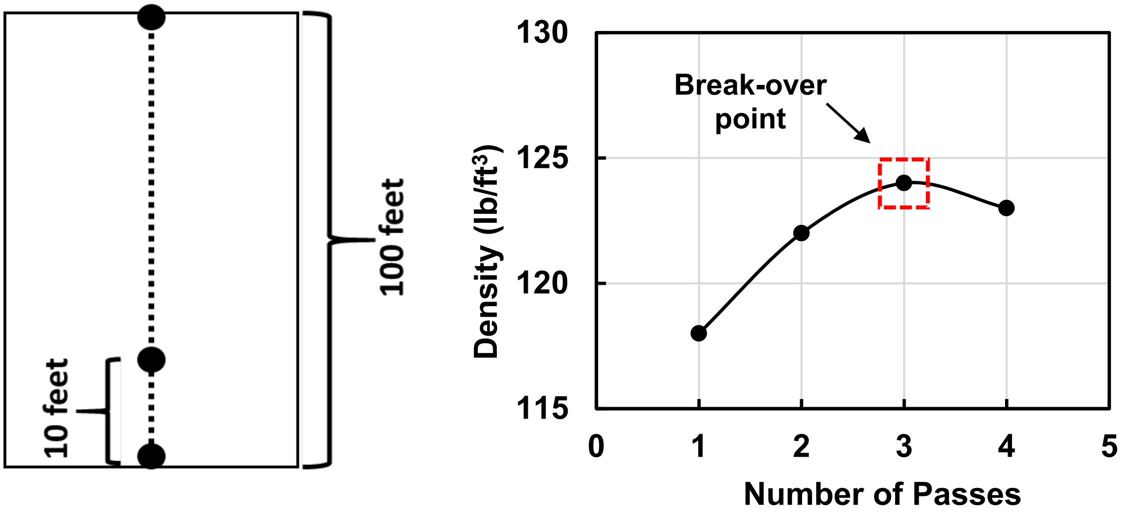
3.3.2.1 Objective

A series of field testing were designed and followed by data analysis to achieve the following objectives:

I. To calibrate the IC roller parameters (i.e. optimum number of passes and ICMV) at a certain frequency and amplitude.
II. To investigate the feasibility of using IC roller feedback data as a QC tool

3.3.2.2 Methodology

The field tests were performed in two different stages. At the first stage, a 100 feet strip was selected for calibrating the IC roller parameters. The nuclear gauge density tests were performed at 10 preselected spots (see Figure 24a) after each roller pass. The average of nuclear gauge density measurements and number of passes were used to determine the break over point (Figure 24b). Then, the density was measured at 15 random spots and the average was compared to the break over point to ensure that the density of the break over point is higher. The correlation between the ICMVs and the nuclear gauge density measurements was used to determine the target ICMV. Once the target ICMV was determined, another 100 ft section of the road was compacted to reach target ICMV. Then, the correlation between ICMV and nuclear gauge density was investigated.



(a) (b)

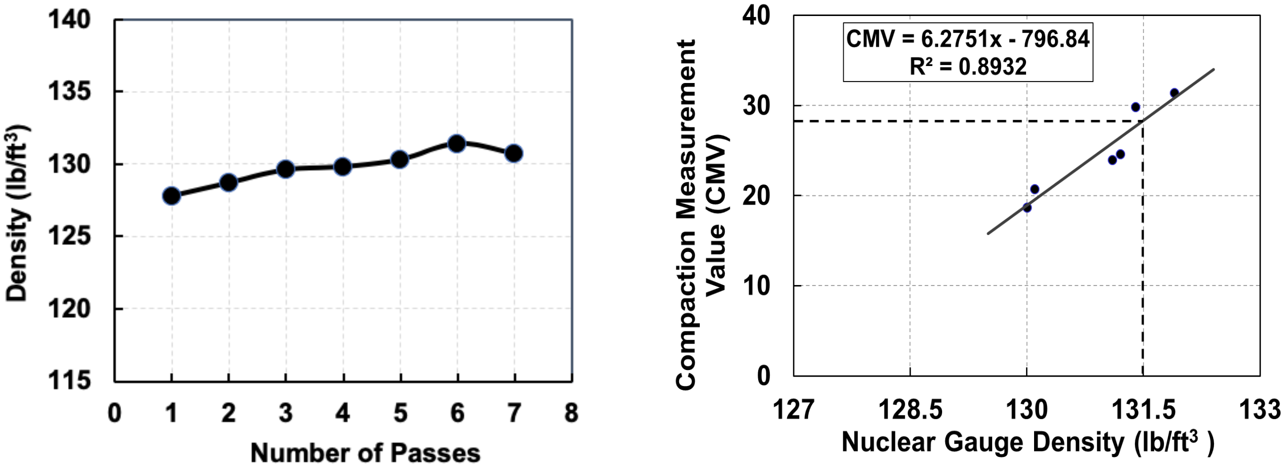
Figure 24. The schematic of (a) test spots on 100 ft. section of the road and (b) determination of break-over point

The second stage of the field test was designed to evaluate the feasibility of using IC roller as a QC tool. The same target ICMV, frequency, and amplitude of the first stage were used to compact a 100 ft section of the road. Initially, the road was compacted without using the onboard display of the IC roller. Then, the areas that were not compacted to the desired level identified using the onboard display and the density at four different spots was measured using the nuclear gauge. Then, the IC roller feedback data was used to compact the weak areas to the desired level. Once the compaction process was completed, the nuclear gauge density at the same spots was measured. The density before and after secondary compaction was compared to investigate any density improvement.

3.3.2.3 Results and Discussion

The average of nuclear gauge density measured at 10 preselected spots were calculated to determine the optimum density and the number of IC roller passes. Figure 25a illustrates the average density after each roller pass. As can be seen, the maximum density of 131.4 lb/ft^3 was resulted after six roller passes. Then, the nuclear gauge density values and ICMVs corresponding to pass 6 were correlated to each other to determine the target ICMV at the highest density. Figure 25b indicates the correlation between the ICMV and nuclear gauge density values. It should be noted that the IC roller lost the signal in some areas, therefore, there was no data to correlate with nuclear gauge densities. The correlation was built using 6 points out of 10. According to the correlation, the target ICMV is estimated to be 28. One should bear in mind that this target ICMV and optimum number of passes in only valid at the same frequency and amplitude. To validate target ICMV and number of passes, another 100 ft. section of the road was compacted using the same frequency, amplitude, and target ICMV and the density at 8 random points was measured using nuclear gauge (see Figure 26). Figure 27 indicates the correlation between the ICMVs and nuclear gauge density at this section of the road. As can be seen the R-squared value of the correlation value between the ICMVs and nuclear gauge measurements is 0.55. This implies that the regression model can explain more than 50% of variability in data, which is considered as a good correlation.

The next stage of field tests was designed to use IC roller feedback data as a QC tool. The road was compacted using the same amplitude, frequency, and target ICMVs determined during the first stage. After rolling without using the IC roller onboard display, the weaker spots were compacted to the satisfactory level. After identification of the weaker areas, 5 spots were selected to compare the nuclear gauge density measurements before and after secondary compaction using the IC roller feedback data. Figure 27 indicates the density value of the weaker spots before and after secondary compaction. According to the results, comparison between the nuclear gauge density values before and after secondary compaction indicates that IC roller feedback data were able to identify the weak spots at this section of the road. As can be seen, the density of all 5 points improved after secondary compaction using IC roller feedback data. According to the results, the average density improved remarkably from 125.5 lb/ft^3 to 128.4 lb/ft^3, which shows that IC roller can be utilized as a reliable QC tool.



(a) (b)

Figure 25. Determination of (a) maximum density and (b) target ICMV

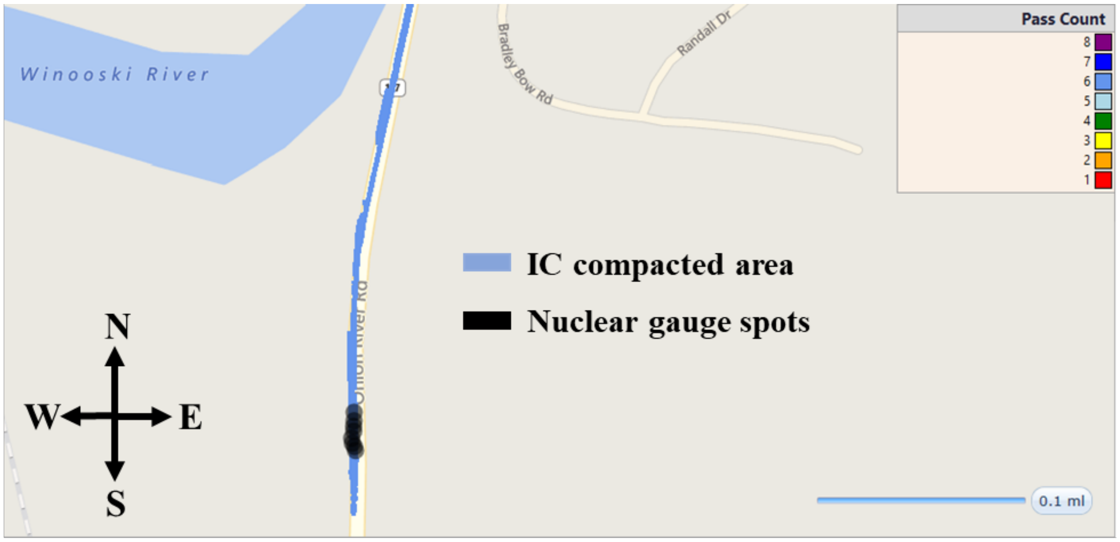


Figure 26. The location of 8 random spots

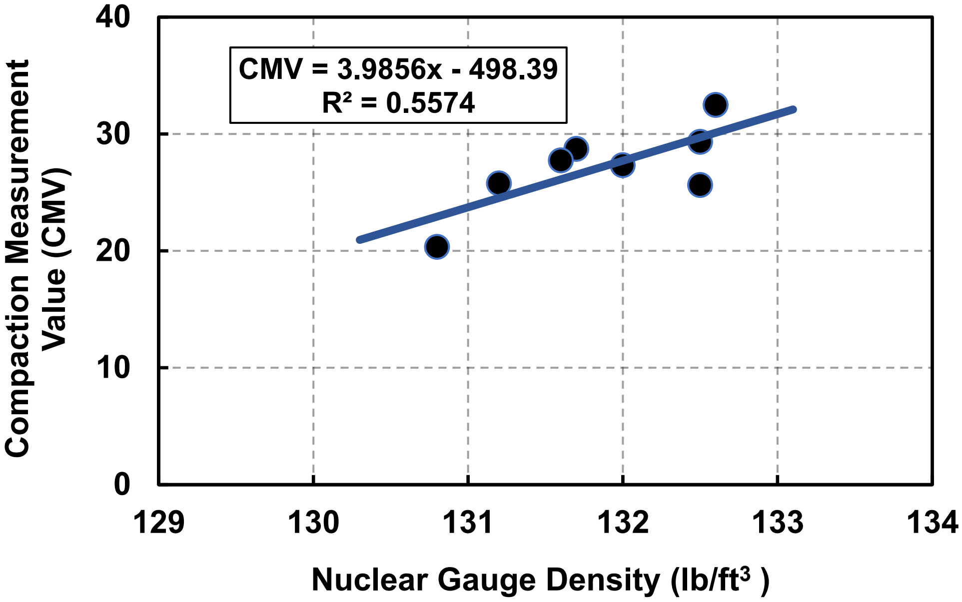


Figure 27. Correlation between nuclear gauge density and ICMVs

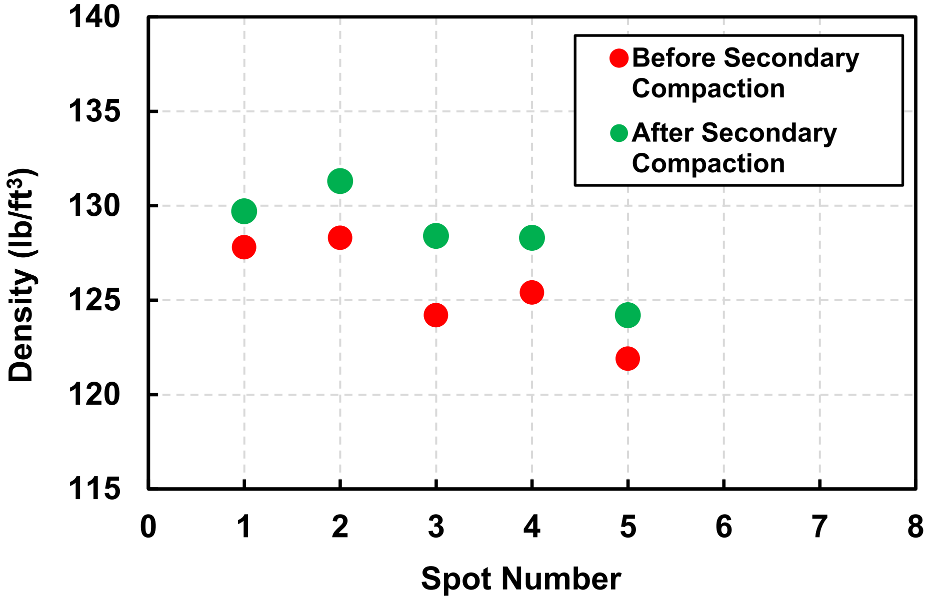


Figure 28. Comparison between the density values before and after using IC roller feedback data

3.3.3 Evaluation of the Consistency of IC Operation

3.3.3.1 Objectives

A series of field tests were designed and followed by data analysis to achieve the following objectives:

- Evaluate improved consistency of compaction using IC roller
- Evaluate reliability and consistency of the IC roller measurements

3.3.3.2 Methodology

ICMV data were collected form the asphalt layer to evaluate the spatial variability of the ICMV and IC performance. Semivariogram is a geo-statistical analysis tool which can be used to assess the spatial uniformity of the compacted area (Wang et al., 2018). The semivariogram model is defined as one-half of the average squared differences between data values that are separated at a distance h (Isaaks and Srivastava 1989):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(\mu_i + h) - Z(\mu_i)]^2$$

Where:

$\gamma =$ Experimental estimate of the underlying variogram function (semivariance)

$N(h) =$ The number of data pairs that are h unit far from each other

$Z(\mu_i) =$ Measured ICMV at the location of the μ_i

The semivariogram can be generated by plotting the semivariance values against the different distances, also called lag distance (Vennapusa et al., 2009). Nugget, Range, and Sill are three main parameters that determine the characteristics of the semivariogram plot (Isaaks and Srivastava 1989). Range is defined as the distance that the semivariogram reaches a plateau, where Sill can be defined as the plateau that the semivariance reaches at the Range. The larger Range value is an indication of greater degree of uniformity (i.e. less spatial variability), while the lower Sill value represents and improved spatial continuity. The semivariogram models were plotted based on the IC data and nuclear gauge density measurements. The semivariogram models were coded in RStudio and the plots were generated in Excel.

A 1000 ft section of the road was selected to investigate the spatial variability of the ICMVs during IC compaction operation. The semivariance data were binned at 20 ft intervals (lag distance =20 ft) to generate the semivariogram plot. A spherical model was fitted to the data to specify the semivariogram model parameters. Then to evaluate the improved consistency of compaction, the real-time monitoring capability of IC was used to compact a 50 ft. section of the road (IC-compaction), while the other 50 ft. section of the road was compacted without using the IC roller feedback system (non-IC-compaction).

During the previous field tests, the IC roller parameters (i.e. target ICMV and target number of passes) were calibrated for the desired road section. For the first part of the data collection process, the operator was asked to use the IC roller on-board display to compact the road to the desired target ICMV and number of passes (IC-Compacted), while for the second part the operator was asked to turn off the real-time monitoring display (non-IC-Compacted). A total of 18 nuclear gauge density (NGD) measurements were performed on the test section using a grid pattern (see Figure 29). Then the semivariogram models were generated to assess the spatial uniformity of the compacted area and create interpolation maps which show the variation of the density over the study area.

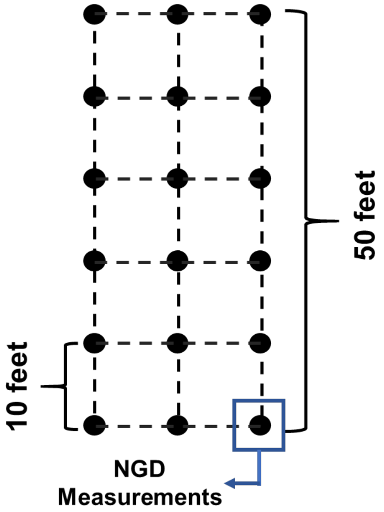


Figure 29. The measurement grid for NGD measurements

3.3.3.3 Results from Second Reclaim Phase

Figure 30 shows the semivariogram for representative ICMVs collected at a 1000 ft. section of the road. As evident from the semivariogram model, the range is approximately 800 ft. and the sill is approximately 2050. The results revealed that after the lag distance of 800 ft. the spatial autocorrelation tend to be zero. The consistency of ICMVs is important in assessing the consistency of compaction using IC rollers. The semivariograms developed for all collected ICMVs can serve as compaction consistency indicator and allows for desired modifications to the ICMVs. The range parameter suggests that up to the distance of 800 ft., the ICMVs of the points that are closer to each other are more autocorrelated than those that are farther from each other. The higher range values can be indication of higher degree of consistency. Although there is no standard value defined for the range parameter, a range equal to 800 ft. in a 1000 ft. portion of the road suggests a reasonable degree of uniformity. The relatively high sill value can be due to the fact that the geo-spatial analysis involves different sections of the road where the material might vary in a larger range due to variability of different material. Therefore, a geo-statistical analysis is required be performed on a smaller region of the road.

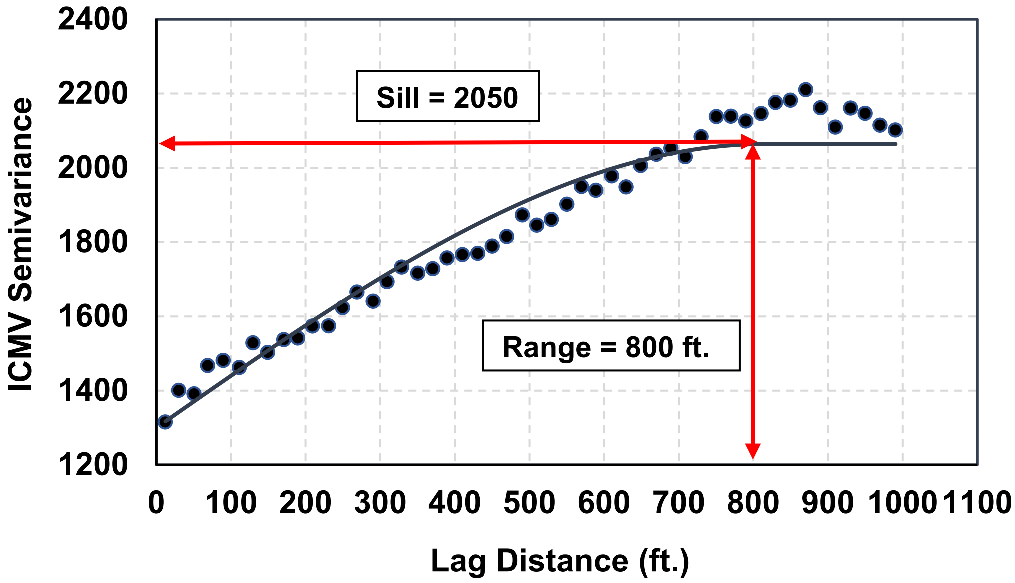
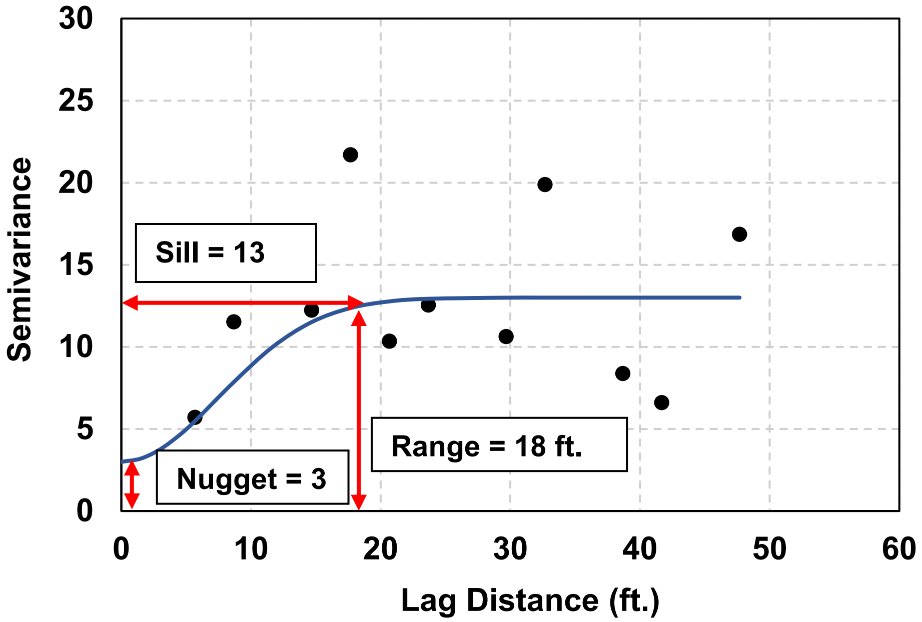
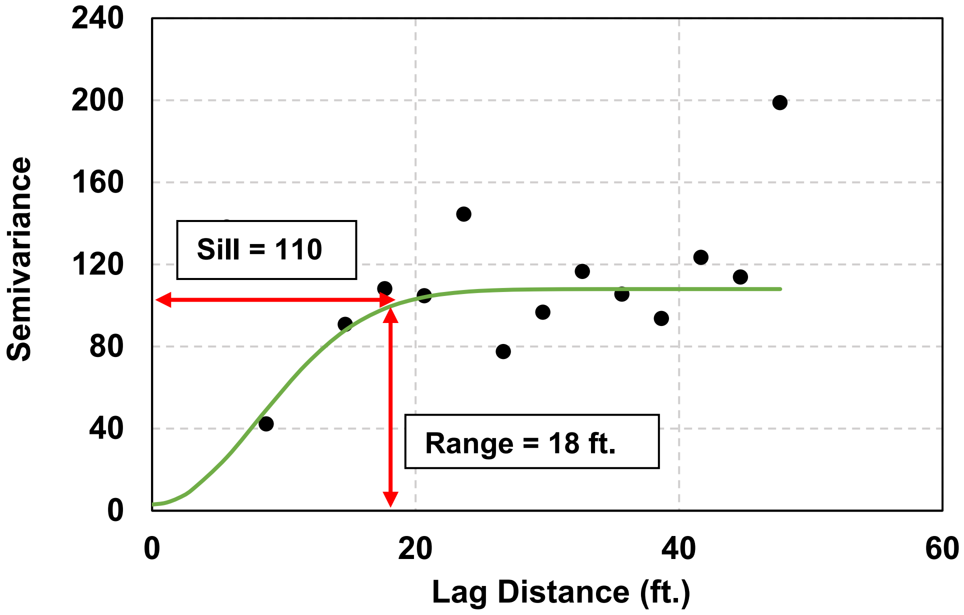


Figure 30. The semivariogram plot for ICMV data

Figures 31(a) and 31(b) show the semivariogram models generated for the IC-compacted and non-IC-compacted regions in the test section, respectively. The IC-compacted semivariogram has a range of 18 ft. and sill value of 13, while the non-IC-compacted area has a range value of 18 and a sill value of 110. The similar range value in non-IC-compacted semivariogram indicates that the distance that spatial autocorrelation vanishes is similar in both IC-Compacted and non-IC compacted cases. However, the significantly lower sill value in case of IC-Compacted semivariogram model revealed an improved uniformity compared to the non-IC-compacted case.



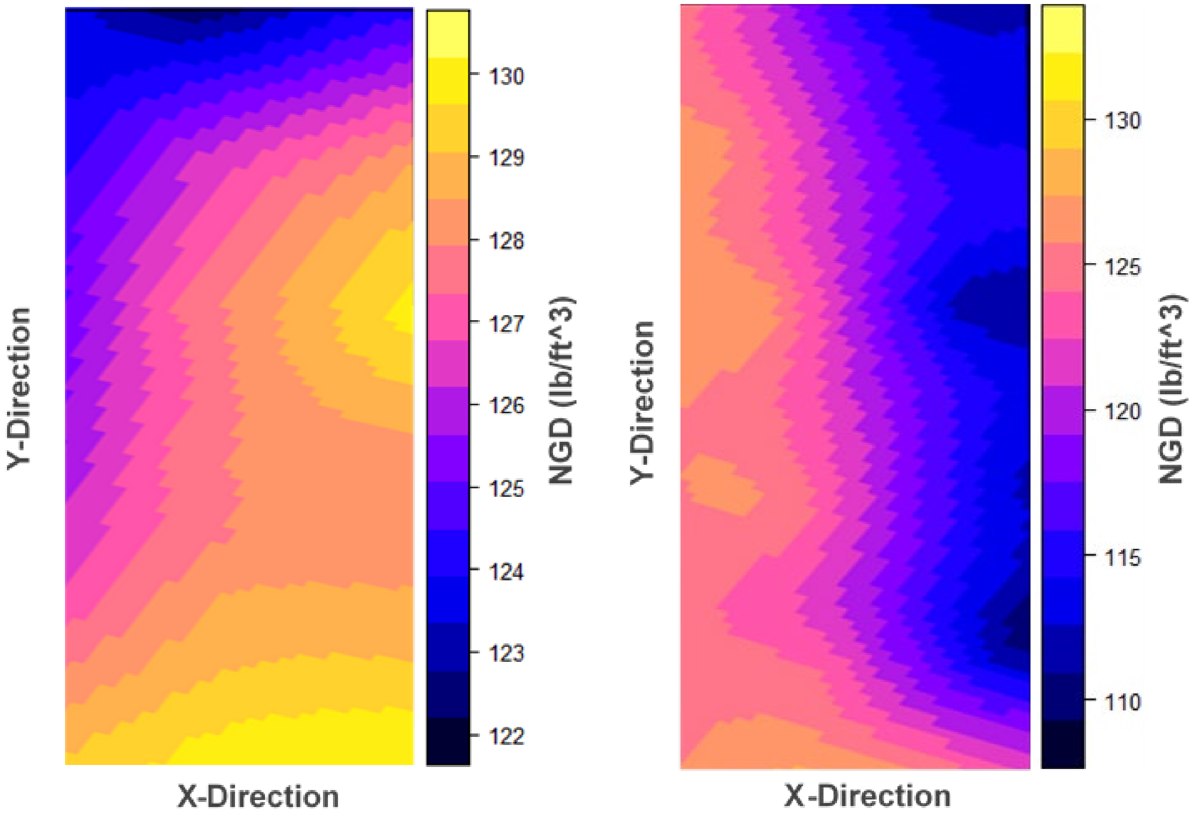
(a)



(b)

Figure 31. Semivariogram models for the (a) IC-Compacted region, and (b) non-IC-Compacted region

Figures 32(a) and 32(b) show the interpolation maps (i.e. variation of the density over the study area) for the IC-compacted and non-IC-compacted areas, respectively. As evident from both figures, the interpolated maps indicate a higher degree of uniformity for the IC-Compacted case compared to the non-IC-compacted case.



(a) (b)

Figure 32. Interpolation maps for the (a) IC-Compacted region, and (b) non-IC-Compacted region

3.3.3.4 Results From Asphalt Layer

In this section of the report, the spatial uniformity of the compacted asphalt layer was evaluated through a geo-statistical analysis of PQI densities (lb/ft^3) measured over a predefined grid. The test was designed to capture the potential discrepancies in the density of IC-compacted and non-IC-compacted on the asphalt layer. However, due to the data collection limitation, data analysis was limited to evaluation of the spatial uniformity of the compacted asphalt layer using the semivariogram model and creating kriging map of the density values over the studied area.

Figure 33 represent the semivariogram model of the PQI density (lb/ft^3). The nugget, sill, and range values are visually selected based on the semivariogram. As can be seen, the measured density values are auto-correlated at the distance of 32 ft. (i.e. range = 32 ft.). The sill and nugget values were selected to be 11 and 2 respectively. Compared to the second reclaimed layer, higher range and lower sill values were resulted from the semivariogram model. Therefore, it can be inferred that this section of asphalt layer is more uniformly compacted compared to the reclaimed layer. Figure 34 illustrates the interpolation map of the PQI density (lb/ft^3) over the studied area. As can be seen from the contour plot, the PQI density (lb/ft^3) values varies between 139 lb/ft^3 and 146 lb/ft^3, which is relatively a small range.

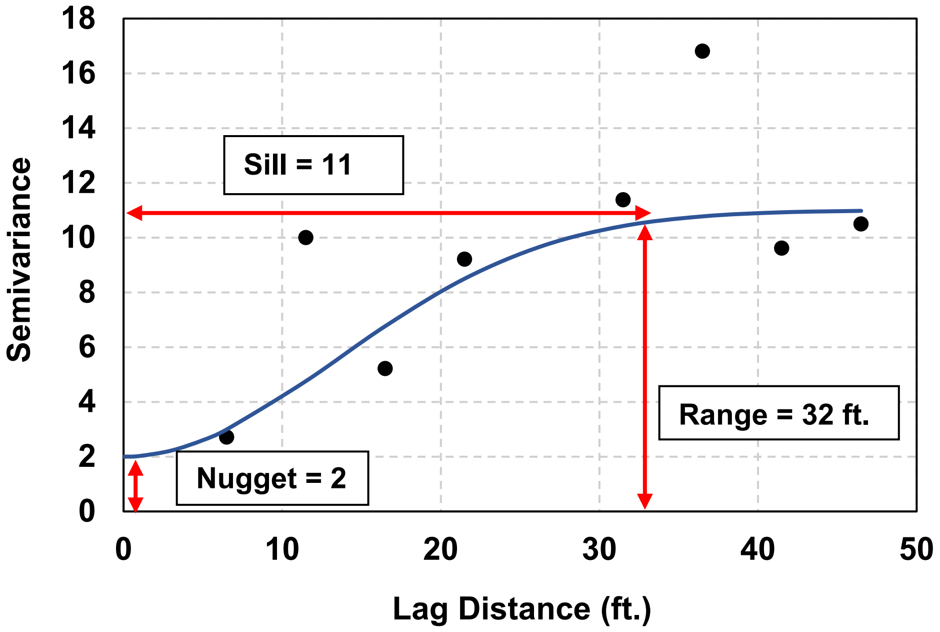


Figure 33. Semivariogram for PQI density (lb/ft^3) on asphalt layer

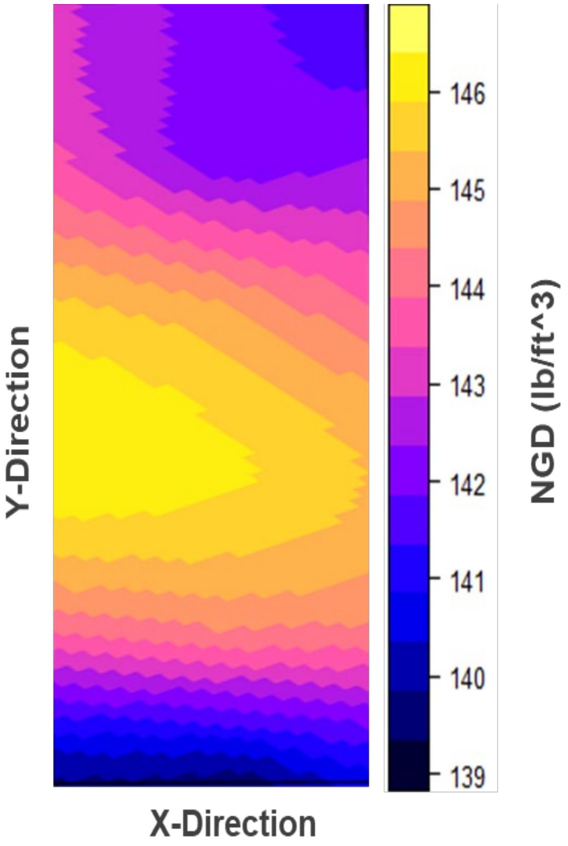


Figure 34. Interpolation map of PQI density (lb/ft^3) data over the studied area

3.3.4 Correlation Between In-situ and IC Measured Temperature

In the course of compacting the asphalt layer, IC roller records the temperature of HMA layer, which can be potentially used as a QC tool. In order to evaluate the reliability of temperature data measured in the course of compaction, the temperature data measured by IC roller sensors is plotted against the in-situ measured temperature to examine the correlation between these two values. Figure 35 indicates the linear regression model between the IC and in-situ measured temperature. According to the regression model, IC and in-situ measured temperatures are positively correlated and the R^2 value is 0.436. This indicates that 43.6% of the variation in temperature data can be explained by the regression model. It can be observed that the R^2 value is highly reduced by one outlier data point (207.5 °F, 233.5 °F), which shows that there is a potential for obtaining a better correlation. Therefore, since there is a meaningful correlation between IC measured temperatures and in-situ measured temperatures, it can be suggested that temperature measured by IC roller infrared thermometers can be potentially used as a reliable QC tool.

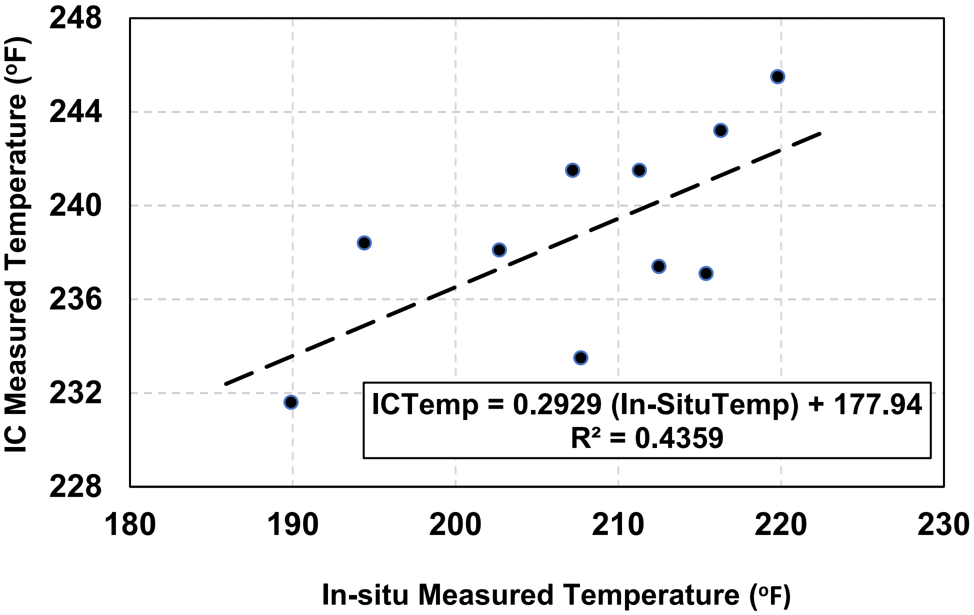


Figure 35. The correlation between the IC measured temperature & in-situ measured temperature

3.3.5 Correlation Between Density and IC Measured Temperature

In order to evaluate the impact of HMA temperature on the quality of the compacted asphalt layer, correlation between the IC measured temperature and in-situ density (lb/ft^3) measurements was investigated. According to the regression model (Figure 36), the in-situ density (lb/ft^3) values and the IC measured temperature are positively correlated with a regression value equal to 0.398 (i.e. $R^2 = 0.398$). This observation indicated that the points with higher temperature during HMA paving ended up with higher density after the compaction.

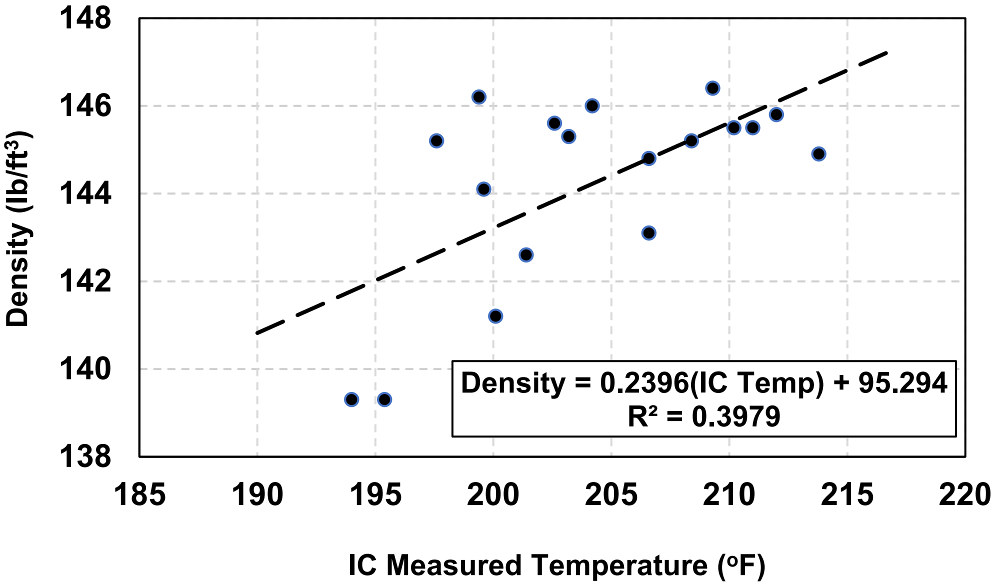


Figure 36. The correlation between the IC measured temperature & in-situ density

3.3.6 Performance Monitoring

Poor compaction of pavement materials usually leads to different types of distress, especially rutting. One of the main advantages of utilizing IC is to achieve consistency in compaction and avoid weak spots that lead to premature failure and limited life service of the pavement. To assess the improvements in the quality of compaction and subsequently the pavement performance due to IC implementation, visual survey on crack counting and rutting measurements at several locations across the test sections was conducted at three different times corresponding to different stages of construction/post-construction. The first stage of monitoring was before laying the final HMA layer (this layer experienced one winter season), second stage was two months after completion of the HMA layer, and the final was four months after completion of the HMA layer. As evident in Figure 37, no significant sign of failure/distress was observed.

(a)

(b)

(c)

Figure 37. Photos of the (a) first, (b) second, and (c) third stages of performance monitoring

CHAPTER 4- CONCLUSIONS

Base on the results from field tests and data analysis the following conclusion can be drawn:

- Statistical analysis of IC data from Bethel-Stockbridge project using R-studio and Veta 5.2 software provided a better insight into the data analysis process. Efficiency of the compaction process was investigated through evaluation of the compaction curve. In addition, since the RMVs directly affect the compaction quality and IC measurements, a statistical analysis of RMV data can determine the degree of reliability of the ICMV data. Moreover, this exercise (i.e. data analysis from previous IC project) highlighted the necessity of recoding the coordinates of in-situ spot measurements, since the spot measurements need to be correlated with corresponding ICMVs.
- The correlations between the roller ICMVs and in-situ measurements (DCPI and NGD) were found to be weak in general. Variation of material properties at different sections, not using constant amplitude and frequency at different sections, the difference in depth of IC roller measurements with NG/DCP measurements are thought to be the potential sources of the weak correlation.
- Target ICMV and number of passes resulted from the corresponding frequency and amplitude were identified based on the NG density. Calibration of the roller parameters and using consistent frequency and amplitude for each section improved the correlation between the NGD values and ICMVs.
- The consistency of the IC roller measurements was investigated through constructing the semivariogram models. The range and sill parameters were used to compare the consistency level and uniformity at different sections of the road. The IC compacted section of the road indicated a higher degree of uniformity and consistency in terms of density.
- Evaluation of the correlation between in-situ temperature data collected using the handheld infrared thermometer and temperature data from the IC roller indicated that IC measured temperature data can be potentially used to monitor the temperature variation in the course of laying the HMA layer.

- In order to evaluate the IC performance, the road was visually inspected for crack counting and rutting measurements at several locations, months following the completion of pavement construction. No indication of cracking or rutting was observed during the performance monitoring, which indicates the performance of IC operation was acceptable.

CHAPTER 5- RECOMMENDATIONS ON IC IMPLEMENTATION

Based on the results from field test and data analysis reports a set of recommendations are presented in this chapter of the report:

- In order to accurately correlate the in-situ spot measurements to ICMVs, it is crucial to record the coordinates of spot tests using a hand-held GPS "rover" with the same coordinate units that IC roller uses to record ICMVs.
- The roller parameters (i.e. target number of passes, target ICMV, frequency, and amplitude) should be calibrated at the beginning of compaction operation at different sections of the road. Each section should be chosen based on the homogeneity of the material. Calibration process should be repeated once the type or properties of the underlying material changes. Using constant roller frequency, amplitude, and speed is recommended through the entire section.
- Target ICMV can be determined by finding the ICMV corresponding to the break-over density. In order to achieve this, the density value obtained from the pass with optimum density value needs to be correlated to the roller ICMVs at the same pass number.
- Target number of roller passes can be used as a QC tool and requires minimum training for the roller operator. The operator can feed the roller with the target number of passes and assign a color to it. Then, the operator can use the on-board display to check the consistency of compaction with respect to target number of passes.
- Use of target ICMV as a QC tool is recommended if the regression model between the spot measurements and ICMVs reveals an acceptable R-squared

value (~ 0.6 or higher). Once the requirements are satisfied, 90% of the ICMVs must be at 90% of target ICMV.

- Using IC live feedback system improves the consistency and uniformity of the compaction. Semivariogram models can be used to check the consistency and uniformity of the IC. Higher range values and lower sill values are the indicative of higher consistency and uniformity.
- IC temperature data can be used as a QC tool in the course of laying the HMA layer. The inconsistency of HMA temperature can potentially result in a non-uniform compaction.
- Although during short-term pavement performance monitoring no significant sign of failure/distress was observed, longer-term pavement performance monitoring is necessary to compare IC performance relative to conventionally compacted sections of the road and gain more confidence on IC performance.
- Implementing IC on projects with significant levels of non-homogeneity in terms of material properties, requires a lot of IC roller parameters' calibration. Therefore, IC implementation in these types of projects could be inefficient and is not recommended.
- Implementation of IC on new roadway reconstruction projects is highly recommend as IC can increase consistency and uniformity of compaction. It should be noted that the roller operators, engineers, and technician involved in the project must be familiar with IC technology.
- It is recommended that the Agency suggests that contractors train their roller operators and technicians. In addition, the Agency will benefit from crafting the codes and standards for IC implementation through independent research project, where the restrictions and limitations concerning the construction project as well as contractor's schedule do not adversely impact the data collection process and other research activities. Agency personnel can also benefit from the training, in case the agency provides certifications.
- Agency specifications need to be revised to include 95% communications coverage through project limits (with repeaters, tower, etc.) and it needs to be

specified with each project, especially in the areas with considerable canopy/poor cellular coverage.

TECHNOLOGY TRANSFER PLAN

The findings of this study were disseminated in different venues to be incorporated into the work-plan for local contractors for implementation of IC technology in Vermont projects. This includes: two factsheets and two poster presentation at VTrans research symposiums in 2018 and 2019, a conference paper at ASCE GeoCongress 2020, and another manuscript submitted to ICTG 2020 conference (under review). In addition, the authors are planning to submit a manuscript to the journal of Automation in Construction.

REFERENCES

Adam, D. (1997). Continuous compaction control (CCC) with vibratory rollers. In *Proceedings of GeoEnvironment* (Vol. 97, pp. 245-250).

Adam, D., & Kopf, F. (2004). *Operational devices for compaction optimization and quality control (continuous compaction control & light falling weight device)*. N/A

Barman, M., Nazari, M., Imran, S. A., Commuri, S., Zaman, M., Beainy, F., & Singh, D. (2016). Quality control of subgrade soil using intelligent compaction. *Innovative Infrastructure Solutions*, *1*(1), 23.

Brau, G., Hartman, K., Pelz, G. (2004). “CCC Testing of Compaction—Implementation in Construction Practice and Procedure-Related Compaction Specifications).” Technischen Universitat München, Heft 897, München.

Chang, G. K., Xu, Q., Rutledge, J. L., & Garber, S. I. (2014). *A Study on Intelligent Compacting and In-Place Asphalt Density* (No. FHWA-HIF-14-017). United States. Federal Highway Administration. Office of Pavement Technology.

Correia, A. G., Winter, M. G., & Puppala, A. J. (2016). A review of sustainable approaches in transport infrastructure geotechnics. *Transportation Geotechnics*, *7*, 21-28.

Fathi, A., Tirado, C., Gholamy, A., Lemus, L., Mazari, M., & Nazarian, S. (2018). Consideration of depth of influence in implementation of intelligent compaction in earthwork quality management (No. 18-02100).

Hu, W., Shu, X., Jia, X., & Huang, B. (2018). Geostatistical analysis of intelligent compaction measurements for asphalt pavement compaction. *Automation in Construction*, *89*, 162-169.

Hu, W., Shu, X., Jia, X., & Huang, B. (2017). Recommendations on Intelligent Compaction Parameters for Asphalt Resurfacing Quality Evaluation. *Journal of Construction Engineering and Management*, *143*(9), 04017065.

Hu, W., Huang, B., Shu, X., & Woods, M. (2017). Utilising intelligent compaction meter values to evaluate construction quality of asphalt pavement layers. *Road Materials and Pavement Design*, *18*(4), 980-991.

Isaaks, E. H., & Srivastava, R. M. (1989). An introduction to applied geostatistics. Oxford Univ. Press, New York. *An introduction to applied geostatistics. Oxford Univ. Press, New York.*

Kumar, S. A., Aldouri, R., Nazarian, S., & Si, J. (2016). Accelerated assessment of quality of compacted geomaterials with intelligent compaction technology. *Construction and Building Materials*, *113*, 824-834.

Krober, W., Floss, R., Wallrath, W. (2001). Dynamic Soil Stiffness as Quality Criterion for Soil Compaction. *Geotechnics for Roads, Rail Tracks and Earth Structure.*

Wang, J., Lu, X., Feng, Y., & Yang, R. (2018). Integrating multi-fractal theory and geo-statistics method to characterize the spatial variability of particle size distribution of minesoils. *Geoderma*, *317*, 39-46.

Arasteh, M., & Nieves, A. (2013). *Intelligent Compaction: Executive Summary* (No. FHWA-HIF-13-051). United States. Federal Highway Administration.

Kamali-Asl, A., Ghazanfari, E., & Dewoolkar, M. M. (2016). Suitability of intelligent compaction for relatively smaller-scale projects in Vermont.

Mazari, M., Beltran, J., Aldouri, R., & Nazarian, S. (2017). "Variability of Intelligent Compaction Data on Embankment and Subgrade Geomaterials." *In Geotechnical Frontiers 2017* (pp. 75-83).

Mooney, M.A., Gorman, P.B., Gonzalez, N.J. (2005). "Vibration Based Health Monitoring During Earthwork Construction." Journal of Structural Health Monitoring, Vol. 2, No. 4, pp. 137–152.

Mooney, M.A., Rinehart, R.V. (2009). "In Situ Soil Response to Vibratory Loading and Its Relationship to Roller-Measured Soil Stiffness." Journal of Geotechnical and Geoenvironmental Engineering, Vol. 135, No. 8, pp. 1022-1031.

Mooney, M., Rinehart, R.V., White, D., Vennapusa, P., Facas, N., Musimbi, O. (2010). "Intelligent Soil Compaction Systems," National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C.

Montoya, M., Pouranian, M. R., & Haddock, J. (2018). Increasing Asphalt Pavement Density Through Mixture Design: A Field Project. In *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions*.

Savan, M., Ng, K.W., Ksaibati, K. (2015). "Implementation of Intelligent Compaction Technologies for Road Construction in Wyoming," MPC15-281, Wyoming Department of Transportation, Laramie, Wyoming.

Thurner, H., & Sandstrom, A. (2000, May). Continuous compaction control, CCC. In *European Workshop Compaction of Soils and Granular Materials, Presses Ponts et Chaussées, Paris, France* (pp. 237-246).

Vennapusa, P. K., White, D. J., & Morris, M. D. (2009). Geostatistical analysis for spatially referenced roller-integrated compaction measurements. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(6), 813-822.

White, D., Thompson, M. (2008). "Relationships Between in Situ and Roller-Integrated Compaction Measurements for Granular Soils." ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134, No. 12, pp. 1763–1770.

White, D., Thompson, M., Vennapusa, P. (2008). Field Validation of Intelligent Compaction Monitoring Technology for Unbound Material. Minnesota Department of Transportation, St. Paul, pp. 123–164.

White, D. J., Vennapusa, P. K., & Gieselman, H. H. (2011). Field assessment and specification review for roller-integrated compaction monitoring technologies. *Advances in Civil Engineering*, *2011*.

White, D. J., Vennapusa, P., Tutumluer, E., & Moaveni, M. (2019, March). Mechanistic Assessment of Layered Pavement Foundation System Using Validated Intelligent Compaction Measurements. In *Eighth International Conference on Case Histories in Geotechnical Engineering (Geo-Congress 2019) American Society of Civil Engineers*.

Zhong, D., Li, X., Cui, B., Wu, B., & Liu, Y. (2018). Technology and application of real-time compaction quality monitoring for earth-rockfill dam construction in deep narrow valley. *Automation in Construction*, *90*, 23-38.