Enhancing Performance of Intelligent Compaction

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16 Abstract

A key step toward ensuring the desired long-term performance of pavements in roadways is effective compaction. The limitations of conventional compaction techniques and current density-based acceptance practice in highway construction have led to non-uniform and unsatisfactory compaction of the pavement materials. Intelligent Compaction (IC) technology has the potential to significantly improve the consistency and uniformity of compaction. However, despite recent advancements in IC technology, several challenges remain to be addressed to enhance IC performance. This project attempted to explore the possibility of utilizing compaction measurement values (CMVs) as a function of vibration amplitude and frequency in the control system with the goal of optimizing the compaction process. In addition, it was attempted to identify potential wireless sensing systems and possible integration with IC roller for field applications. The analysis of data from an IC project indicated that linear models can reasonably express the CMVs as a function of vibration amplitude and frequency at different sections of the road. However, the variability of CMVs caused by factors both from the roller and the pavement side makes it difficult to obtain strong correlations between CMVs, vibration amplitude and frequency. In terms of enhancing performance of IC using wireless sensing, considering the complexity of sensing in subsurface, passive wireless sensing appears to be a better choice among existing wireless sensing systems. Proper pressure sensor ruggedization/packaging is critical, particularly for the sensors embedded right below the surface of the pavement.

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Abstract

A key step toward ensuring the desired long-term performance of pavements in roadways is effective compaction. The limitations of conventional compaction techniques and current density-based acceptance practice in highway construction have led to non-uniform and unsatisfactory compaction of the pavement materials. Intelligent Compaction (IC) technology has the potential to significantly improve the consistency and uniformity of compaction. However, despite recent advancements in IC technology, several challenges remain to be addressed to enhance IC performance. This project attempted to explore the possibility of utilizing compaction measurement values (CMVs) as a function of vibration amplitude and frequency in the control system with the goal of optimizing the compaction process. In addition, it was attempted to identify potential wireless sensing systems and possible integration with IC roller for field applications.

The analysis of data from an IC project indicated that linear models can reasonably express the CMVs as a function of vibration amplitude and frequency at different sections of the road. However, the variability of CMVs caused by factors both from the roller side and the pavement side makes it difficult to obtain strong correlations between CMVs, vibration amplitude and frequency. In terms of enhancing performance of IC using wireless sensing, considering the complexity of sensing in subsurface, passive wireless sensing appears to be a better choice among existing wireless sensing systems. Proper pressure sensor ruggedization/packaging is critical, particularly for the sensors embedded right below the surface of the pavement. Installing the data acquisition system and two antennas in the front and rear sides of the IC roller can potentially facilitate integration of the passive sensing system with the IC technology.

Chapter 1: Introduction and Background

1.1 Project Motivation

A key step toward ensuring the desired long-term performance of pavements (sub-base, base, and pavement layer) is effective compaction. It is well known that slight reduction in air voids during pavement compaction can lead to few years of extended life service of the pavement. A major contributor to the premature pavement failure is known to be the poor compaction (Mooney et al., 2010; Chang et al., 2014; Nieves, 2017). The limitations of conventional compaction techniques and current density-based acceptance practice in highway construction have led to non-uniform and unsatisfactory compaction of the pavement materials (Nieves, 2017). Lower productivity and higher maintenance costs are other issues associated with conventional compaction techniques (Nieves, 2017). In addition, the existing quality-control (QC) and quality-assurance (QA) testing devices are usually employed to evaluate a small portion of the compacted area (i.e. ~ 1%), providing only spot checks, rather than wide measure of uniformity and consistency of the compacted area. More importantly, a transition from the current density-based acceptance practice to stiffness-based inspection practice is highly desired from QA-QC perspective (Mooney et al., 2010; Chang et al., 2014).

Intelligent Compaction (IC) technology has the potential to significantly improve the consistency and uniformity of compaction, extend the pavement life service, and reduce the maintenance costs (Kamali-Asl et al., 2016). IC (Fig. 1) uses rollers equipped with accelerometers, highly accurate GPS, onboard computer, and infrared thermometers. IC has the potential to overcome several problems encountered in conventional compaction techniques. Using IC instead of conventional compaction techniques can (i) increase the compaction uniformity; (ii) provide a global stiffness-based inspection practice; (iii) facilitate the real-time monitoring and identification of weak areas that need re-compaction; (iv) optimize the construction time and productivity; (v) provide IC base map that allow maintaining construction records; and (vi) lead to potential savings in maintenance costs and extended service life of the pavement (Mooney et al., 2010; Nieves, 2017, Tirado et al., 2019).

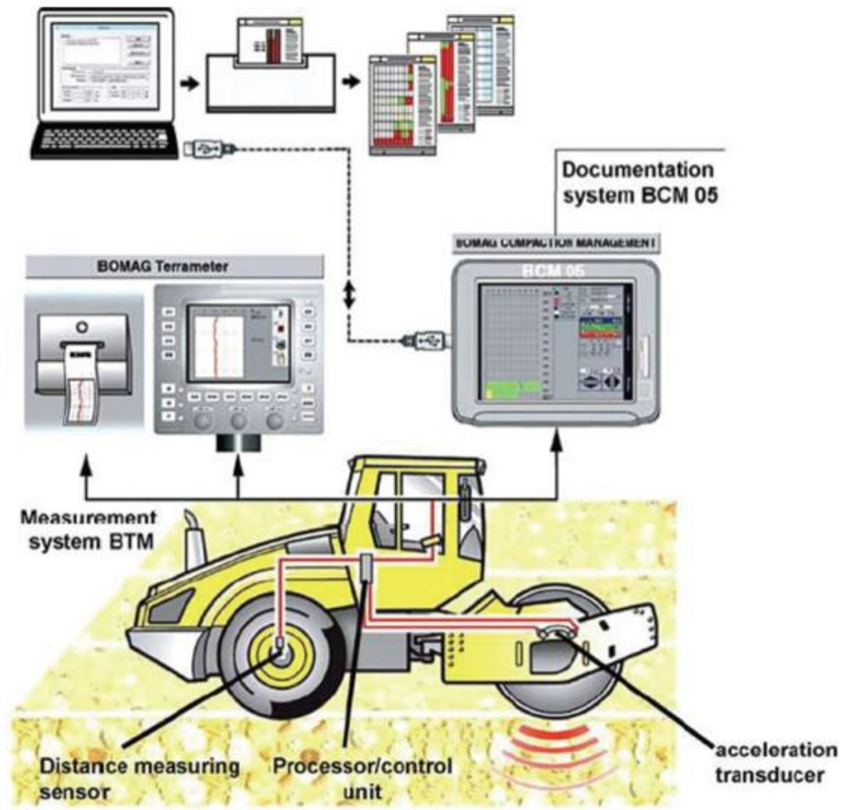


Figure 1. Schematic of IC components (Source: BOMAG)

The calculated values based on accelerometer measurements are referred to as compaction measurement values (CMVs), which are correlated with the material properties (e.g. stiffness and density). The reaction force from the compacted material is captured by accelerometers, processed by the control system using different models/methods, and computed as CMVs. To use IC as an acceptance tool, it is necessary to establish correlations between stiffness-based CMVs and in-place density and stiffness obtained from spot-test measurements.

Some of the important factors that affect CMVs include soil type and moisture content, thickness of layer, sub-base support condition, mixture proportion and temperature for asphalt, operating parameters such as slope of the grade, speed, and vibration amplitude and frequency (Nieves, 2017). In general, for density and modulus, more consistency in correlations between CMVs and spot test measurements are reported (e.g. Savan et al., 2015) for compacted soil than compacted asphalt. Another key component of IC technology is the feedback control system, which facilitates optimal compaction performance, by continuous adjustment of the vibration amplitudes and frequencies (e.g. Nieves, 2017). However, significant variations in vibration amplitude and frequency creates uncertainty in CMV measurements and subsequently reduces the effectiveness of feedback control system.

Despite recent advancements in IC technology, several challenges remain to be addressed. Particularly, the correlations between the CMVs and vibration amplitude and frequency involve uncertainty and need further improvement. In addition, monitoring of pavement compaction/performance during construction/operation is critical to the extended service life of these infrastructures. To address some of the limitations associated with IC, this project attempted to explore the possibility of utilizing CMVs as a function of vibration amplitude and frequency in the control system with the goal of optimizing the compaction process. In addition, it was attempted to identify potential wireless sensing systems and possibility of integration of the sensing system with IC roller for field applications.

1.2 Research, Objectives

Enhancement of IC performance by using (i) wireless sensing system, and (ii) CMVs as a function of vibration amplitude and frequency in the control system can facilitate real-time monitoring, identification of weak areas, and making informed decisions on proper course of action during compaction. Improved IC performance can potentially lead to improved durability of highway/roadway infrastructure.

The objectives of this project were to:

(i) Explore the use of CMVs as a function of vibration amplitude and frequency in the control system; and

(ii) Explore effective wireless sensing systems and integration potential with IC technology.

1.3 Report Overview

Chapter 2 provides research methodology. The results and discussion on IC data analysis, wireless sensing systems and potential integration option with IC technology are provided in chapter 3. Chapter 4 provides conclusions and recommendations on potential approaches to enhance performance of IC technology in the field. References are provided at the end of the report.

Chapter 2: Methodology

2.1 Literature Review

A literature review with the focus on existing problems associated with IC technology and potential approaches to improve the outcome of IC was performed. In addition, different wireless sensing systems that are implemented in subsurface conditions with the focus on application along with IC technology to enhance its performance were reviewed.

2.1 IC Data Analysis

IC Data provided by the Vermont Agency of Transportation (VTrans) were used to investigate possibility of utilizing CMVs as a function of vibration amplitude and frequency in the control system, with the goal of optimizing the compaction process. Distributions of the vibration amplitude, vibration frequency and CMVs in the entire project, small sections of the road, as well as randomly selected subsections of the road were investigated. Different models were considered to develop correlations between the CMVs and vibration amplitude and frequency. The data analysis was performed using MATLAB.

2.2 Sensor System

Different sensing systems, including active and passive systems, and their potential for implementation along IC technology were reviewed. To gain a better insight on the faced challenges during pressure sensing/measurements using embedded sensors, limited small-scale controlled laboratory experiments were conducted. Effects of embedment depth, pressure magnitude, and different material (i.e. base/sub-base) were investigated.

Chapter 3: Results and Discussion

3.1 IC Data Analysis

Roller's vibration amplitude (mm) and frequency (vibration per meter: vpm) significantly affect the CMVs (e.g. Kamali-Asl et al., 2016; Nieves et al., 2017; Foroutan et al., 2020). The feedback control system automatically optimizes the amplitude (mm) and frequency (vpm) of the roller. To gain a better understanding of the variations of CMV with vibration amplitude and frequency, IC data from Bethel-Stockbridge project **(**Route-107 VT, shown in Figure 2), provided by Vermont Agency of Transportation, were analyzed. The Bethel- Stockbridge project was aiming at compacting the natural sub-grade to the desired level using a single drum vibratory roller, Caterpillar CS54B.

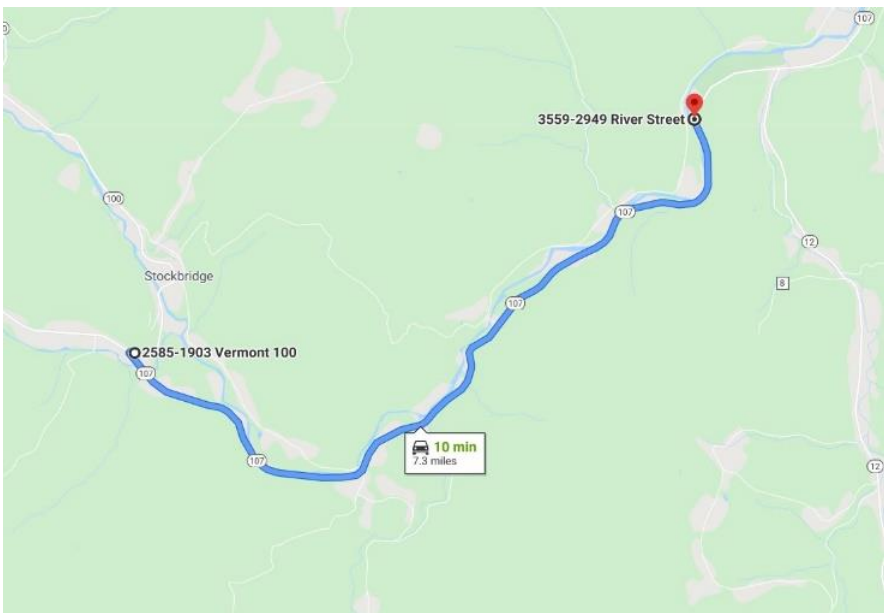


Figure 2. Location of the road section for IC data analysis

3.1.1 Distribution of vibration amplitude, vibration frequency, and CMV

Figures 3, 4, and 5 illustrate the histograms of vibration amplitude, vibration frequency, and CMVs for passes 1 to 4, respectively. There exists a small range of variation in the vibration amplitude and frequency data. As expected, with increase in the number of roller's passes, the vibration amplitude and frequency decreases from pass 1 to 4. CMVs distribution for the entire road section appears to be close to normal condition. Since the dynamic response of the roller affects CMVs, analyzing CMVs can help optimize the compaction process.

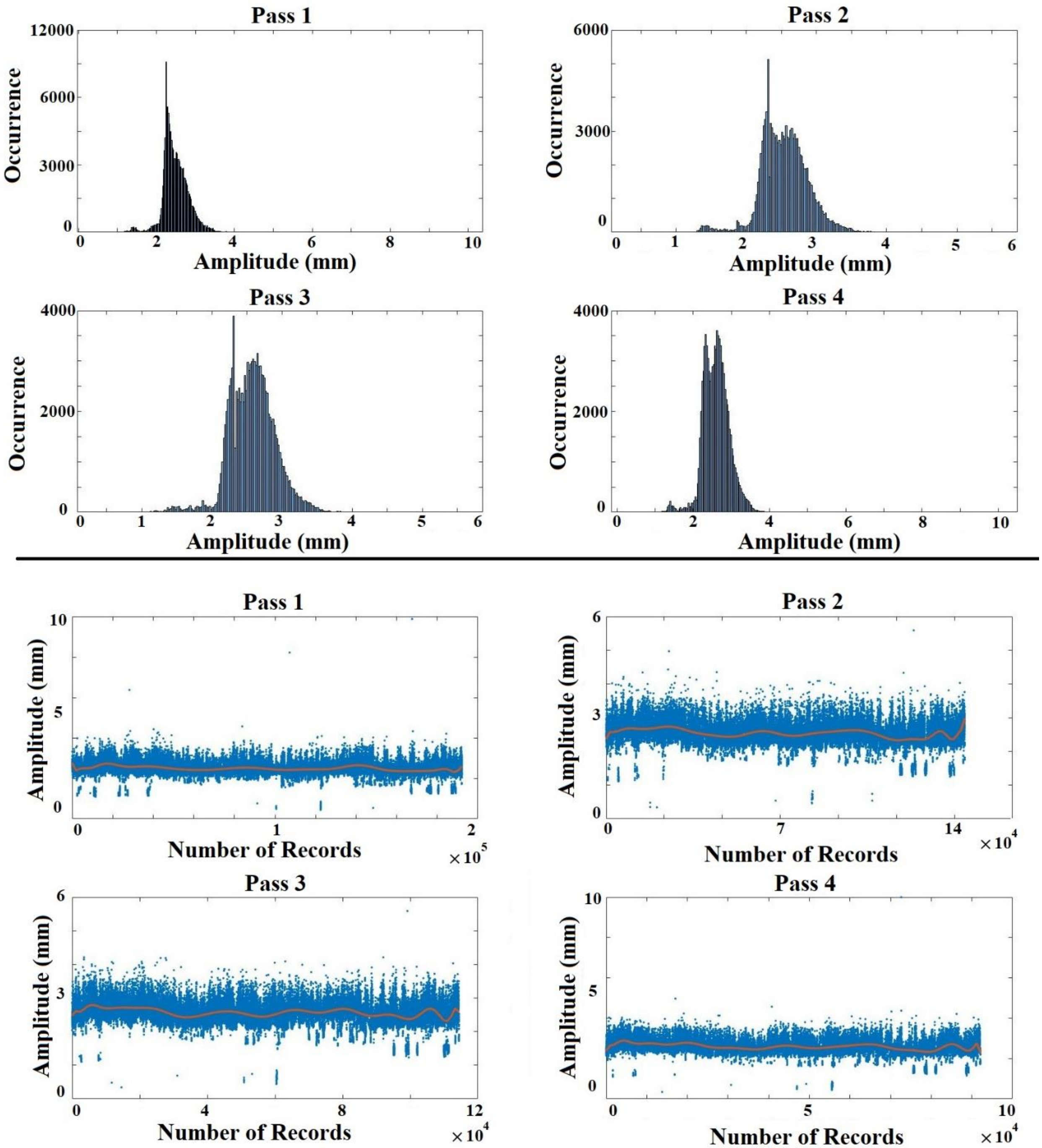


Figure 3. Histograms of vibration amplitude for passes 1 to 4

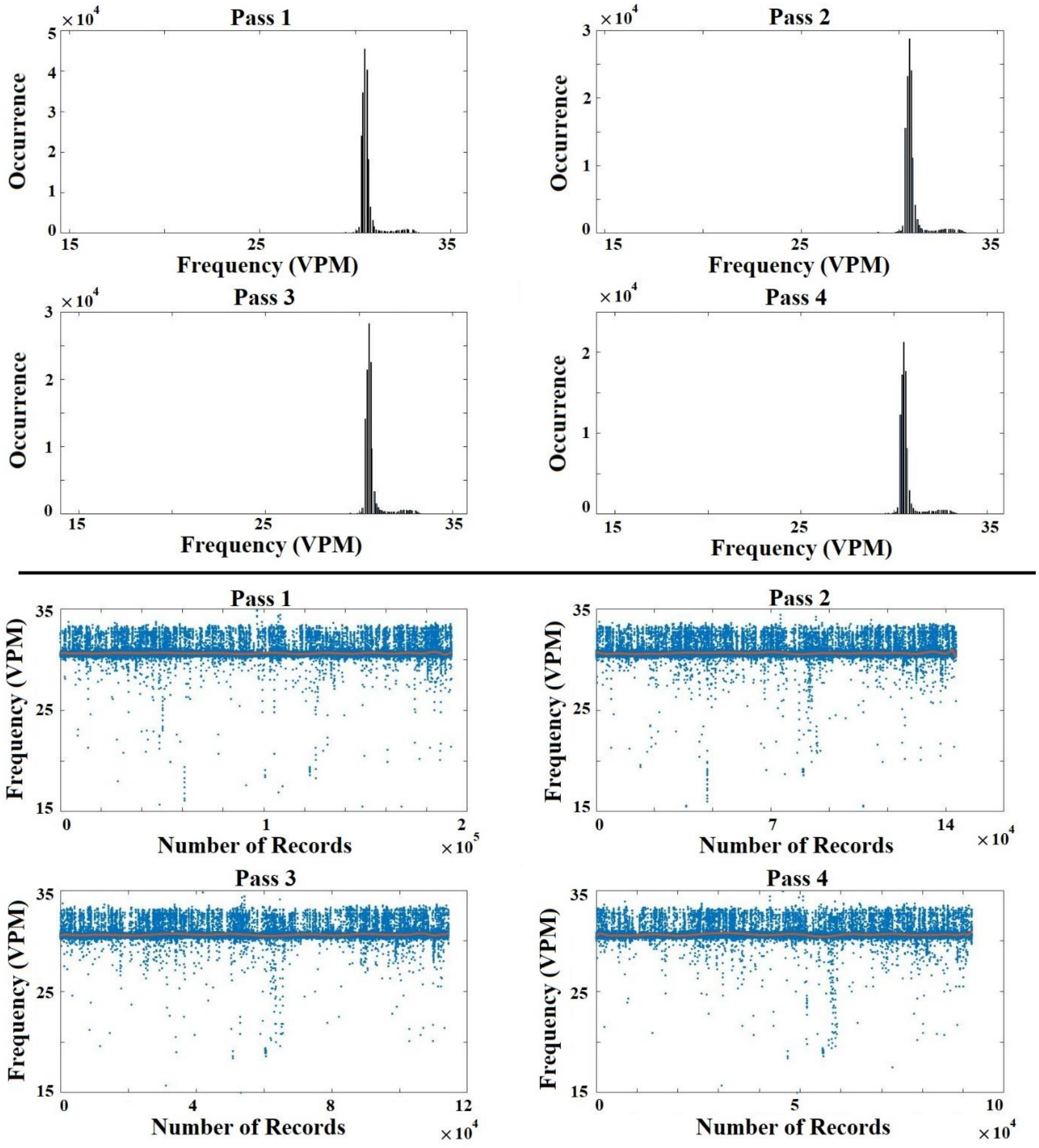


Figure 4. Histograms of vibration frequency for passes 1 to 4

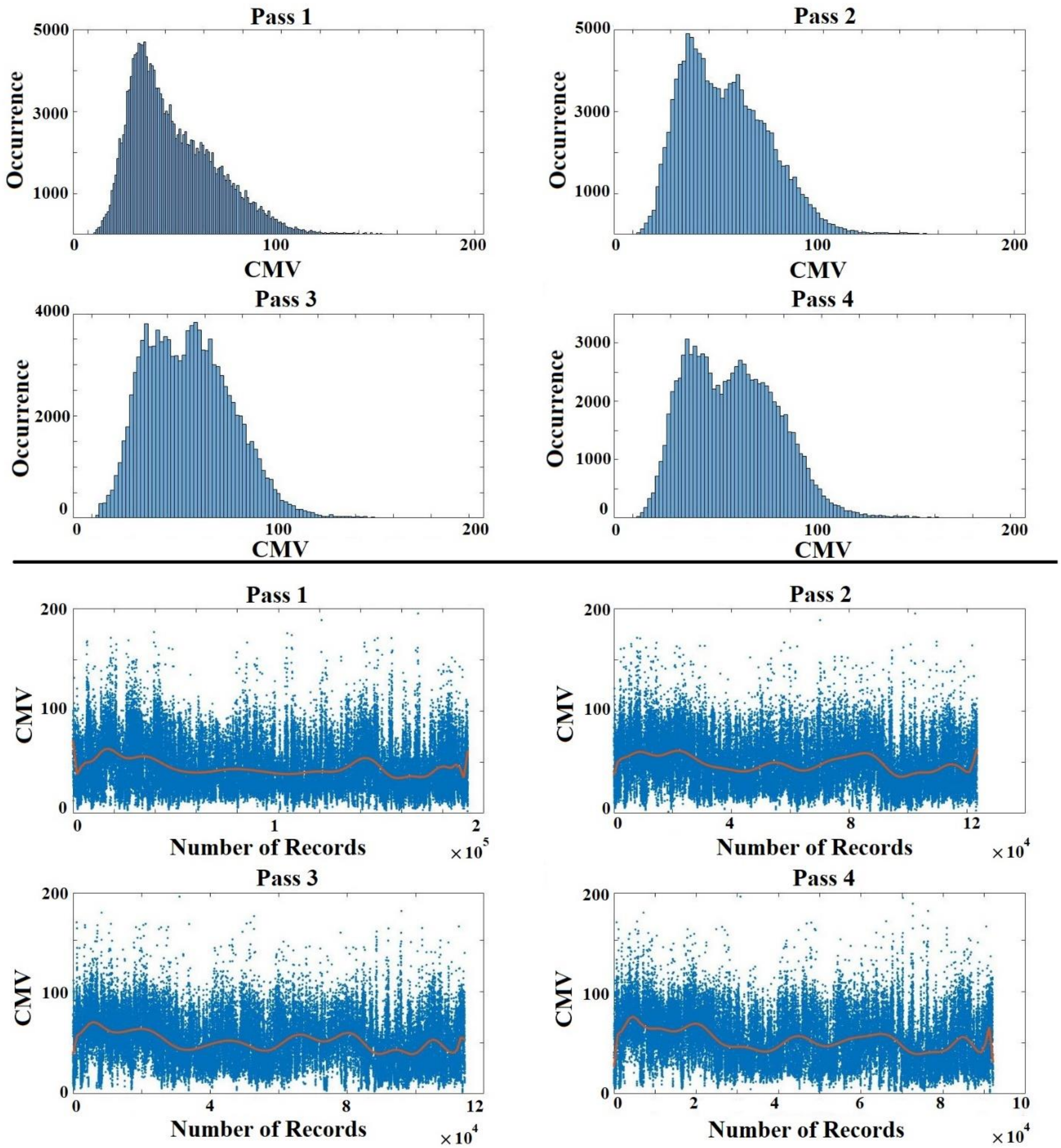


Figure 5. Histograms of CMVs for passes 1 to 4

3.1.2 Correlations between vibration amplitude, frequency, and CMV in the first section of the road

A subsection of the Bethel-Stockbridge Road with approximate length of 0.2 miles was selected for further analysis. Figures 6, 7, and 8 illustrate the histograms of vibration amplitude, vibration frequency, and CMVs with their corresponding color-coded variation along the selected road section for all passes, respectively.

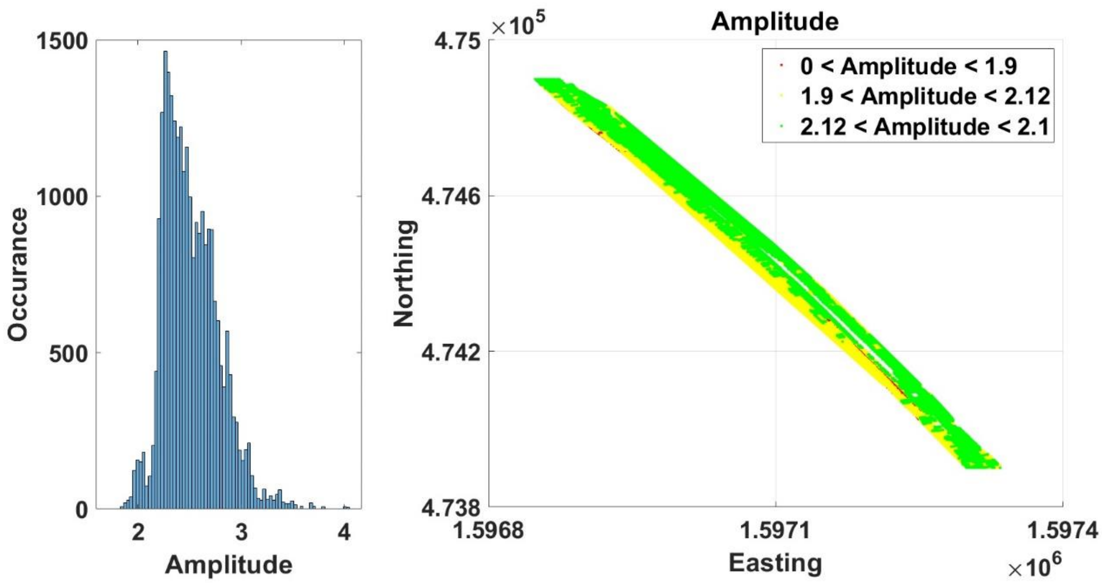


Figure 6. Amplitude histogram and interpolated data

As it can be seen in Figures 6 and 7, significant variation in vibration amplitude values exist, while vibration frequency data seems to have small variation. As evident from Figure 8, CMVs close to the boundary of the road deviate from the target CMV, whereas the CMVs at the middle section of the road are for largely close to the target CMV. In general, more consistent CMVs can point to improved consistency of the compaction with increased number of passes. Figure 9 illustrates the change in CMVs for passes 1 to 3. As evident and expected, as the number of passes increase, the consistency of CMVs increases indicating improved consistency of compaction.

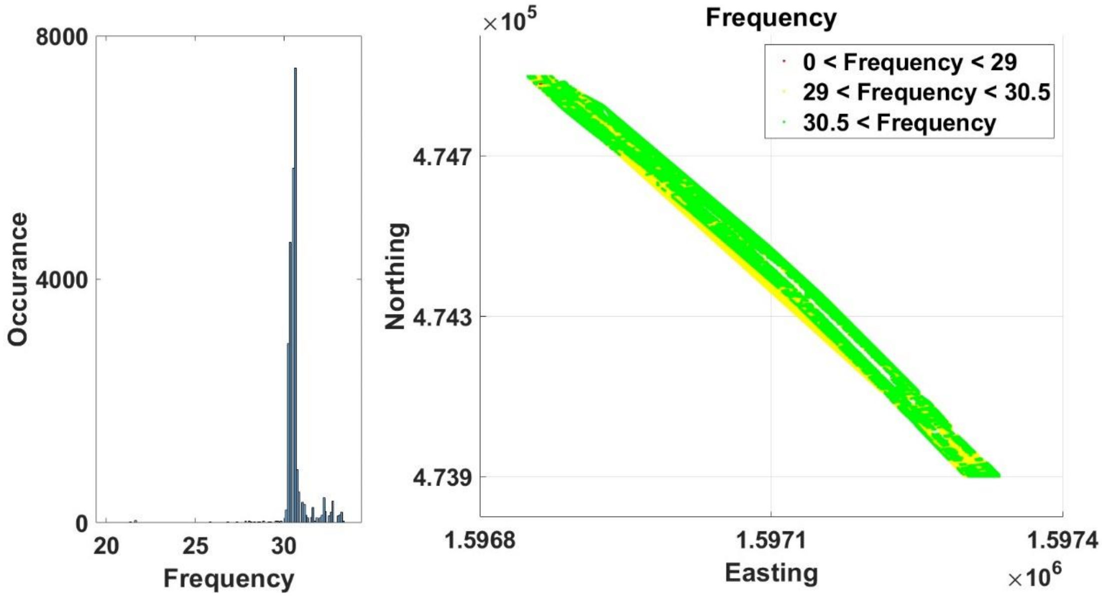


Figure 7. Frequency histogram and interpolated data

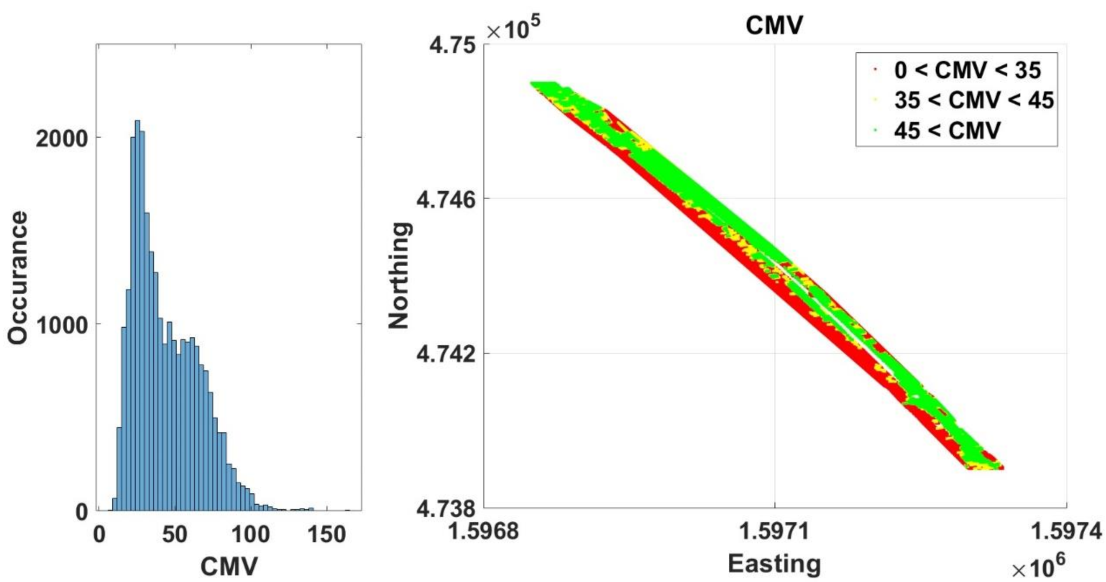


Figure 8. CMV histogram and interpolated data

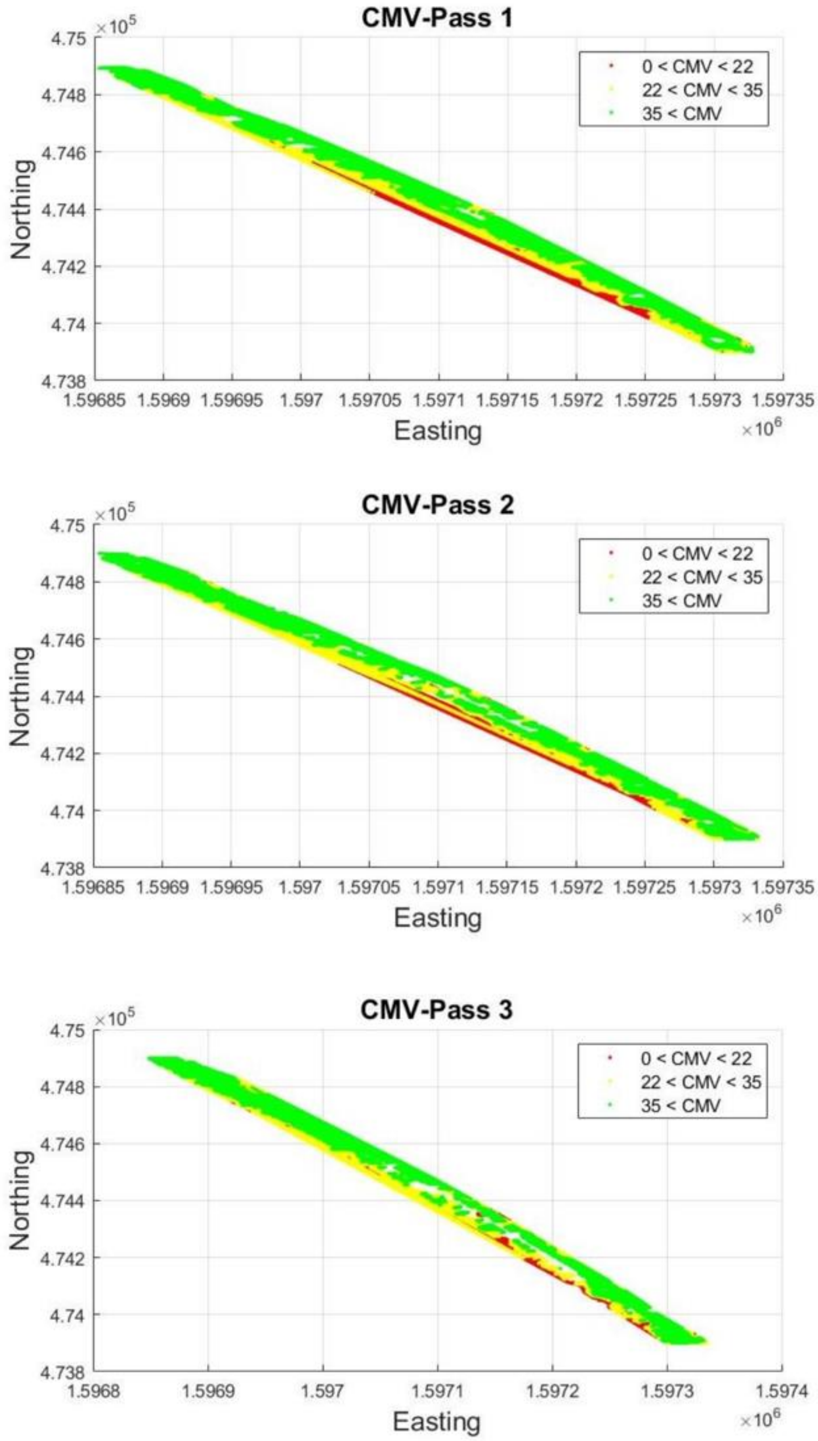


Figure 9. Comparison between CMV of the first three passes

Figures 10 and 11 illustrate the correlations (linear and cubic models) between CMVs with vibration amplitude and frequency, respectively.

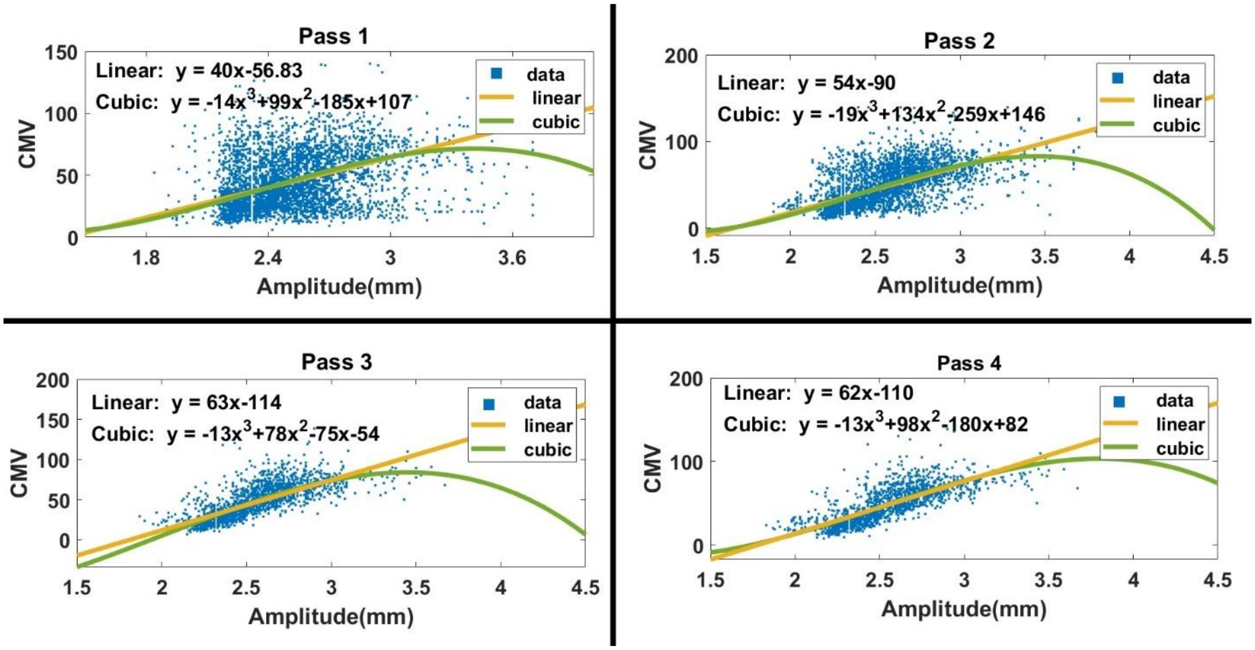


Figure 10. Correlations between CMV and vibration Amplitude

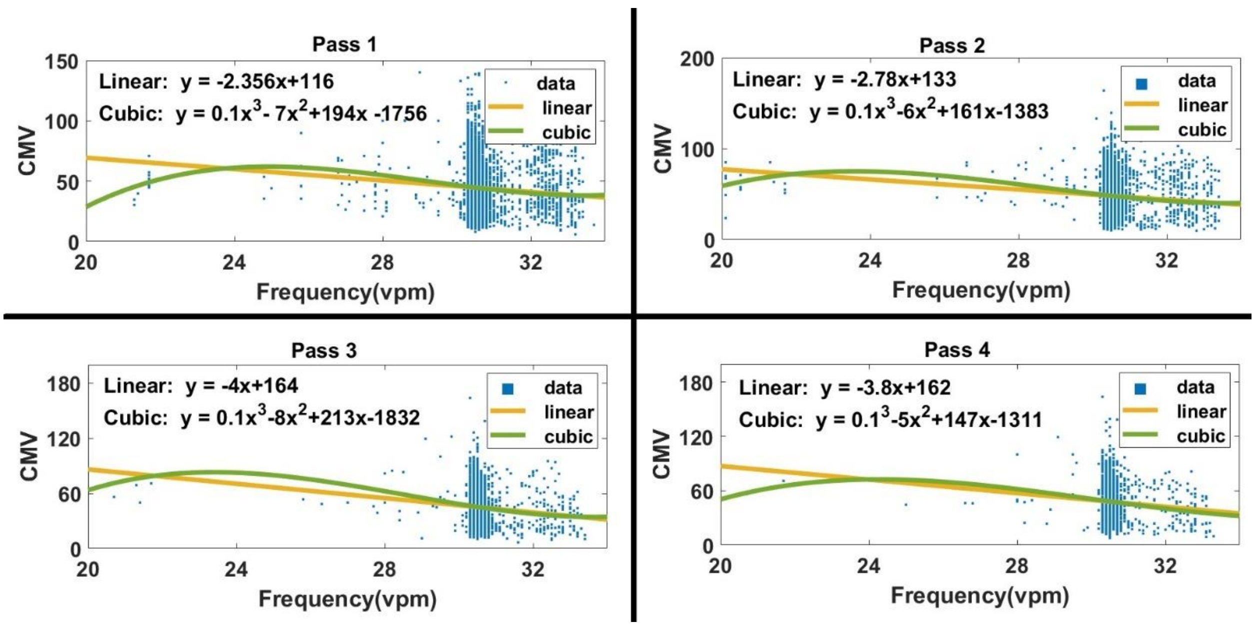


Figure 11. Correlations between CMV and vibration frequency

In addition to the linear and cubic fits, it was attempted to find the best non-linear function to correlate CMVs with vibration Amplitude, and vibration frequency and the results are summarized in Table 1. As evident from Table 1, reasonable correlations exist between CMVs and vibration amplitude, while no correlations can be found between CMVs and vibration frequency.

Table 1. Non-linear function correlations between CMV-amplitude and CMV- frequency (first section of the road)

Function	R-square (x=Amp, f(x)=CMV)	R-square (x=Freq, f(x)=CMV)
$f(x) = a + \frac{b}{x}$	0.6692 0.5871 0.5966 0.5906	0.01662 0.02757 0.02117 0.01433
$f(x) = \frac{a+bx}{1+cx}$	0.6714 0.5944 0.5992 0.5978	0.003589 0.02605 0.008894 0.009552
$f(x) = a + b\,e^{-cx}$	0.662 0.5911 0.5962 0.5974	4.965e-05 3.737e-08 -0.03907 1.081e-12

In order express CMVs as a function of vibration amplitude and frequency, multiple regression using two different models were performed and the result of are summarized in Table 2. Note that, x is vibration amplitude, y is vibration frequency, and f(x,y) = CMV

Table 2. Correlations of CMV with vibration amplitude and frequency (first section of the road)

Pass	Coeff. (95% confidence bounds)	Goodness of fit	R-square
linear model: f(x,y) = P0 + P1*x + P2*y + P3*x^2 + P4*x*y + P5*y^2			
Pass 1	P0 = -442.6 P1 = 238.9 P2 = 10.35 P3 = -18.61 P4 = -3.289 P5 = -0.06203	SSE: 2.403e+06	R-square: 0.2277 RMSE: 19.56
Pass 2	P0 = -309.2 P1 = 235.8 P2 = 0.1815 P3 = -20 P4 = -2.487 P5 = 0.08024	SSE: 1.432e+06	R-square: 0.4332 RMSE: 17.09
Pass 3	P0 = -395.5 P1 = 249.4 P2 = 5.622 P3 = -28.56	SSE: 5.52e+05	R-square: 0.6095 RMSE: 12.62

	P4 = -1.186 P5 = -0.09188		
Pass 4	P0 = -200.5 P1 = 85.71 P2 = 8.059 P3 = -11.61 P4 = 1.234 P5 = -0.2524	SSE: 4.266e+05	R-square: 0.6064 RMSE: 13.54
general model: f(x,y) = a + b*sin(m*pi*x*y) + c*exp(-(w*y)^2)			
Pass 1	a = 45.74 b = -2.878 c = 0.1916 m = 0.03792 w = 0.4519	SSE: 2.911e+06	R-square: 0.06427 RMSE: 21.53
Pass 2	a = 47.73 b = 0.1296 c = 0.6948 m = 0.398 w = 0.9502	SSE: 2.526e+06	R-square: 0.0003391 RMSE: 22.69
Pass 3	a = 44.56 b = 0.9383 c = 0.6991 m = 0.8896 w = 0.9593	SSE: 1.412e+06	R-square: 0.001079 RMSE: 20.19
Pass 4	a = 47.71 b = -1.684 c = 0.9172 m = 0.2728 w = 0.7572	SSE: 1.081e+06	R-square: 0.003132 RMSE: 21.55

The linear model can reasonably express the CMVs as a function of vibration amplitude and frequency, whereas the regression values for the general model are zero. As expected, with the increased number of passes, the regression values improve indicating a stronger correlation between the variables, which in turn points to improves consistency of the compaction. Prior to implementation of IC roller, the roller parameters need to be calibrated (Foroutan et al., 2020). Usually, the calibration process is achieved in a test section. It is important to ensure the proper performance of the feedback control system during this calibration process. The developed expressions of CMVs as a function of vibration amplitude and frequency can further assist in verifying and fine tuning the outcome of the feedback control system.

3.1.3 Correlations between vibration amplitude, frequency, and CMVs for the second section of the road

To further analyze the variation of CMVs as a function of vibration amplitude and frequency, a second section of the road (~ 0.2 mile) with three IC roller passes was considered as shown in Figure 12.

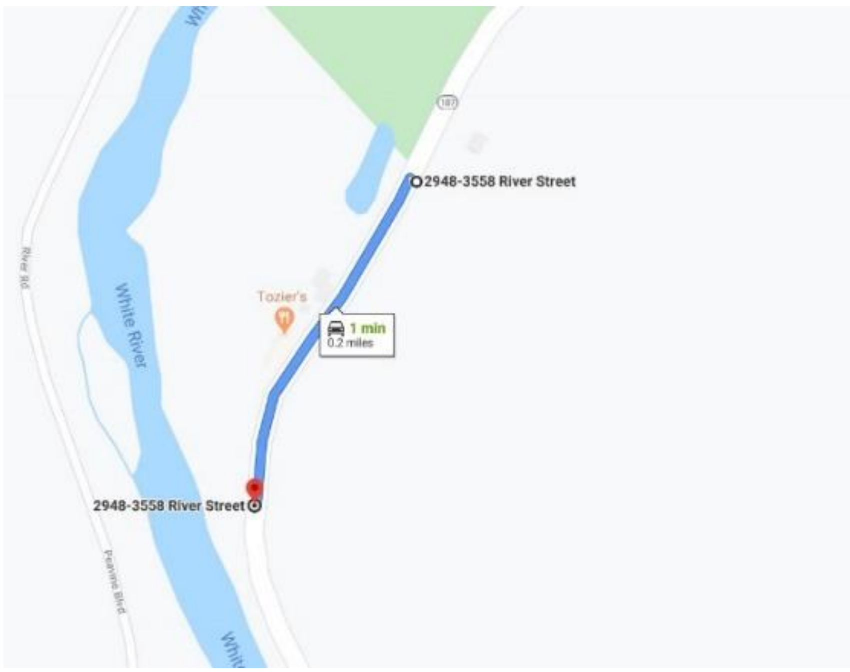


Figure 12. Location of the selected second section of the road

Figures 13 and 14 show the correlations between CMV with vibration amplitude and frequency for this section of the road, respectively. As it can be seen in Figures 13 and 14, reasonable correlations exist between CMVs and vibration amplitude, while no correlations can be found between CMVs and vibration frequency.

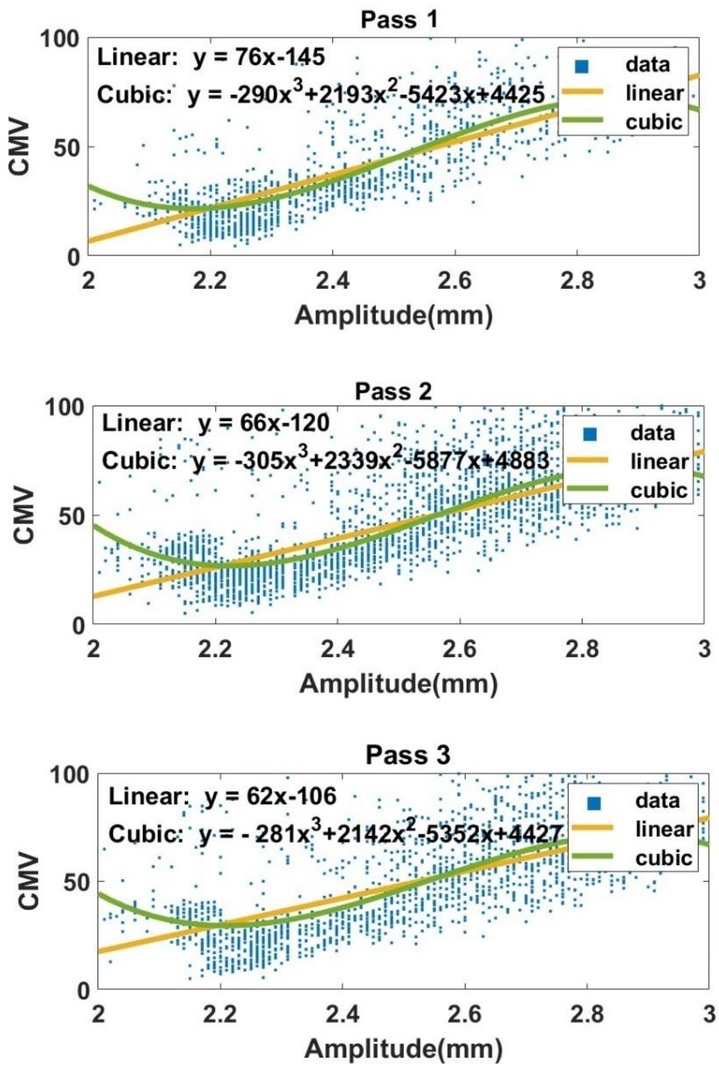


Figure 13. Correlation between CMV and vibration amplitude for the second section of the road

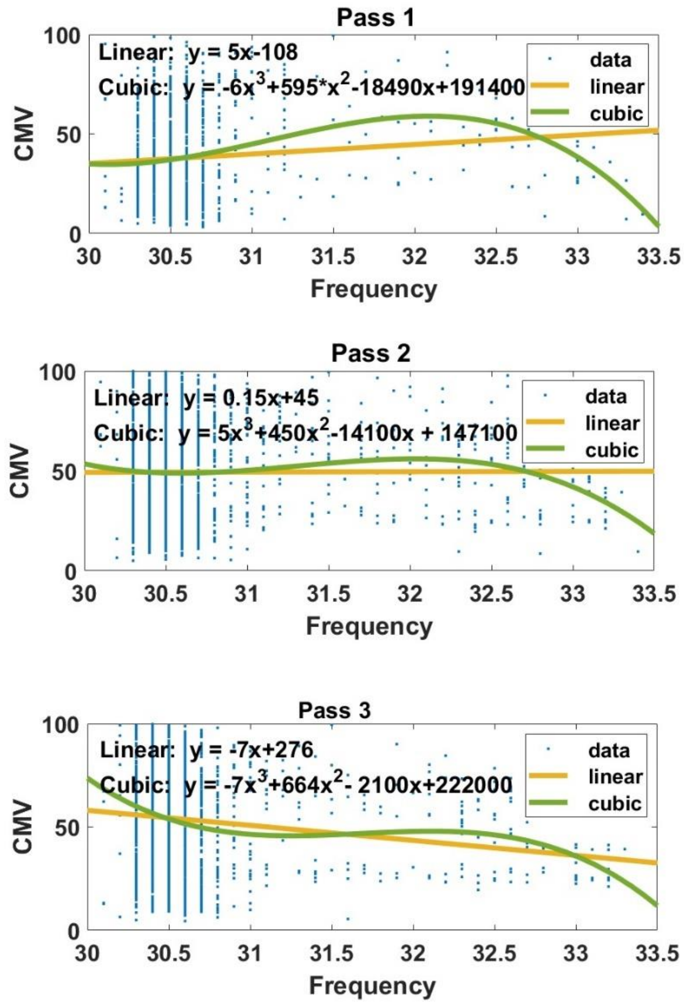


Figure 14. Correlation between CMV and vibration frequency for the second section of the road

Table 4 summarizes the results of fitting non-linear functions to correlate CMVs with vibration amplitude, and vibration frequency. As evident from Table 3, reasonable correlation exist between CMVs and vibration amplitude. The result of multiple regression using two different models for the second section of the road are summarized in Table 4. Note that x is vibration amplitude, y is vibration Frequency, and f(x,y) = CMV.

Table 3. Non-linear correlations between CMV-amplitude and CMV- frequency (second section of the road)

Function	R-square (x=Amp, f(x)=CMV)	R-square (x=Freq, f(x)=CMV)
$f(x) = a + \frac{b}{x}$	0.6105 0.5482 0.4596	0.01141 -3.753e-05 0.02327
$f(x) = \frac{a+bx}{1+cx}$	0.6223 0.5650 0.4669	0.006117 -0.00314 0.003034
$f(x) = a + b\,e^{-cx}$	0.6223 0.5654 0.4666	-0.000301 -0.000882 -0.0005014

Table 4. result of multiple regression for second section of the road

Pass	Coeff.	Goodness of fit	R-square
f(x,y) = P0 + P1*x + P2*y + P3*x^2 + P4*x*y + P5*y^2			
Pass 1	P0 = 371.2 P1 = -249.8 P2 = -4.063 P3 = 30.72 P4 = 5.191 P5 = -0.181	SSE: 1.696e+06	R-square: 0.5762 RMSE: 15.19
Pass 2	P0 = 783.3 P1 = -203.3 P2 = -35.43 P3 = 7.483 P4 = 7.084 P5 = 0.2851	SSE: 2.387e+06	R-square: 0.4763 RMSE: 17.42
Pass 3	P0 = 1071 P1 = -139 P2 = -55.69 P3 = -2.422 P4 = 6.587 P5 = 0.5789	SSE: 1.633e+06	R-square: 0.4276 RMSE: 18.93
f(x,y) = a + b*sin(m*pi*x*y) + c*exp(-(w*y)^2)			
Pass 1	a = 38.94 b = -0.129 c = 0.9172 m = 0.3057 w = 0.7572	SSE: 4.002e+06	R-square: 2.529e-05 RMSE: 23.34
Pass 2	a = 50.6 b = -0.7888 c = 0.7749 m = 1.239 w = 0.8687	SSE: 4.555e+06	R-square: 0.0005319 RMSE: 24.07
Pass 3	a = 55 b = 0.7495 c = 0.7749 m = 1.176 w = 0.8687	SSE: 2.852e+06	R-square: 0.000454 RMSE: 25.01

The linear model does not appear to be able to reasonably correlate the variables for this section of the road. The range of regression values for this linear model is close to that of the first section, confirming that CMVs can be reasonably expressed as function of vibration amplitude and frequency.

3.1.4 CMVs as a function of vibration amplitude and frequency at randomly selected sections of the road

The linear model regression values for 10 randomly selected sections of the road are summarized in Table 5. Note that, x is vibration amplitude, y is vibration frequency, and f(x,y) = CMV

Table 5. Correlations of CMV with vibration amplitude and frequency for 10 randomly selected sections of the road

Linear model **f(x,y) = P00 + P10*x + P01*y + P20*x^2 + P11*x*y + P02*y^2**		
Road section	Coeff.	Suitability of the fit
1	p00 = 317 p10 = 459.1 p01 = -58.87 p20 = -23.6 p11 = -8.365 p02 = 1.249	SSE: 6.987e+04 R-square: 0.684 RMSE: 11.89
2	p00 = -156.1 p10 = 640.9 p01 = -41.55 p20 = -25.6 p11 = -14 p02 = 1.177	SSE: 6.678e+04 R-square: 0.6883 RMSE: 11.63
3	p00 = 980.8 p10 = 594.3 p01 = -109.1 p20 = -11.5 p11 = -14.83 p02 = 2.268	SSE: 7.156e+04 R-square: 0.6565 RMSE: 12.04
4	p00 = 2152 p10 = 337.1 p01 = -163.9 p20 = -8.443 p11 = -6.932 p02 = 2.829	SSE: 6.457e+04 R-square: 0.7038 RMSE: 11.43
5	p00 = 473.1 p10 = 350.6 p01 = -59.22 p20 = -7.851 p11 = -7.661 p02 = 1.219	SSE: 5.063e+04 R-square: 0.7171 RMSE: 10.12
6	p00 = 2075 p10 = 422.5 p01 = -166 p20 = -22.66 p11 = -7.473 p02 = 2.891	SSE: 6.373e+04 R-square: 0.6863 RMSE: 11.36
7	p00 = 1576 p10 = 439.2	SSE: 6.67e+04 R-square: 0.675

	p01 = -136.2 p20 = -27.19 p11 = -7.287 p02 = 2.421	RMSE: 11.62
8	p00 = 198.8 p10 = 446.9 p01 = -49.37 p20 = -33.79 p11 = -6.526 p02 = 1.015	SSE: 6.568e+04 R-square: 0.6605 RMSE: 11.53
9	p00 = 2024 p10 = 542.5 p01 = -172.2 p20 = -8.4 p11 = -13.65 p02 = 3.237	SSE: 6.86e+04 R-square: 0.6696 RMSE: 11.78
10	p00 = 363.9 p10 = 404.8 p01 = -55.03 p20 = -21.04 p11 = -7.184 p02 = 1.104	SSE: 6.139e+04 R-square: 0.7077 RMSE: 11.15

The regression values indicate that the linear model can reasonably express CMVs as a function of vibration amplitude and frequency. Using CMVs as a function of vibration amplitude and frequency, the feedback control system can optimize compaction performance with continuous adjustments of vibration amplitude and frequency. When the vibration amplitude is large and its frequency is low, compaction effort ensures good compaction for layers in depth (e.g. Anderegg and Kufmann, 2004, Tirado et al., 2019). With increased compaction effort in subsequent passes, the vibration frequencies increase, and the feedback control system reduces the vibration amplitudes. This continuous adjustment of the vibration amplitude and frequency result in optimal compaction (Anderegg and Kufmann, 2004).

Although expressing the CMVs as a function of vibration amplitude and frequency for use in the control system is not straight forward, it can significantly enhance the IC performance. Due to the complexity involved in roller-soil/asphalt interaction, obtaining accurate ICMV measurements is challenging, which in turn makes developing functions challenging as well. It should be noted that depending on the project type (e.g. reclaimed project, asphalt, etc.), this task may prove challenging. As in the case of 10 randomly selected sections of the road, the developed linear model expressions of CMVs as a function of vibration amplitude and frequency can facilitate in verifying and fine tuning the outcome of the feedback control system during IC roller calibration and operation.

3.2 Wireless Sensing Systems

3.2.1 Wireless Sensing in subsurface Environment

Several studies have explored employing wireless sensor network (WSN) technology for subsurface monitoring (e.g. Terzis et al., 2006; Ghazanfari et al., 2012). In general, the subsurface wireless sensing relies on point sensing or electromagnetic (EM) signal-probe (See Fig. 15). Although the point sensing approach eliminates the need for wired link, usually cannot provide the coverage/accuracy of wired sensor networks (Ghazanfari et al., 2012).

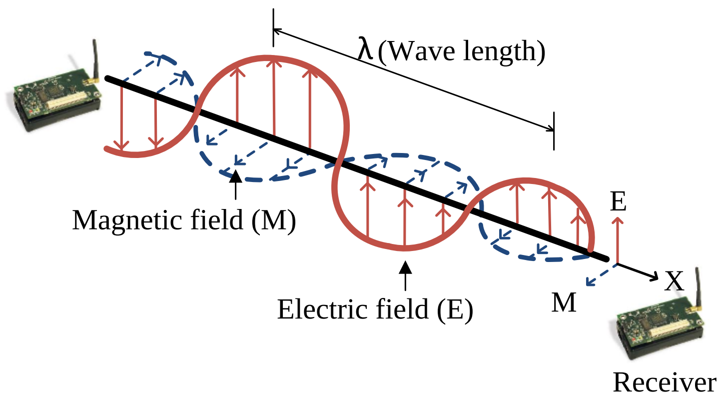


Figure 15. Schematic of EM wave propagation (source: Ghazanfari et al., 2012)

The key shortcomings of the EM signal-probe approach are (i) the added overhead due to the extra frequency band requirement, and (ii) battery power consumption (Yoon et al., 2015). To overcome these shortcomings, an explored alternative is explored is integration of the EM signal's functionality as both a messenger and a probe to potentially detect and/or monitor subsurface geo-events (Ghazanfari et al., 2012; Yoon et al., 2015).

The change in the physical properties (e.g. water content, salinity, density) of a host porous medium affects the strength of the EM waves (Ghazanfari et al., 2012). If the EM attenuation characteristics in a given medium (e.g. soil) with its initial properties are established, subsequent changes in these properties can be detected using the spatially distributed sender-receiver radio nodes, as they affect the EM attenuation characteristics (Ghazanfari et al., 2012; Yoon et al., 2015).

Compared to traditional WSN techniques, this approach offers limited hardware and energy consumption.

Figure 16 shows the laboratory experiment result from water intrusion simulation in a proof-of-concept study (Ghazanfari et al., 2012), where a linear array of radio transceivers (MICAz, 2.4 GHz) were placed in a test box (118cm x 13cm x 13 cm, made of PVC panels) filled with clean fine sand at 8% moisture content.

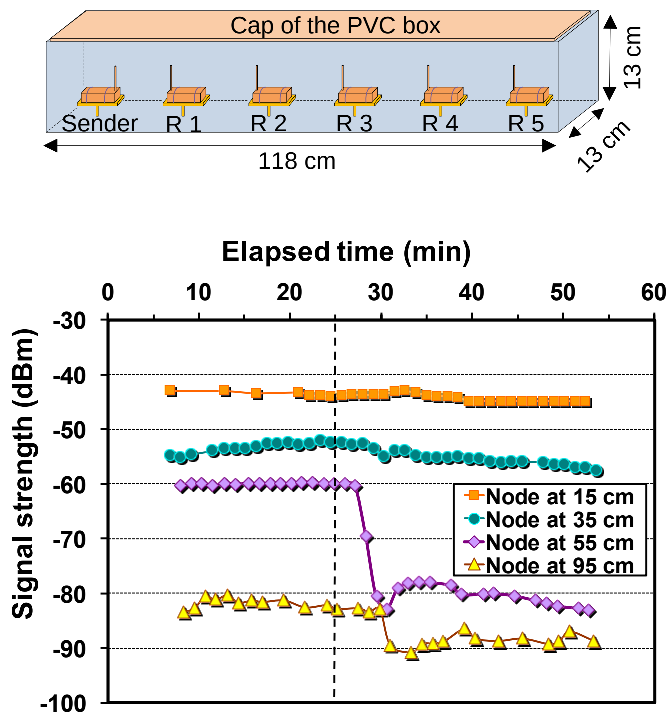


Figure 16. Water intrusion simulation in sandy soil (source: Ghazanfari et al., 2012)

At about 25-minute mark, water was introduced over the soil on the upstream side of the R3 node, located at 55-cm from the sender. A significant decrease in the received signal strength was recorded at this node and a similar signal strength depletion was recorded at the downstream node R4, located at 95 cm from the sender. In contrast, no significant change in the signal strength was recorded at the upstream nodes R1 and R2 (at 15 cm and 35 cm from the sender), where no change in the moisture content occurred (Ghazanfari et al., 2012).

3.2.2 Challenges Associated with Active Sensing in Pavement Structures:

The embedded MEMS sensors have been successfully implemented for detecting the degree of hydration of concrete structures (Ceylan et al., 2011). However, the key challenges for employing embedded MEMS sensors for QA/QC and health monitoring of sub-base, base and pavements are reported to be the requirement for (i) powering the electronics, and (ii) ruggedizing the sensors to survive the compaction process (Lin et al., 2015). In addition, the existing limitations in communication distance restricts effective performance monitoring of sub-base and base layers using MEMS sensors.

3.2.3 Passive Wireless Sensing System:

In passive wireless sensing system, an embedded device is interrogated at frequency f_1 by an active transceiver that is located above the ground. A remote tag is activated by this signal and returns a response back to the interrogator over a reverse link operating at frequency f_2 (Frolik et al., 2018). Whether a wireless link is successful will be dependent on the RF signal attenuation through the transmission medium (i.e. soil or asphalt). Radio Frequency Identification (RFID) is among wireless approaches that has been used for general detection and tracking applications and is also being adapted for sensing purposes. An RFID system consists of an interrogator and a number of RFID tags. The reader transmits a continuous wave signal at frequency (f_1), which is captured by a tag. Using the captured energy, the tag will return a modulated backscatter signal at the same frequency, i.e., $f_2 = f_1$ (Finkenzeller, 2010).

The frequency doubling reflectenna (FDR)-based passive wireless sensors, embedded in soils and operating at a frequency range of 1.3 to 2.6 GHz, have shown to effectively detect the changes in moisture content and potentially density of the soil (Frolik et al., 2018). Compared to active sensing, passive sensing has several advantages including (i) lower energy consumption, (ii) more compact sensor/packaging design, and (iii) lower cost. The passive wireless sensing system has the potential to be integrated with IC to facilitate the process of geomaterial compaction and pavement performance monitoring. Inexpensive passive sensors can be embedded in loose geo-materials (i.e. soil/asphalt) before compaction. Signatures from these sensors can be tracked to (i) assess the effectiveness and uniformity of compaction, (ii) reduce the existing uncertainty in the correlations between ICMVs and the material stiffness, and (iii) potentially monitor the performance of pavement over time. In addition, there is potential to integrate IC with passive wireless sensing system to detect changes in the geomaterials moisture content and stiffness, which can play a big role in complementing the IC technology.

3.3 Pressure Sensing

Different wireless sensing systems and pressure sensors that are suitable to work alongside IC were considered. As discussed in section 3.2, passive sensing system appears to be a better option for IC application. It would be inevitable to ruggedize the sensing package such that (i) the transducer sensing capabilities are not impacted, and (ii) the device survives the high temperatures expected during the laying of asphalt (up to ~150 °C) and several years of being embedded under the roadway. Developing a robust and yet compressible packaging design is one of the key steps in utilizing passive sensing systems alongside IC for field applications. Among passive sensing systems, The FDR does not require harvested energy to operate and thus its response to the interrogation signal is instantaneous (Frolik et al., 2018). This also benefits automated collection using a quickly moving interrogator. Low-cost, capacitive-based pressure transducers can be integrated into existing FDR designs (Frolik et al., 2018).

For preliminary laboratory analysis, a square pressure sensor (40mm x 40mm), with the 0 - 50 PSI pressure measurement range, a product of Sensor Products Inc. along with Tactilus Developer Toolkit was used (see Figure 17).

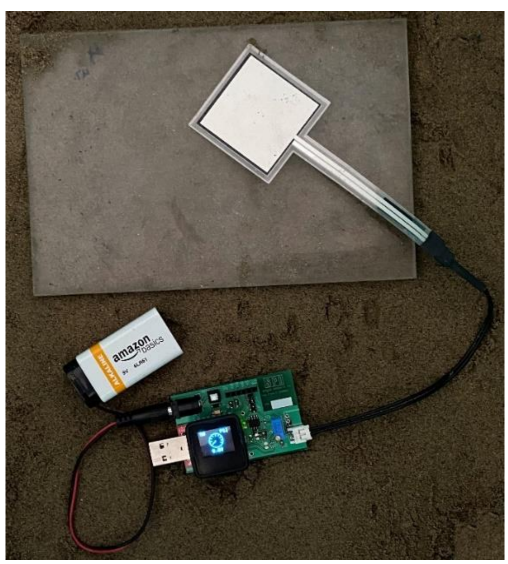
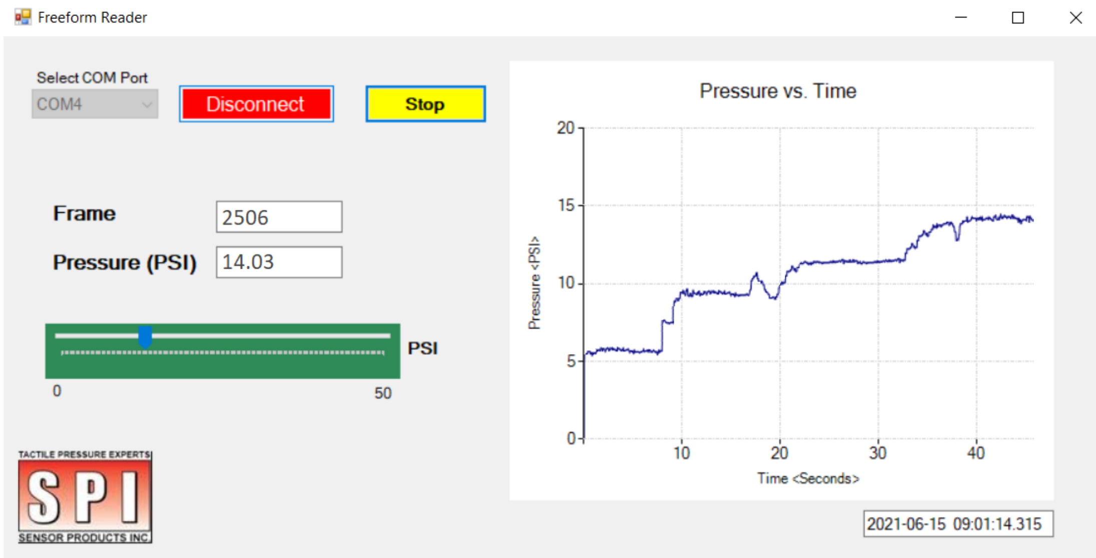


Figure 17. Photo of the pressure sensing package in the sand box

After hardware and software synchronization was conducted (see Figure 18), the pressure sensor was calibrated. For sensor calibration and testing purposes, two solid and light plexiglass sheets with dimensions of 1.5 x 1.5 inch were used on both sides of the pressure sensor (see Figure 19) to uniformly transfer the applied pressure (using dead weights) to the sensor and to the soil.



(a)

(b)

Figure 18. (a) Hardware and software synchronization, (b) sensor calibration process

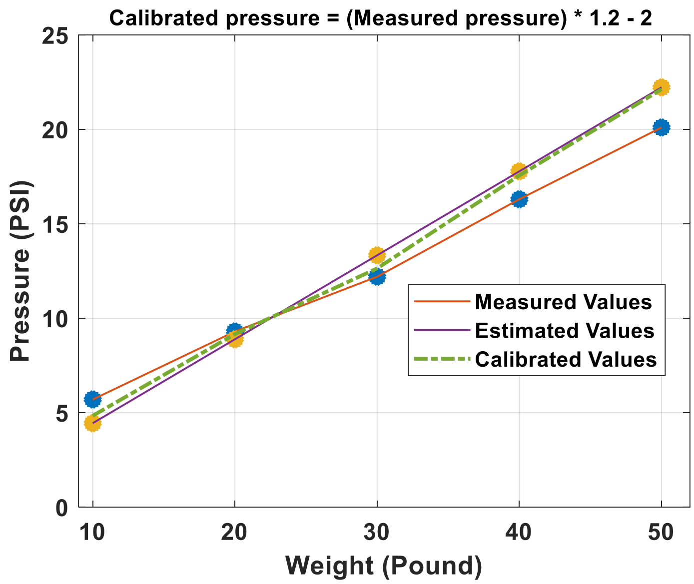


Figure 19. Pressure measurements for the pressure sensor calibration

The calibrated sensor was placed on a hard and sturdy sheet and buried in a box (see Figure 20) with approximate dimensions of 35 x 25 x 15 inch and filled with uniform sand. Different dead loads (i.e. weights) were applied at the surface of the sand box, while the pressure sensor was placed at different depths in the box.

Figure 20. Pressure sensor buried in the sand box

At a specific sensor embedment depth, different loads were applied at the surface and pressure measurements were carried out. Figure 21 shows variation of measured pressure with depth. As evident from Figure 21, the measured pressure profile along depth is consistent for different levels of applied load at the surface. In addition, the measures pressures significantly decrease with increased depth, where the maximum pressure is recorded right below the applied load at the surface.

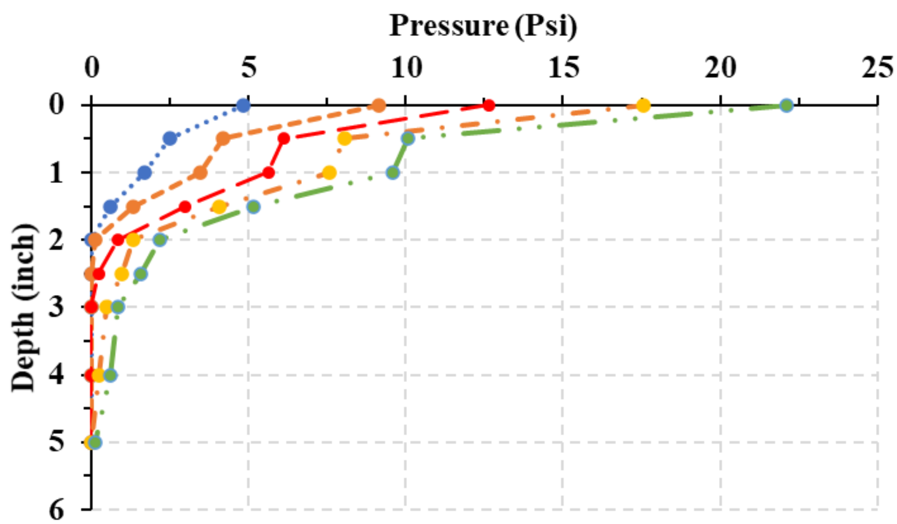


Figure 21. Variation of measured pressure with depth in the sand box

The pressure sensor did not work properly, and the measurements were not accurate for the following cases: (1) when the applied pressure range was increased to about 45 psi, and (2) once the sub-base material consisting of larger aggregates was used instead of the uniform sand. The pressure magnitude primarily depends on depth (below roller), roller type/size, and the material being compacted such as asphalt, base, and sub-base (e.g. Fratta et al., 2015). For example, the pressure right under the surface (Z=0) of an average size IC roller compacting soil could be as high as 150 psi, but decreases significantly with increased depth (~30 psi at Z=25 cm; ~15 psi at Z= 50 cm; ~5 psi at Z=75 cm; and ~1 psi at Z=100 cm) [e.g. Fratta et al., 2015]. Therefore, proper sensor ruggedization/packaging is needed to withstand extreme pressure and heat during compaction, particularly for the sensors embedded right below the surface of the pavement.

3.4 Potential IC Integration with Passive Sensing System

In order to integrate the passive sensing system with the IC technology, data acquisition system and two antennas in the front and rear sides of the IC roller can be installed as shown in Figure 22. As the roller moves along the compaction path, first the front antenna will interrogate the embedded sensors in the soil layer. Then, as the roller passes the compacted region, the rear antenna will re-interrogate the same sensors. This allows comparing the transmitted/received power before and after compaction in a path. This procedure will be repeated along the compaction path until the target ICMV (i.e. corresponding to maximum dry density) is achieved.

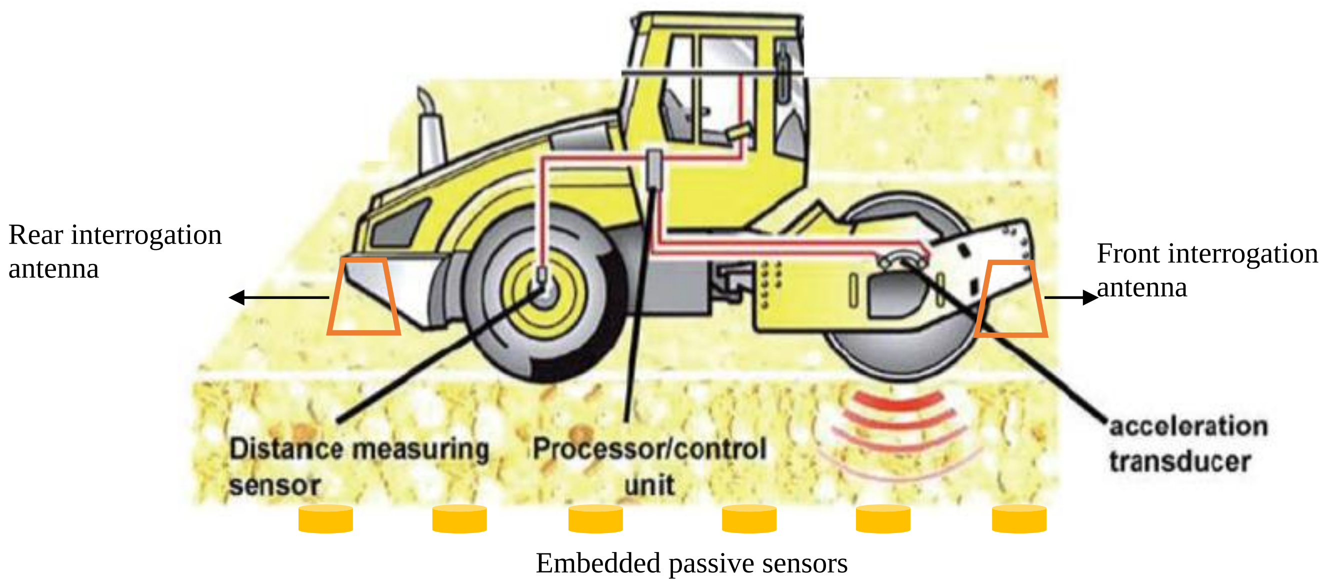


Figure 22. Example of integration of IC with passive sensing (adapted and modified from BOMAG website)

Chapter 4: Conclusions and Recommendations

Enhancement of IC performance using wireless sensing system and feedback control system can facilitate making informed decisions on proper course of action during compaction, which in turn leads to improved consistency and uniformity of compaction and subsequently improved durability of highway/roadway infrastructure. Based on the results from this study, the following conclusions can be drawn, and a few recommendations are made:

- Linear models can reasonably express CMVs as a function of vibration amplitude and frequency, which can be used in the feedback control system to optimize compaction performance with continuous adjustments of vibration amplitude and frequency. Prior to implementation of IC, it is recommended to first investigate the performance of the feedback control system by checking the variation of CMVs with vibration amplitude and frequency in a test section to ensure optimized compaction during IC operation.

- The IC roller calibration process including determination of target CMV is necessary at the beginning of compaction operation. It is recommended to repeat the calibration process once the material type or properties change at different sections of the road.

- Among wireless sensing systems, passive sensing systems appear to be a better option for IC application. This is in part due to (i) lower energy consumption, (ii) more compact sensor/packaging design, and (iii) lower cost compared to other sensing systems. Additional laboratory and field testing is recommended to ensure robust and accurate measurements during IC compaction using embedded passive wireless sensors.

- Proper sensor ruggedization/packaging is needed to (i) prevent damage to the sensing capability, and (ii) survive high pressure and temperature expected during compaction as well as several years of being embedded under the roadway for monitoring.

- There is potential to integrate the passive sensing system with the IC technology by installing data acquisition system and two antennas in the front and rear sides of the IC roller.

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Appendices

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