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Intelligent Compaction of Asphalt Pavement Implementation

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16. Abstract

The main purpose of this research is to determine the possibility of substituting in-place core density (% Gmm) for Hot Mix Asphalt (HMA) Quality Assurance (QA) in Indiana Department of Transportation Specification with Intelligent Compaction (IC) measurements. A questionnaire survey and interviews were conducted to gather information on: (1) the usage of IC technology in other states, (2) the benefits of applying IC technology, and (3) the application of IC technology for Quality Control/ Quality Assurance (QC/QA). Also the data available from IC demonstration performed on US 52 in 2009 was analyzed to identify the relationship between in-place density values (i.e., Non-Nuclear Gauge, NNG) and the IC Measurement Values (ICMVs).

According to survey responses from 26 agencies, there was no state DOT using IC for QA as of June 2014. Only two DOTs, including Alaska and Vermont have adopted IC in HMA compaction for QC. The reasons for not using IC technology in current QC/QA practices were: (1) satisfaction with existing QC/QA procedure, (2) difficulty of adjustment due to the lack of specifications in determining stiffness in HMA, and (3) lack of availability of IC equipment with contractors. However, it was responded that the most benefits of IC was night time paving and uniform compaction in QC.

Analysis of the ICMV data obtained from a demonstration project on US 52 indicated that a NNG correlation showed an R2 value of 0.67. This finding supports the IC implementation in the current INDOT HMA QC. It should be noted that a correlation between core-density and ICMV could not be determined due to lack of reliable data.

In conclusion, the research could not identify any possibility of adding IC into the INDOT specification for QA based on the survey, phone interviews and analysis of the data obtained from IC demonstration on US 52.

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EXECUTIVE SUMMARY

INTELLIGENT COMPACTION OF ASPHALT PAVEMENT IMPLEMENTATION

Introduction

Asphalt pavement performance is affected by the quality of pavement structure, material, and construction. Hot mix asphalt (HMA) should be constructed with appropriate in-place density and impermeability to moisture, which affects long-term performance.

Material-related measurements for the pay factors include binder content, air voids at N_{des}, and voids in mineral aggregate (VMA) at N_{des}. In addition, in-place density (% Gmm) and smoothness are construction-related measurements. The in-place density is considered an indicator to evaluate the pavement performance and to identify the asphalt pavement construction quality.

There are three types of in-place density tests: (1) the core density test, (2) the nuclear density gauge test, and (3) the non-nuclear density gauge test. The density (% Gmm) from a randomly selected core is a percent ratio of the bulk specific gravity (G_{mb}) to the maximum specific gravity (G_{mm}). The nuclear density gauge test and non-nuclear density gauge tests are the non-destructive tests. The Indiana Department of Transportation (INDOT) has adopted the core density test to collect the in-place densities for HMA quality assurance (QA); however, it has several inherent problems with the coring process, representativeness, and cost effectiveness.

Intelligent compaction (IC) technology offers several advantages over conventional methods of compaction. The Federal Highway Administration (FHWA) added IC to their Every Day Counts initiatives for accelerating its implementation. IC rollers can provide uniform compaction over pavements since operators can receive feedback about the condition of the materials being compacted and the number of passes over the asphalt mat in real time. The IC rollers are equipped with an integrated on-board documentation system, a Global Positioning System (GPS), an infrared temperature sensor, and an accelerometer. Therefore, the IC features can be more beneficial for nighttime operation, which is becoming more common for high traffic volume roads.

In this synthesis study we conducted a survey and interviews to gather information on (1) the usage of IC technology by other state DOTs, (2) the benefits of applying IC technology, and (3) the application of IC to the asphalt pavement construction QC/QA. We also analyzed the data from IC technology demonstration performed on US 52 in West Lafayette, Indiana, in 2009, in conjunction with the FHWA IC research project, to validate the possibility of substituting the in-place density with the intelligent compaction measurement values (ICMVs).

Findings

The main purpose of this research was to investigate the application of IC technology in QC/QA. A questionnaire survey was sent to AASHTO members to determine the current use of IC technology. A total of 26 AASHTO members participated in the survey. Only 2 states, Alaska and Vermont, have adopted IC technology for QC, while the other 24 respondents have not used it for either QC or QA. The reasons given for not using IC technology were (1) satisfaction with existing QC/QA procedures, (2) difficulty with adjustment due to the lack of specifications in determining stiffness in HMA, and (3) availability of IC equipment from contractors. In addition, 13 of the respondents stated that they do not have a plan for using IC technology in the future.

We conducted phone interviews to obtain practical information on the IC application in detail. We selected three states that have adopted IC technology and two states that have not adopted the technology. In addition, we interviewed three states and three IC vendors who had conducted IC demonstration projects between 2012 and 2014. The phone interview results revealed that night-time paving and uniform compaction were the most important benefits of IC technology. Also, five out of six states indicated that IC technology is cost effective. Although using IC rollers can add cost, it does not significantly affect the total cost for the construction project since the IC compaction is a small portion of the total construction cost. With respect to the possibility of IC technology as a QA tool, the DOTs (Utah, Florida, and Maine) and vendors (HAMM, SAKAI, and Caterpillar) who participated in IC demonstration projects expressed some concerns about the relationship between in-place density and ICMV.

The objectives of analyzing the data obtained from the IC demonstration on US 52 were to explore the possibility of substituting the in-place density with the ICMV by determining the relationship between them. There are two in-place density tests: the non-destructive density test and the core density test. During the US 52 IC demonstration, the core density data were randomly selected while other test data (i.e., compaction control value (CCV), non-nuclear density gauge (NNG), temperature, and pass count) were collected at designated locations. Consequently, the core density data had to be excluded from the data analysis for establishing the relationship between core density and ICMV. In terms of the correlation between NNG and ICMV, the multiple regression model (predicted variable: non-nuclear density) indicated an R^2 value of 0.67 with statistically significant P-values for the independent variables (i.e., pass count, temperature, and CCV). Additionally, the pass count was identified to be an important variable affecting the multiple regression model based on the Analysis of Variance (ANOVA) test. This research also performed the optimal pass count and the compaction coverage analysis for the data available from IC demonstration on US 52.

Implementation

Based on the analysis of the results of the survey, phone interviews, and analysis of the data from IC demonstration on US 52, this research team determined that IC technology can be applied for QC but not for QA, as discussed below. With regard to the application of IC in QA, there is no solid evidence for the relationship between core density and ICMV to date to support the possibility of substituting in-place density with IC technology.

In terms of QC, IC technology can improve the compaction coverage and the uniform compaction achieved. The measurement of ICMV can improve the uniformity of compaction by determining a target optimal pass count. Also, as mapping is controlled by IC rollers, the compaction coverage can be identified. Several states are currently using IC technology for QC of pavement compaction and indicated satisfaction with IC technology in phone interviews. IC equipment costs more than normal compaction equipment. However, real-time compaction measurement and uniform compaction would help contractors reduce pay adjustment issues. Also, the IC compaction is a small portion of the total construction and does not significantly affect the total cost for the construction project.

The relationship between non-destructive density, one of requirements of QC, and ICMV varied across the demonstration projects. The results of the demonstration data from other states (Chang, Xu, & Rutledge, 2012a, 2012b, 2013a, 2013b) indicated low correlations (less than 0.2 of R^2). Also, the result of the analysis of data obtained from IC demonstration on US 52 indicated 0.38 of R^2. Therefore, more pilot studies should be conducted to improve the confidence of the relationship between non-destructive density and ICMV.

For IC application for QA, it is unlikely that ICMV could improve the effectiveness of QA. Based on the literature review, several IC demonstration projects have been conducted to identify the correlation between core density and ICMV data. However, their results do not indicate a strong correlation between core density and ICMV data.

Phone interviews conducted in the present research revealed that Utah, Florida, and Maine DOTs and IC roller vendors HAMM, SAKAI, and Caterpillar were apprehensive of the relationship between in-place density and ICMV. Also, as indicated earlier, the core density data available for this research were not reliable and thus could not be used for establishing the correlation between ICMV and the core density. As a result, this research is inconclusive about the relevance of ICMV in satisfying the requirements for QA.

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1. INTRODUCTION

1.1 Research Background and Need Statement

Asphalt pavement performance (roughness, rutting, cracking, etc.) is generally a result of quality of pavement structure, material, and construction. Indiana Department of Transportation (INDOT) or consultants design the pavement structures and contractors procure materials and construct pavements. The contractors are paid according to the construction quality of their end product. In other words, there is a bonus or penalty to the contractors based on pay factors quantifying the quality. INDOT specifies the pay factors for quality control/quality assurance (QC/QA) hot mix asphalt (HMA) Specification Section 401.19. INDOT has implemented Percent Within Limit (PWL) (ITM588) since 2010 for the pay factors of dense grade mixture greater than or equal to one lot. Material-related measurements for the pay factors include binder content, air voids at N_{des}, and voids in mineral aggregate (VMA) at N_{des}. In addition, in-place density (% Gmm) and smoothness are construction-related measurements. The density acceptance criterion for INDOT Section 401 mixtures is based on meeting 90% of field core densities within limits with a lower threshold limit of 91% of maximum theoretical specific gravity (G_{mm}). The average density needed to comply with this specification is approximately 93% (7% air voids). The result is that when the in-place density specification is met, 10% of the pavement area may have a density of less than 91%, meaning air voids of more than 9%.

There are three types of in-place density tests: the core density test, the nuclear density gauge test, and the non-nuclear density gauge test. The density (% Gmm) from a randomly selected core is a percent ratio of the bulk specific gravity (G_{mb}) to the maximum specific gravity (G_{mm}). American Association of State Highway and Transportation Officials (AASHTO) T 166, Method A or AASHTO T 275 and AASHTO T 209 are used for the bulk specific gravity and the maximum specific gravity measurements, respectively [INDOT 401]. The nuclear density gauge test (ASTM D 2950) and non-nuclear density gauge test (ASTM D 7133) are the nondestructive tests. INDOT has adopted the core density test to collect the in-place densities for HMA QA due to its reliable accuracy; however, it has several inherent problems with coring process, representativeness, and cost effectiveness. Taking core sample is a destructive test in nature, which can affect pavement performance by causing cracks. Since the core density is measured from randomly sampled cores, the restrictive cores may not represent the entire compaction condition and reflect the condition of the uninform compaction of the road. Taking core samples, measuring densities, and performing data analysis can prolong the timeline for construction projects and consequently cause an increase in construction cost (Beainy, Commuri, & Zaman, 2012).

Intelligent compaction (IC) is a better system for compaction technology which the Federal Highway Administration (FHWA) added IC to their Every Day Counts initiatives for accelerating its implementation. IC rollers can provide uniform compaction over pavements since operators can receive feedback about the condition of the materials being compacted and the number of passes by the asphalt mat in real time. The IC rollers are equipped with an integrated on-board documentation system, a Global Positioning System (GPS), an infrared temperature sensor, and an accelerometer. Therefore, the IC features can be more beneficial for night time operation that is becoming more common for high traffic volume roads. Indiana has implemented IC for QC of subgrade and HMA (ITM No. 803-13P HMA Pavement QCP).

Along with the growing interest in IC technology, the possibility has been raised that IC technology can address the issues of the current practice of the density test. Accordingly, there is a need for a synthesis study to understand the state of the practice to determine feasibility of the IC application to INDOT QA.

1.2 Research Objectives

This study aims to identify the benefits of IC technology for HMA QC/QA and the current trends in applying this technology in various state DOTs. The possibility of adding IC technology into the INDOT specification 401 should be explored. In addition, this study reviewed the IC demonstration in September 2009 on US 52 in West Lafayette, Indiana.

1.3 Study Work Scope

The scope of this study was mainly to conduct a synthesis of current IC practices through a survey and phone interviews. First, a literature review was necessary to explore the importance of IC technology in QC/QA. A Survey and interviews with state DOTs were performed to understand the use of IC technology for QC/QA.

TASK-1: Preliminary literature review of IC technology

This study reviewed the history of IC technology, the meaning of intelligent compaction measurement value (ICMV), the current results of IC technology projects related to QA in HMA, and the relationships between ICMV and stiffness.

This innovative technology has been studied for over 30 years. With the active cooperation of the Federal Highway Administration (FHWA), a series of research projects were conducted across the U.S. FHWA and the Transportation Pooled Fund Program (TPF) conducted IC project (Chang et al., 2011b) with 12 states, including INDOT in 2009, to develop an IC technology specification and to evaluate current IC equipment. Recently, in terms of QA in HMA, a new project entitled "Intelligent Compaction: QA for In-Place Density Acceptance" has been in progress. Four states have finished the demonstration and published their results (Chang et al., 2012a, 2012b, 2013a, 2013b). Data from these reports was compared as part of the literature review.

TASK-2: Survey and interviews of state DOTs and vendors

The survey questionnaire was provided to ASHTO member states across the country to obtain information on the current state of the practice in IC technology application. The survey identified the methods and standard specifications of QC/QA used by other state DOTs. The leading state DOTs (Group1) were selected for phone interviews to explore their procedures in determining QA using IC technology. Group2 for the phone interview was added to obtain more information from the participants in the field demonstration projects conducted between 2012 and 2014. The survey and phone interview questions were designed under the guidance of the Study Advisory Committee (SAC).

TASK-3: Review the data from IC demonstration in 2009

The FHWA research project (Chang et al., 2011b) included a demonstration of IC technology on US 52 in West Lafayette between 2009 and 2010. Two types of IC vendor equipment (provided by SKAI and Bomag) were used along with non-nuclear gauge (NNG) density, Falling Weight Deflectometer (FWD), and core sampling tests for density. This study re-evaluated the relationship between ICMV and NNG, and the relationship between ICMV and core density. Additionally, this research performed the optimal pass count and the compaction coverage analysis for QC by using the demonstration projects data on US 52.

1.4 Report Organization

This report is divided into seven chapters. Chapter 1 presents the research background and problem statements of IC technology application in QC/QA and subsequently explains the research needs as well as the work scope and objectives. An extensive literature review is presented in Chapter 2 covering the background of IC technology, the meaning of ICMV, and the current trend of the application of IC technology. A comparison of correlation results from four demonstration projects was conducted and is also presented in this chapter. Chapter 3 describes the data collection from the survey and the result of the survey. To obtain a deeper understanding of the application of IC technology, a phone interview was performed and the results are illustrated in Chapter 4. Chapter 5 illustrates the analyses on the data obtained from the demonstration on US 52 in West Lafayette, Indiana. Chapter 6 presents an overall summary and conclusions for the survey, interviews, and the review of the demonstration data. Also recommendations and limitations are covered in Chapter 6. The survey questions and results are illustrated in Appendix A. The interview questions and results for the IC technology and the GPS only application are illustrated in Appendices B and C, respectively.

2. LITERATURE REVIEW

2.1 Introduction

Intelligent compaction (IC) technology has been studied in several fields and for several purposes since Heinz Thurner's pioneer work in 1974. The concept of IC technology developed in Europe has been utilized in the U.S. since the 1990s (Thurner & Sandström, 2000). The first application of IC technology was used for soil compaction; and thereafter the Federal Highway Administration and the Transportation Pooled Fund Program (FHWA/TPF) IC project (Chang et al., 2011b) was conducted in 12 states to develop IC technology specifications and to evaluate currently available IC equipment in soil and Hot Mix Asphalt (HMA). As the application of IC technology in quality control (QC) has increased, projects related to the application of IC technology in quality assurance (QA) have progressed. This study compares and analyzes the current trends in IC technology and the outcomes of the demonstration implemented across the country. Since the primary objective of this study was to synthesize all the levels of knowledge of IC technology, this literature review extensively focuses on (i) introducing IC technology; (ii) determining the current trends of IC application; and (iii) investigating the relationship between intelligent compaction measurement value (ICMV) and stiffness.

2.2 Introduction of IC Technology

"IC technology" provides the following information: (1) the precise location being paved using Global Positioning System (GPS); (2) the framework of the vibratory roller with an auto-feedback system; (3) compaction response data including the speed, number of passes, frequency, temperature, and amplitude from the material being compacted; and (4) ICMV utilizing compaction meters or accelerometer (Chang et al., 2011b).

IC technology equipment has the following three important devices included in an on-board computer display: (1) GPS provides the precise location of the roller and speed and tracks the roller passes; (2) an infrared temperature sensor monitors the pavement surface temperature; and (3) an accelerometer measures the compaction effort, frequency, and response from the materials being compacted. As shown in Figure 2.1, there are several different IC roller manufacturers; and their auto-feedback systems, integrated on-board documentation systems, and compaction response values vary by models.

2.2.1 Integrated On-Board Documentation System

"An integrated" on-board documentation system shows real-time color-coded maps of ICMV, the location of the roller, and the compaction response data, as shown in Figure 2.2. Since compaction operations are generally conducted at night, an integrated on-board documentation system helps the IC operator to identify the location of the roller and the condition of compaction.

The data from the display software can be stored in a computer system to implement data analysis via Veda. Veda (pronounced as "Vehda"—means "knowledge") is a software for compaction analysis (Chang et al., 2011b). Various intelligent compaction machines have their own documentation system and display software. Veda can now import data from the machines and perform standardized data

Figure 2.1 IC rollers (Chang et al., 2011b).

processing (Chang, Xu, Dick, & Rutledge, 2011a). Table 2.1 explains the different systems for integrated on-board documentation. Compaction response data (location, speed, ICMV, frequency, amplitude, direction, etc.) are identified through integrated on-board documentation systems. ICMV for Ammann/Case is stiffness or ground bearing capacity (K_b) and the display software is ACE-Plus®. Bomag has developed an ICMV called a Vibration Modulus (E_{vib}) with BCM05®, and an automatic feedback control system. Caterpillar's ICMV is the Compaction Meter Value (CMV) and Machine Drive Power (MDP). Especially, the IC roller provided by Caterpillar has wireless system. SAKAI applied a compaction control value (CCV) and uses the software named "AithonMT" measuring, displaying and recording their compaction information. HAMM/Wirtgen makes use of Compaction Meter Value (CMV) as an ICMV. HAMM Compaction Quality (HCQ®) is the software that HAMM uses. HCQ also has wireless and the option of a split screen-view. For example, the temperature screen and the pass count screen can be shown at the same time.

2.2.2 Global Positioning System (GPS)

The most important factors for compaction operations are uniformity and consistency of the compaction. If the degree of compaction and load-bearing capacity can be measured in real time, the compaction operation can be easily controlled; and GPS makes that measurement possible. By tracking the position being paved, GPS identifies the status of the compaction. FHWA recommends the Real-time Kinematic (RTK) GPS, which supplies GPS position accuracy to within 0.5 in. A separate base station is required that is located within approximately five miles of the mobile GPS units (Chang et al., 2011b). The GPS base station contains a single ground-based system including the GPS receiver, GPS antenna, radio, and radio antenna. The fundamental concept of RTK GPS is to reduce errors using the GPS base station. Correction data from the base station is converted to the rover station in real time as illustrated in Figure 2.3. GPS manufacturers including Trimble, TopCon, and Leica participated in the IC demonstration projects in 2009. The specific details for setting the GPS are well described in the FHWA specification (FHWA, 2014).

Figure 2.2 Integrated on-board documentation system (HAMM).

Virtual Reference Stations (VRS) is a GPS based on the RTK network. VRS is developed to improve accuracy of RTK system as little as a centimeter with operating over distances up to many tens of kilometers. The effective range of a VRS system is more than 40 miles without a GPS base station (Landau, Vollath, & Chen, 2002; Rizos & Han, 2003). The accuracy is similar to the conventional RTK at centimeter-level. As can be seen in Figure 2.4, the reference stations are connected to computer center (RTK network sever) and provide raw data to generate network-wide the models of distance-dependent error. Once the rover of IC roller sends the approximate location to the RTK network sever, RTK network sever models the errors that are caused by tropospheric refraction and the geometric location of the reference stations, and continuously sends data to the rover. However, a rover of IC roller must move within the area defined by the reference station network. VRS is needed to subscribe to an RTK network depending on the geographic location of the network.

On the other hand, satellite based augmentation system (SBAS) does not need a base station or reference stations. The Federal Aviation Administration established the Wide Area Augmentation system (WAAS) based on SBAS. Using several ground stations monitoring and gathering data on the GPS satellite, the satellite signal can be received. Therefore, possible navigation data is created and sent for broadcast via multiple satellites. However, WAAS provides low accuracy levels (39.4 to 394 in.) under clear-sky condition (Bolstad, Jenks, Berkin, Horne, & Reading, 2005). Also topographic characteristics significantly affect the accuracy level. High hills and wide forest cause the reduction of the accuracy by blocking the signal from the GPS satellites. The FHWA recommends RTK system rather than VRS or WAAS (Chang et al., 2011b).

Given that HMA compactor should equip GPS to identify compaction in HMA, there are two types of GPS compaction rollers: an IC roller and a conventional roller equipped (retrofitted) with a GPS unit. Table 2.2 shows the differences between the roller types. While the IC roller equipped with three important devices: GPS, Infrared thermometer, and accelerometer; the conventional GPS roller is only equipped with a GPS unit. Both roller operators can receive real-time compaction map through on-board documentation system. The GPS for IC roller is based on RTK GPS or VRS. RTK requires a base station and VRS requires several reference stations to get high accuracy level with error of below 0.5 in. The conventional GPS roller is a station-free SBAS. It does not need either a base station or reference stations, but the position errors range from 39.4 in to 394 in.

2.2.3 Infrared Temperature Sensor

An infrared temperature sensor provides the pavement surface temperature. A series of papers based on laboratory experiments have proven that insufficient compaction with inconsistent air voids in the pavement lead to a decrease in pavement life (Willoughby, Mahoney, Pierce, Uhlmeyer, & Anderson, 2002). Temperature affects the achievable density which is related to the air voids in the pavement. The appropriate temperature for compaction for HMA is 225 °F when the mixture is in the viscoelastic state in which the compaction reaches consistency and a uniform outcome. According to the results of a research in Washington State, more than 50% of Washington State DOT paving projects had temperature differentials around 25 °F, which caused density variations in the compacted mat. As a result, the insufficient compaction outcome from the temperature differentials showed that maintenance and rehabilitation are necessary earlier than the designed life (Willoughby et al., 2002). From a recent study, it was observed that the relationship between temperature and ICMVs is significant (Mooney et al., 2010). Therefore, mounting the infrared temperature sensor helps to avoid the problems caused by temperature differentials since temperature affects ICMV. Furthermore, measuring the temperature in real time determines the efficiency of the compaction practice. Figure 2.5 shows the temperature sensor of the IC roller.

2.2.4 Accelerometer

An accelerometer monitors the compression applied to the pavement to determine the compaction effort, the frequency of the packing, and the response from the pavement compacted. The readings from the accelerometer estimate the effectiveness of the compaction operation. As the material is compacted by the vibrating IC rollers, the acceleration is calculated and presented as a compaction response value. Compaction response values differ depending on vendors. ICMV is the name utilized for several different compaction response values by the manufacturers. ICMV is also known to be related to the stiffness of the materials being compacted. IC roller manufacturers currently instrument only one side of the roller drum in an edge-mounted (EM) configuration for the calculation of the ICMV.

2.2.5 Intelligent Compaction Measurement Value (ICMV)

The fundamental concept of ICMV starts from a hypothesis that the properties of asphalt pavement under

TABLE 2.1
Integrated on-board documentation systems

Feature	Ammann/Case	Bomag	Caterpillar	SAKAI	Dynapac	HAMM/Wirtgen
ICMV type	K_b (MN/m)	E_{vib} (MPa)	MDPCMV	CCV	CMV	CMV
Display software	ACE-Plus®	BCM05®	AccuGrade®	AithonMT®	DCA®	HCQ®
Documentation system	NA	BCM 05 office and mobile	AccuGrade®	AithonMT®	DCA®	HCQ®
Automatic feedback control	NA	YES	NA	NA	NA	NA
Output documentation	Date/time, location, direction, vibration, stiffness (K_s), amplitude (actual), speed, frequency	Date/time, location, EVIB, frequency, amplitude (actual), speed, jump	Date/time, location, speed, CCV, CMV, ICMV, frequency, amplitude, direction, vibration (on/off)	Date/time, location, CCV, temperature, frequency, direction, vibration, (on/off) GPS, quality	Location, direction, CMV, bouncing, frequency, speed, amplitude	Date/time, location, density, estimator, temperature, passes, frequency, speed, amplitude

Where, K_b: Stiffness or ground bearing capacity,
E_{vib}: Vibration modulus,
CMV: Compaction Meter Value,
CCV: Compaction Control Value,
MDP: Machine Drive Power.

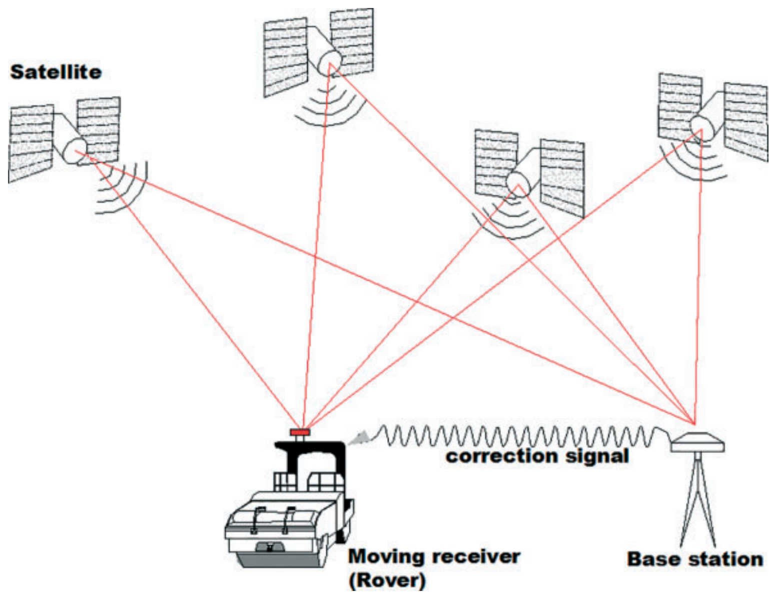


Figure 2.3 Real-Time Kinematic (RTK) GPS system.

the compaction operation will be correlated to changes in stiffness in asphalt mat (Swanson & Randolph, 2000). The mechanical and analytical model of HMA pavement is shown in Figure 2.6.

The basic concept for ICMV is the derivative of the displacement. The relationship between displacement and acceleration is as follows:

$$acceleration = a = -\omega^2 A \tag{2.1}$$

$$acceleration = a = -A(2\pi f)^2 \tag{2.2}$$

where, a: acceleration,

A: amplitude,

ω: circular frequency (rad/s),

f: frequency.

Therefore, acceleration is the function of deflection (amplitude) and frequency. When the mechanical model (see Figure 2.6) is considered, the mass refers to the weight of the rollers as a constant. The damping, R_v, can be ignored because the roller provides a significantly low frequency. Therefore the stiffness, K_v, remains constant. If the stiffness (K_v) and damping (R_v) in the machine are negligible, the stiffness (K_p) and damping (R_p) in the pavement affect acceleration (a(t)). When low frequency vibration is applied,

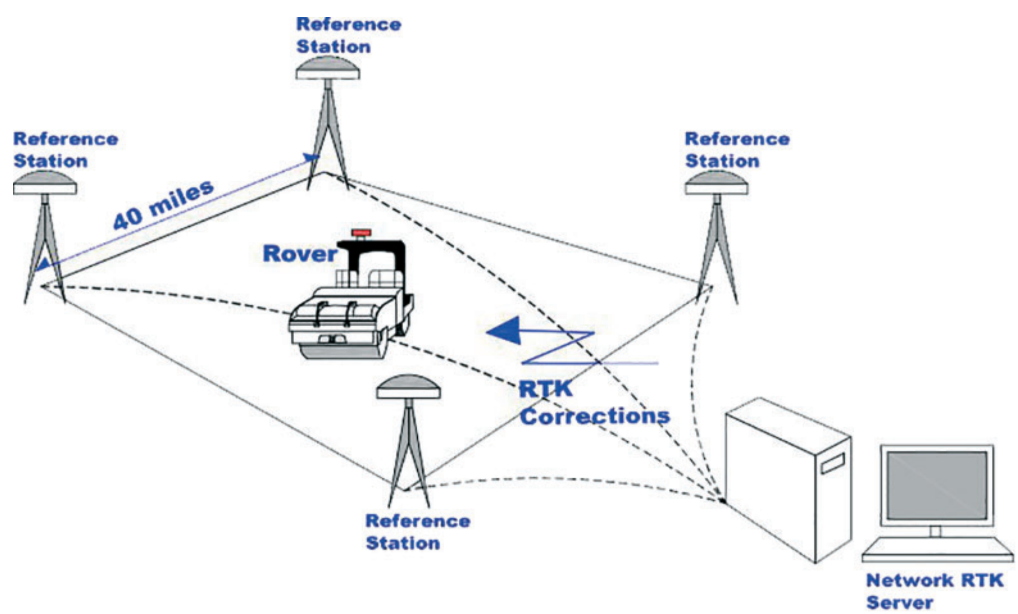
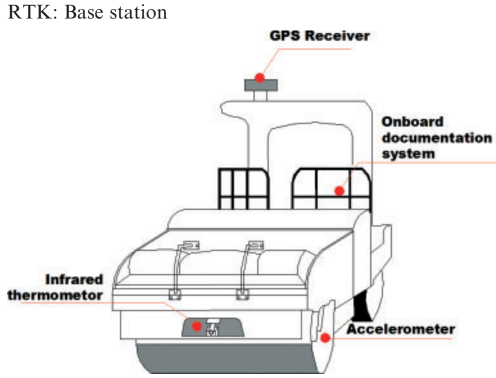
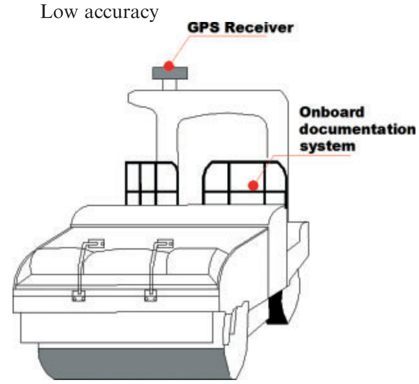


Figure 2.4 Virtual Reference Stations (VRS) GPS system.

TABLE 2.2
Differences between the roller types

Feature	IC roller	Conventional roller retrofitted with GPS unit
Attribute	A variety of measurements for compaction are available to improve the coverage and the uniform compaction (ICMV, mapping, temperature, optimal pass count)	HMA compaction roller provides pass count mapping for asphalt compactors; it is easy to use as it can be operated without a GPS base station (mapping, pass count)
GPS type	VRS RTK	SBAS
Manufacturer	IC manufacture: Ammann/Case, Bomag, Caterpillar, SAKAI, Dynapac, HAMM GPS manufacture: Trimble, TopCon, Leica	GPS manufacture: Trimble
Effective range	RTK: 3 miles in radius VRS: 50 ~ 70 miles in radius	Affected by sky condition Affected by topographic characteristics
Accuracy	Position errors below 0.5 in.	Position errors between 39.4 in and 394 in.
Disadvantage	RTK: Base station	No accelerometer (No ICMV) Low accuracy
Figure		

the stiffness (K_p) serves as a physical factor that directly has an impact on acceleration (a(t)). The damping (R_p) in the pavement is negligible under the frequency domain condition. As a result, the roller mass (M) and stiffness (K_v) are constant, and R_v and R_p are negligible. Thus, acceleration a(t) is proportional to stiffness K_p of the HMA being compacted (Minchin & Thomas, 2003; Minchin, Thomas, & Swanson, 2001; Swanson & Randolph, 2000).

$$acceleration, a(t) \equiv stiffness, K_p \equiv density \tag{2.3}$$

As pavement become dense, the air voids decrease, which leads to higher density and greater stiffness in asphalt mat. As the acceleration of the compaction increases, the density of the pavement increases. This simple theory can be applied to the relationship between ICMV (acceleration parameter) and density.

Figure 2.5 Infrared temperature sensor. (Source: http://www.intelligentcompaction.com/)

Compaction Meter Value (CMV). CMV is one of the ICMVs used by Caterpillar, Dynapac, and HAMM. The accelerometer mounted on the IC roller obtains the information of the complicated waveform shown in Figure 2.7.

The Fast Fourier Transform (FFT) is an algorithm that converts time to frequency (Thurner & Sandström, 2000). As can be seen from Figure 2.7, the waveforms of the vibratory roller are not simple sinusoidal waves. In order to characterize the waveforms, they are transformed to the combination of frequencies by converting time domain into frequency domain through FFT (e.g., fundamental frequency (Ω), second harmonic frequency (2Ω)). In the Fourier series, the fundamental frequency is defined as the lowest sinusoidal waveform and the harmonic frequency is defined as an integral multiple of the fundamental frequency.

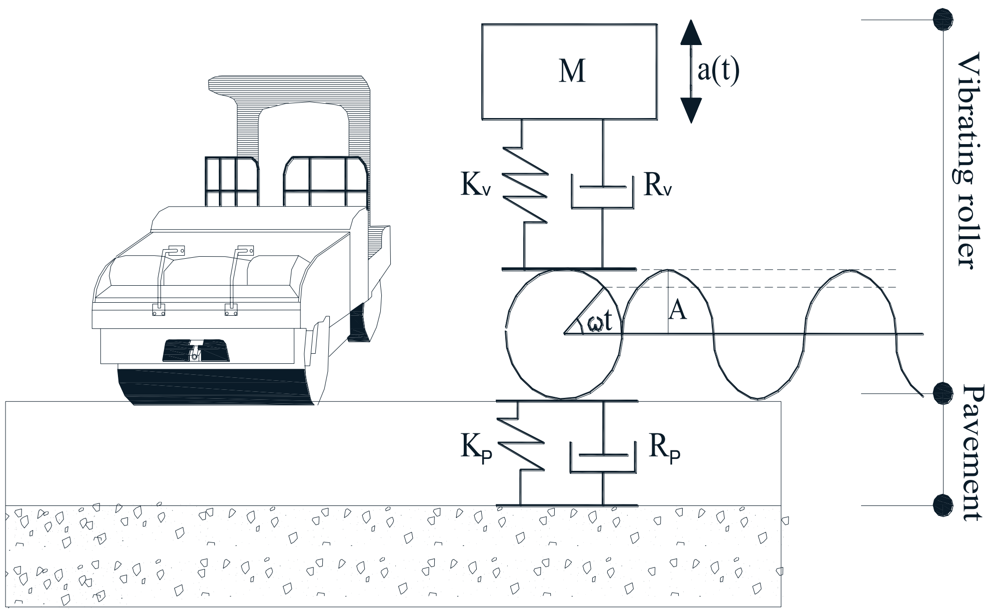


Figure 2.6 Mechanical and analytical model for the pavement. (where, a(t): acceleration, M: roller mass, K_v: spring stiffness of vibrating roller, R_v: damping of vibrating roller, A: amplitude, ω: circular frequency, t: time, K_p: spring stiffness of pavement, R_p: damping of pavement).

Each frequency component shows the associated acceleration amplitudes including A_Ω and $A_{2\Omega}$. Therefore, CMV is a mechanical value of the amplitude based on the FFT with fundamental frequency and harmonic frequency. In addition, several studies refer CMV as the primary stiffness (Mooney & Adam, 2007; Mooney, Gorman, & Tawfik, 2003; Thurner & Sandström, 2000). CMV can be calculated using the following equation:

$$CMV = C\frac{A_{2\Omega}}{A_\Omega} = 300 \times \frac{A_{2\Omega}}{A_\Omega} \tag{2.4}$$

where, A_Ω: Acceleration amplitude at the fundamental frequency,
$A_{2\Omega}$: Acceleration amplitude at the second harmonic.

In this case, the constant (300) has been chosen to give a full scale reading of 100.

The compaction operation varies across the contact area and contact pressure, which leads to a nonlinear roller-soil system (Anderegg & Kaufmann, 2007). Since the compaction response is not sinusoidal, Fourier analysis is applied to the compaction waveform (Mooney & Adam, 2007; Mooney & Rinehart, 2009). The acceleration amplitude and frequency from the IC roller have been found to affect the relationship between CMV and soil density and stiffness based on empirical research. As seen in Figure 2.8, the vibration condition in soil can correspond with the different harmonic wave spectra according to the components of the soil (Chang et al., 2011b).

Compaction Control Values (CCV). SAKAI developed CCV, which is applied to sub-harmonic frequency (0.5_Ω) and

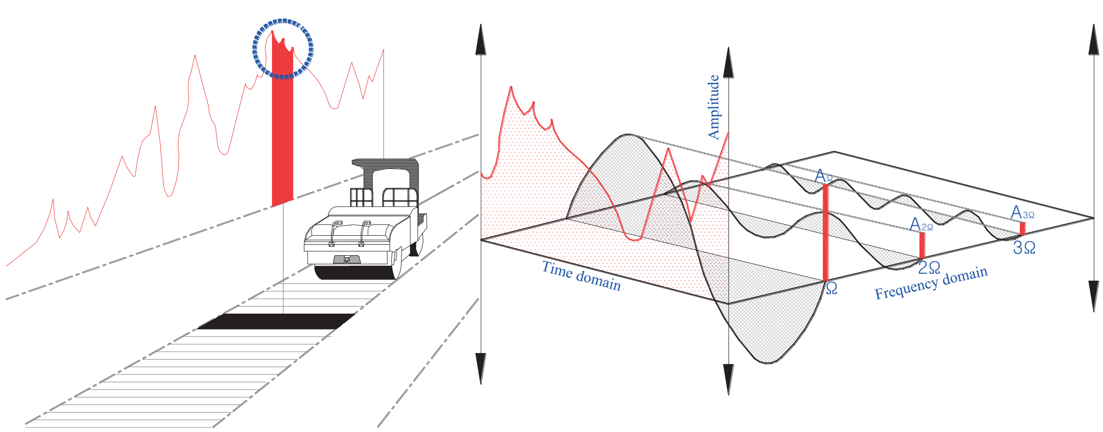


Figure 2.7 Compactor principle for compaction meter (Texas Instruments, 1980; Thurner & Sandström, 2000).

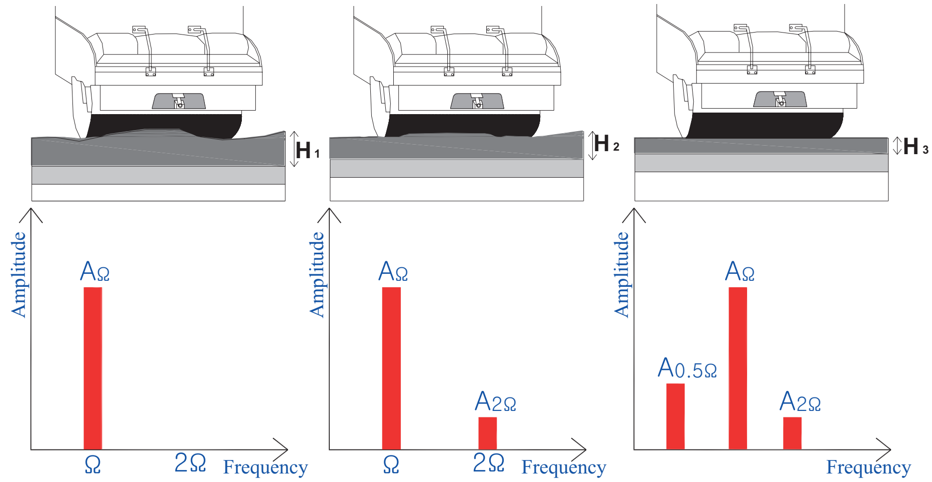


Figure 2.8 Harmonic wave spectrum (Chang et al., 2011b).

higher-order harmonics compared to CMV. As CCV contains various jumping modes (see Figure 2.9) which the roller drum enters, SAKAI reflects several vibration states including amplidues at various frequencies (i.e., 0.5_{Ω}, 1.5_{Ω}, 2.5_{Ω}, 3_{Ω}). CCV can be calculated using the following equation (Chang et al., 2011b; Willoughby et al., 2002):

$$CCV = \frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}} \times 100 \quad (2.5)$$

where, A_{Ω}: Acceleration amplitude at the fundamental frequency,
$A_{0.5\Omega}$: Acceleration amplitude at the sub-harmonic frequency,
$A_{0.5\Omega}$, $A_{1.5\Omega}$, $A_{2\Omega}$, $A_{2.5\Omega}$, $A_{3\Omega}$: Acceleration amplitude at the higher-order harmonics.

Vibration Modulus (E_{vib}). Bomag developed vibration modulus (E_{vib}) as a soil-compaction system. E_{vib} is based on a homogeneous and isotropic elastic half-space as shown in Figure 2.10. This principal is explained by a rigid and static cylinder through Lundberg's theory (Mooney & Adam, 2007). As seen from the monograph in Figure 2.10, when the certain force is applied, an increase in displacement leads to a decrease in stiffness (vibration modulus E_{vib}).

The displacement of Z_d equation is as follows:

$$Z_d = \frac{(1-\eta^2)}{E_{vib}}\frac{F_S}{L}\frac{2}{\pi}\left(1.8864 + \ln\frac{L}{B}\right) \quad (2.6)$$

$$B = \sqrt{\frac{16}{\pi}\frac{R(1-\eta^2)}{E_{vib}}\frac{F_s}{L}}$$

where, η: Poisson's ratio of the material,
L: length of the drum,
B: contact width of the drum,
R: radius of the drum,
E: Young's modulus,
F_s: Force (Static solution),
E_{vib}: Vibration Modulus (Bomag's ICMV).

Aside from those ICMV equations above, there are various model definitions. Table 2.3 indicates the ICMVs depending on the IC roller vendors. Caterpillar, Dynapac, and HAMM use CMV measuring frequency which is the accelerometer-based stiffness. Caterpillar also utilizes Machine Drive Power (MDP) measuring rolling resistance which is energy-based stiffness. Roller Integrated Stiffness (K_b) refers to the compacted layer's stiffness which is introduced by Ammann/-

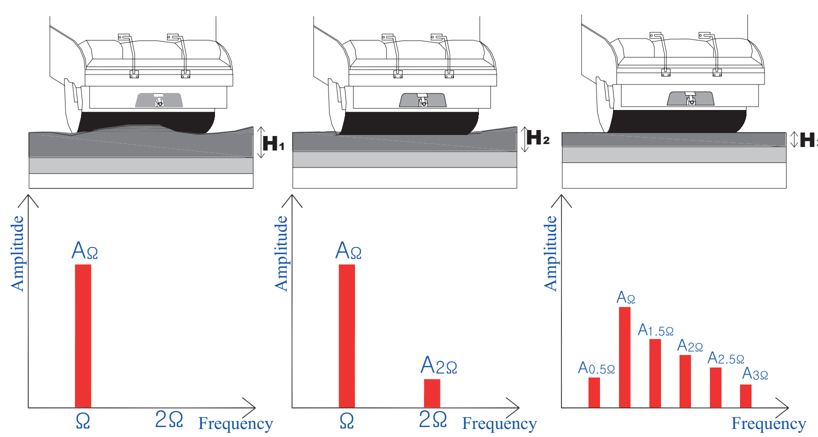


Figure 2.9 Changes in amplitude spectrum with increasing ground stiffness (Chang et al., 2011b).

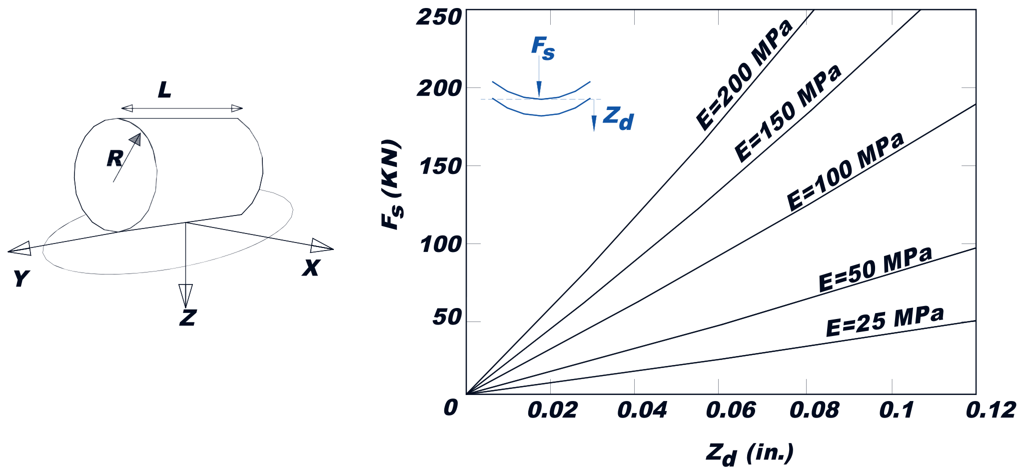


Figure 2.10 Relationship between contact force and drum displacement per cylinder on elastic half-space theory (Mooney & Adam, 2007).

Case rollers. SAKAI introduced more complicated acceleration amplitudes at the various harmonic frequencies which reflect the various jumping modes in soil.

2.3 History of IC Technology

Heinz Thurner of the Swedish Road Administration started studying IC technology in 1974 by applying the notion of IC technology to soil compaction properties with a five-ton tractor-drawn Dynapac vibratory roller equipped with an accelerometer (Chang et al., 2011b; Xu, Chang, & Gallivan, 2012). The study explained that the relationship between the amplitude of the fundamental harmonic and that of the excitation frequency affected the stiffness of the soils (Mooney & Rinehart, 2009; Mooney et al., 2010).

Afterwards, Heinz Thurner established Geodynamik to develop the concept and introduced ICMV in 1975. In 1978, Geodynamik introduced the CMV for the first time. Most of vendors accepted the CMV in the 1980s. Shortly thereafter, individual manufacturers started developing their own compaction measurement values. Bomag introduced the Omega value and developed the measurement value E_{vib}, which indicates the soil dynamic modulus (Minchin & Thomas, 2003). Ammann developed the roller-integrated stiffness (K_b) measurement value. Adam and Kopf (2004) experimented with the different ICMVs' performance (Minchin & Thomas, 2003). As the soil is compacted, the condition of the soil is divided into three modes: continuous contact, partial uplift, and double jump. The ICMVs showed linear changes in the continuous contact mode. However, as the mode entered into the partial uplift and double jump modes, the ICMV became sensitive to increases of modulus soil (E-modulus) with nonlinear forms.

Scholars (Mooney & Adam, 2007; Mooney & Rinehart, 2007) investigated the various ICMVs that determine soil stiffness, which was strongly subjective to vibration amplitude. Moreover, understanding the underlying heterogeneity of soil properties is the challenging task to go forward in the development of ICMV. Field spot tests were conducted to identify the application of IC technology by determining the correlations to ICMVs. Several spot tests, including the lightweight deflectometer (LWD), dynamic cone penetrometer (DCP), sand cone (moisture and density), and static plate loading test (PLT) were performed. The final report of the FWHA project (Chang et al., 2011b) introduced several correlation studies (see Table 2.4) between field spot tests and ICMVs. Although the results varied across soil types, the studies showed good correlations between the ICMVs and the spot test results (see Table 2.4).

On the other hand, in 1998, David C. Swanson et al. applied for a patent entitled "Compacted material density measurement and compaction tracking system." This patent provided the fundamental concept for the current IC technology by introducing GPS and a way to measure the compaction density of HMA pavement. The primary contribution of their work to the development of IC

TABLE 2.3
Summary of ICMVs (Chang et al., 2011b)

IC Systems	IC Measurements	Units	Model Definition
Caterpillar, Dynapac HAMM	Compaction Meter Value (CMV)	Unitless	$CMV = C\frac{A_{2\Omega}}{A_{\Omega}} = 300 \times \frac{A_{2\Omega}}{A_{\Omega}}$
Caterpillar	Machine Drive Power (MDP)	Unitless	$MDP = P_g - W_v(sin\alpha + \frac{A'}{g}) - (mv + b)$
SAKAI	Compaction Control Values (CCV)	Unitless	$CCV = \frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}} X100$
Ammann/Case	Stiffness(K_b)	MN/m	$K_b = \omega^2\left[m_d + \frac{(m_o e_o \cos\phi)}{Z_d}\right]$
Bomag	Vibration Modulus(E_{vib})	MN/m	$Z_d = \frac{(1-\eta^2)}{E_{vib}}\frac{F_S}{L}\frac{2}{\pi}\left(1.8864 + ln\frac{L}{B}\right)$

TABLE 2.4
Field correlation studies (Chang et al., 2011b)

Reference	Roller ICMV	Soil type(s)	Point-test	Correlations
Brandl and Adam (1997)	BOMAG CMV		PLT	Regression in partial uplift $R^2 = 0.9$ double jump conditions $R^2 = 0.6$
White et al. (2006a, b)	Caterpillar MDP	Well-graded silty sand	NG DCP	R^2 value ranging from 0.5 to 0.9
White et al. (2007b)	Caterpillar MDP	Sandy lean clay	NG DCP	$R^2 = 0.87$ for density and MDP $R^2 = 0.96$ for DCP and MDP
White et al. (2008c); Vennapusa et al. (2009)	Caterpillar MDP	Crushed gravel base	DCP LWD	R^2 value ranging from 0.74 to 0.92
White et al. (2009b)	Caterpillar CMV	Poorly graded sand with silt to silty sand	LWD, PLTDCP	R^2 value ranging from 0.2 to 0.9
White et al. (2009b)	Caterpillar CMV	Granular subbase and select granular base	LWD, PLT, FWD, SSG	$R^2 > 0.5$ (for LWD, FWD, PLT, and SSG)

technology was the introduction of GPS and ICMV in HMA. The concept of ICMV originated from the compaction density meter, which is related to the acceleration from the IC rollers (Minchin & Thomas, 2003; Swanson & Randolph, 2000).

2.3.1 Trend of IC Technology in QC

The FHWA Transportation Pooled Fund released a strategic plan in 2007 called the (Chang et al., 2011b). To implement IC technology in the U.S., 12 states participated in this project and 15 demonstration projects were carried out. FHWA conducted the asphalt IC demonstration in September 2009 on US 52 in West Lafayette, Indiana.

TABLE 2.5
State of practice for use of IC for QC

Agencies with specification for asphalt and/or soil	Asphalt specification: Availability	Asphalt specification: QC or QA	Soil specification
FHWA	Y	QC	Y
AASHTO	Y		Y
Central Federal Land Highway Division	Y	QC	
Eastern Federal Land Highway Division	Y		
Alaska	Y	QC	
California	Y	QC	
Georgia	Y		Y
Indiana			Y
Iowa	Y	QC	Y
Michigan			
Minnesota	Y		Y
North Carolina	Y		Y
Pennsylvania	Y	QC	Y
Rhode Island	Y	QC	
Tennessee	Y	QC	
Texas			Y
Utah	Y	QC	
Vermont Agency of Transportation	Y	QC	
Total	**15**		**9**

Several state agencies released specifications for IC technology for HMA and soil. Table 2.5 shows the state of practice for the use of IC for QC. Fifteen agencies have the IC specification for QC in HMA, and nine agencies have the IC specification for QC in soil. Most of the states have followed the IC specification FHWA released; a few states have their own criteria. For example, Alaska, Vermont, and Pennsylvania have more detailed IC specifications. Indiana doesn't have an IC specification for HMA. However the application of IC technology is to a certain extent allowed in ITM No. 803-13P HMA Pavement Quality Control Plan (QCP). The application of IC technology has been mentioned in ITM No. 803-13P that IC technology may be used to measure the ICMV and temperature of the mixture instead of a non-destructive testing (INDOT, 2013).

The FHWA IC specification includes IC technology quality control plan (QCP). The IC QCP evaluates the coverage, uniformity, stiffness (ICMV), and test section during construction operations (FHWA, 2014; INDOT, 2013; Ketchikan-Airport Taxiway and Apron Rehabilitation, 2013). IC technology can provide the compaction uniformity and therefore would improve QC in HMA compaction. The IC QCP is summarized as follows:

1. *Mapping:* GPS mapping plays an important role in the QC of HMA compaction operation. It implements the function of data collection and displays the real time position. The roller width is divided into a series of divisions for mapping roller coverage. Post-processing and visualization of data can be performed by the Veda software.
2. *Temperature:* The contractor should provide the specific plan for the minimum mat temperature for the compaction operation. The compaction operation should be finished when a minimum of 240 °F is reached for the initial phase (breakdown) and 200 °F for the intermediate phase.
3. *Test section:* Test sections are necessary to identify the compaction curve of the HMA in conjunction with the number of roller passes and the stiffness of the mixture. Test sections are conducted every lift and consists of approximately

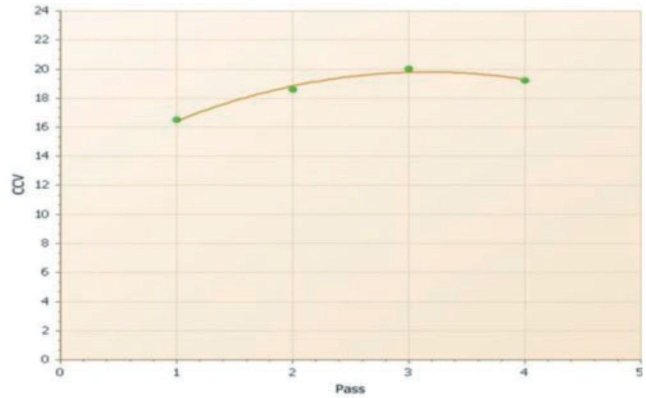


Figure 2.11 Compaction curve (by Veda).

300 tons of mainline mixture. During the initial phase, the IC roller needs to have low vibration amplitude and the same setting (speed and frequency). After each roller pass, a nondestructive device (NG test) should be performed to identify the density of the paved mixture at five locations uniformly spaced throughout the test section.

4. *Target optimal pass count and target ICMV:* These readings can be taken throughout the compaction curve. The target density should correspond with the reading of the nondestructive device. The target ICMV is the point when the deflection in an upward trend of the curve is less than 5% on the compaction curve between the passes. The IC curve is defined as the relationship between the ICMV and the roller passes. Figure 2.11 shows the example of compaction curve.
5. *Pre-mapping:* IC mapping of the overlay operation (the existing support material) is crucial to identify weak support areas for corrective actions prior to the compaction of the HMA. Pre-mapping can progress to increase the bearing capacity of the pavement structure by identifying the weak locations.

2.3.2 Trend of IC Technology in QA

Along with the growing interest in IC technology, a possibility that IC technology will address the issues of the current practice of QA density test has been raised. There is an ongoing FHWA project entitled "Intelligent Compaction: Quality Assurance for In-Place Density Acceptance." The purpose of the project is to evaluate the application of IC technology for QA in HMA compaction. Currently four states have finished the demonstration projects and published their own reports (Chang et al., 2012a, 2012b, 2013a, 2013b). This research compared the correlation results presented in these four reports to include: (1) the correlation between non-destructive density test data and core density test data; (2) the correlation between compaction response values and FWD/LWD; (3) the correlation between compaction response values and core density data; (4) the correlation between ICMV and non-destructive density test (final coverage); and (5) the correlation between ICMV and non-destructive density test (all passes data). These correlations are discussed in the following paragraphs.

The pavement thickness and compacting layer for each state (CA, OH, UT, and ME) are shown in Figure 2.12. California conducted IC demonstration on the 3 in. intermediate HMA layer on an ongoing project (Humer, 2012). Ohio and Maine conducted the demonstration on new pavement projects. IC demonstration was performed on a 1.75 in. intermediate course in Ohio and a 2 in. intermediate course in Maine (See Figure 2.12). Meanwhile, in Utah, IC demonstration was conducted on the 2.5 in. base course of an existing pavement. The existing layer was milled by 4 in. and a 2.5 in HMA base course and a 1.5 in. Stone Mastic Asphalt (SMA) course were paved.

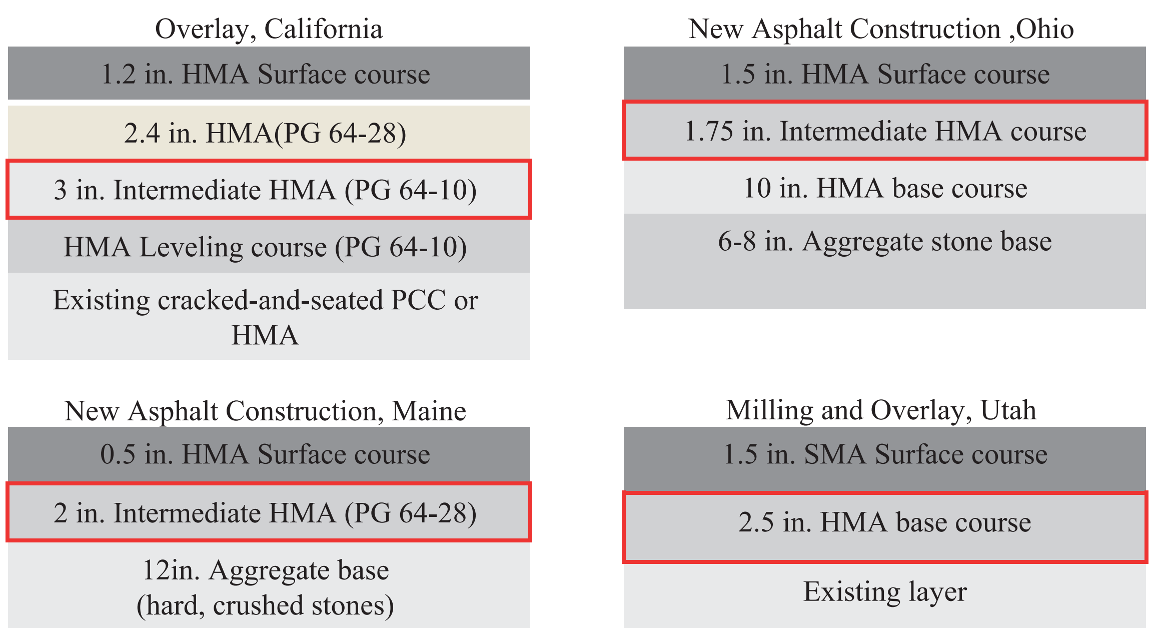


Figure 2.12 IC demonstration layers in the four selected projects in CA, OH, ME, and UT. (Note: The target layers are illustrated with a box around it.)

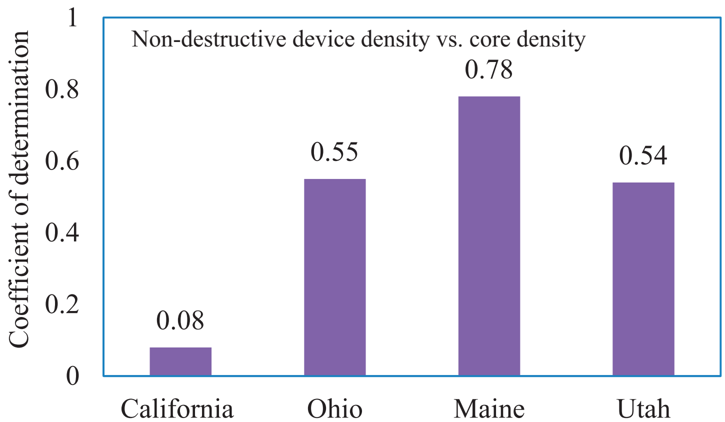


Figure 2.13 Coefficient of determination for the four IC demonstration projects.

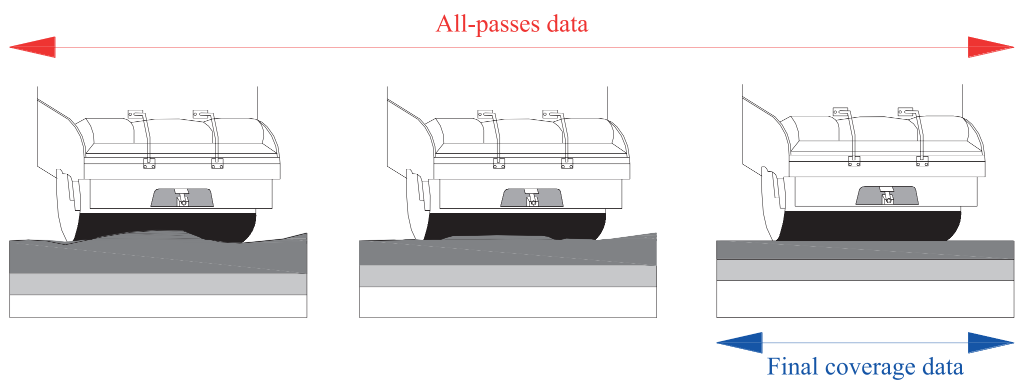


Figure 2.14 Final coverage and all-passes data.

The correlation between non-destructive density test data and core density test data. Based on available reports, this research team compared several correlations from the four demonstration projects. In general, a non-destructive density test is performed by contractor, while a core density test is conducted by the DOTs to evaluate the compaction operation. INDOT also applies core density test as one of the criteria for HMA compaction (INDOT, 2013). Figure 2.13 presents a relationship between non-destructive device density (nuclear gauge density (NG)) and core density data obtained from the four demonstration projects (Chang et al., 2012a, 2012b, 2013a, 2013b). The results show a low R^2 value of 0.08 in California, 0.55 in Ohio, 0.78 in Maine, and 0.54 in Utah. The highest R^2 value of 0.78 attributed to the pavement in Maine. Based on this comparison it is hard to conclude that NG test could effectively replace core density test.

The correlations between compaction response values and FWD/LWD, and core density data. The compaction response values include ICMV, frequency, amplitude, temperature, and pass counts obtained from the IC roller. There are two options for determining the correlation between the compaction response values and values from spot tests: final coverage and all-passes. Final coverage measures the compaction response values for the last pass count to estimate the end results of compaction. All-passes measures all the compaction response values from the first pass count to the last one (see Figure 2.14).

Figure 2.15 (a) illustrates comparison for the correlations between FWD or LWD and the compaction response values for the four demonstration projects. The graph in Figure 2.15 only contains the highest values among the compaction response data based on final coverage. Although the correlations with LWD are higher than FWD, all the R^2s do not show more than 0.5, which means that the compaction response values do not have correlation with the deflection from the FWD or the layer moduli from the LWD. The results of the correlations between core density and the compaction response data (see Figure 2.15 (b)) showed a similar pattern to the correlations in Figure 2.15 (a) by showing from 0.1 to 0.3 of R^2s. Therefore, it is unlikely that the compaction response values based on the final coverage data analysis have correlations between the results of the core density test and FWD/LWD test.

The correlations between NG density and ICMV. The other correlation between the NG density and ICMV is shown in Figure 2.16. The correlations between NG density and ICMV for the final coverage option were also in a lower

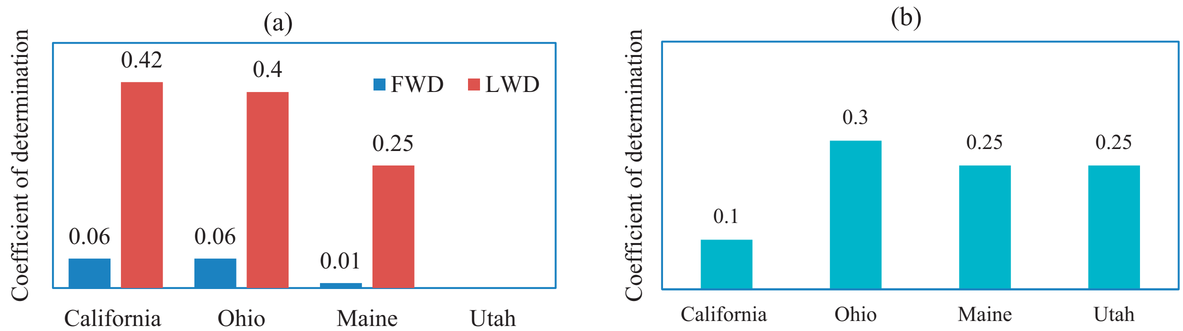


Figure 2.15 Correlations of final coverage data for the four IC demonstration projects: (a) FWD/LWD and compaction response values; (b) core density and compaction response values.

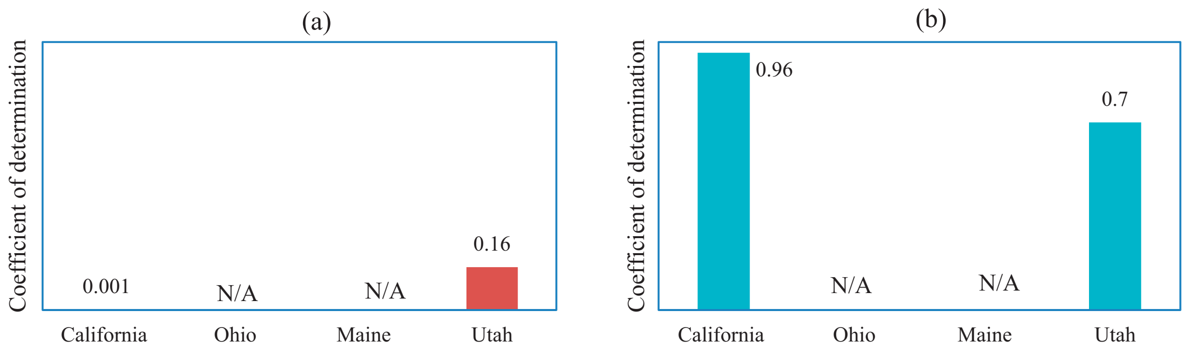


Figure 2.16 Correlations between NG density and ICMV data for the four demonstration projects: (a) final coverage; (b) all-passes data.

range, but the correlations for the all-passes count data showed a high R^2 of 0.95 in California and 0.7 in Utah. The coefficient of determination between NG density and ICMV for the all-passes was more than seven times as high as that of the final coverage. Therefore, it is obvious that the number of pass counts is considered as an important factor in determining the correlation.

3. SURVEY

3.1 Data Collection

The main purpose of the survey was to gather data from the state Department of Transportations (DOTs) and other transportation agencies about (1) the usage of IC technology in their state, (2) the benefits of applying IC technology, and (3) the application of IC to asphalt pavement construction quality control/quality assurance (QC/QA). The survey questionnaire was provided to AASHTO members throughout the country. A total of twenty six AASHTO members responded to this survey. The questions included in the survey are listed in Appendix A. All the questions were prepared to collect data to satisfy the study objectives and were reviewed by the Study Advisory Committee (SAC) members. It was then distributed to AASHTO members. There were 11 questions in the survey targeted to address the above survey objectives.

The questions were divided into two groups based on the response to the first question "Does your agency currently adopt IC technology?" As shown in Figure 3.1, Group 1 respondents answered that their agencies have adopted IC technology for QC and/or QA. Thereafter, they answered the next six in-depth questions about the application. The Group 2 indicates participants responded that they have not adopted IC technology, and this group was split into two sub-groups (Group2-1 and Group 2-2). Group 2-1 consisted of the states having plans to use IC technology in the future, while Group 2-2 were the states having no plans to use IC technology in the future.

3.2 Responses to Survey

As mentioned earlier, twenty six AASHTO members responded to the questionnaire through the web-based survey tool, SurveyMonkey®. Results indicate that only a few states have adopted IC technology to date. The questions in the survey are discussed in this chapter, and the entire survey results are shown in Appendix A.

3.2.1 Group 1: Application of IC Technology

The first question, as can be seen from Figure 3.2, addressed the application of IC technology. Two states (Alaska and Vermont) responded to have adopted IC technology for QC and/or QA, while the remaining 24 respondents (92%) have not used it. It should be noted that Pennsylvania acknowledged to have used IC for Hot Mix

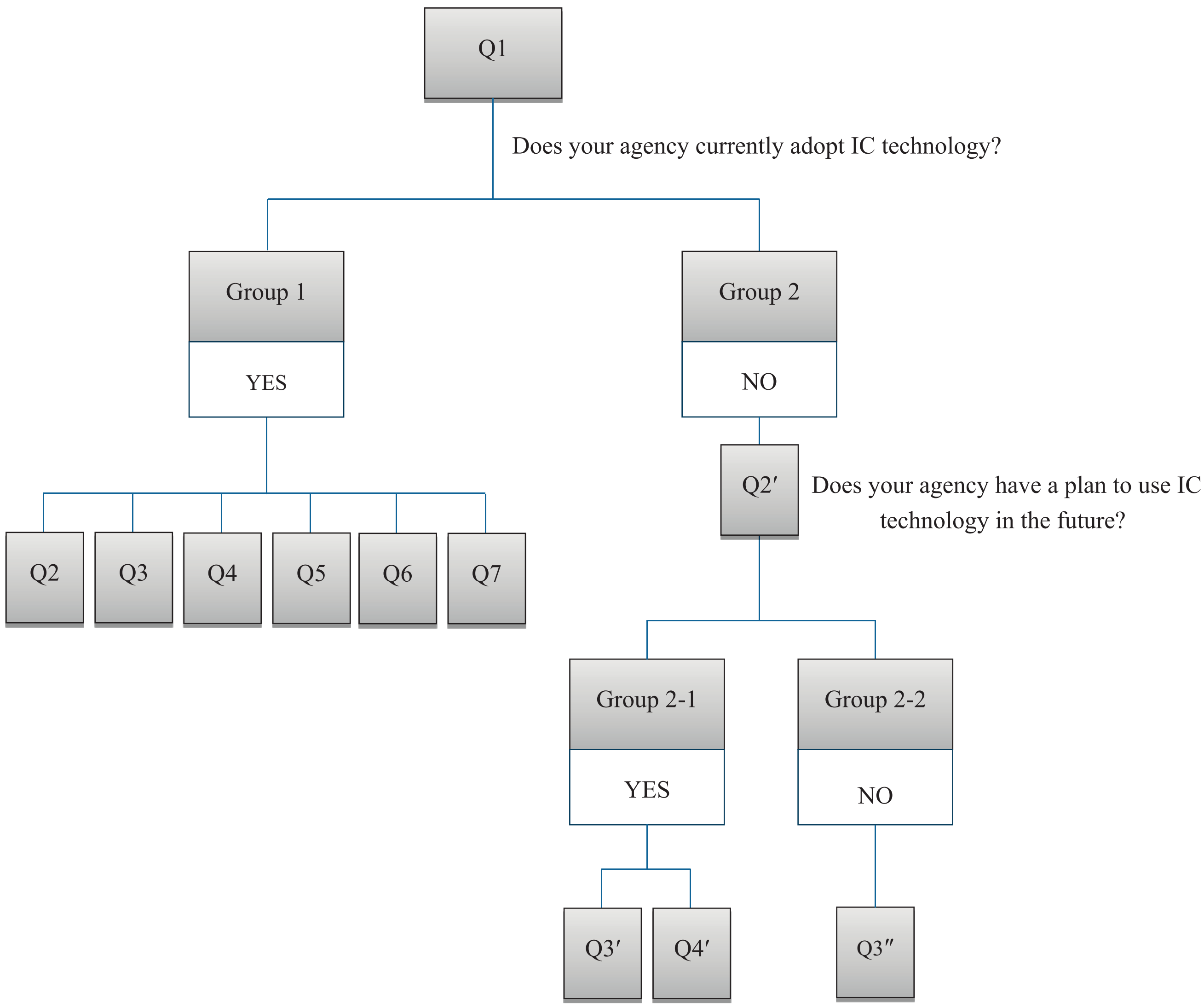


Figure 3.1 Survey plan.

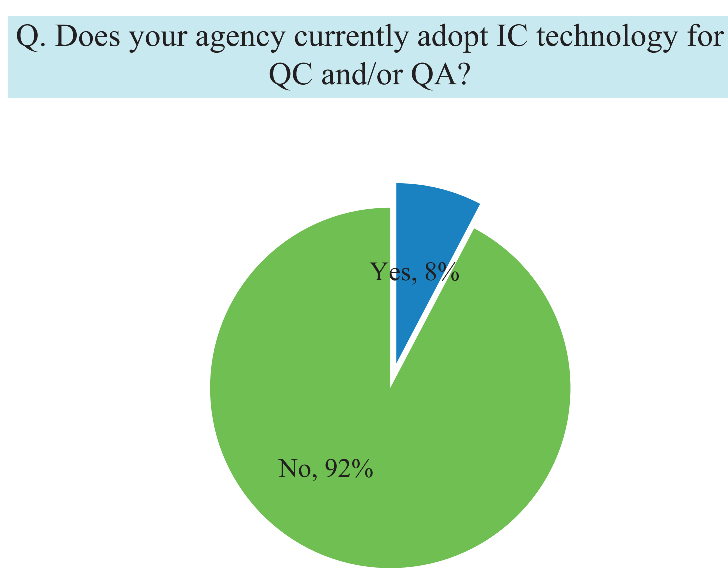


Figure 3.2 Current state of the application of IC technology (Group 1).

Asphalt (HMA) during the interview stage, making a total of three states (Alaska, Vermont and Pennsylvania) to have used IC technology for QC.

According to the comments, the reasons for not using IC technology differed from state to state. The most common reason was that the states are in the process of preparing their specification for IC technology and have future plans to perform demonstration projects (New Mexico, Oklahoma, Louisiana, and Utah). Additional comments from the respondents are shown in Appendix A.

The respondents were asked the benefits of IC technology (see Figure 3.3). They offered the following: enhanced productivity, better quality control process, real-time compaction measurement, uniform compaction, less pavement maintenance, and operations cost. Alaska DOT commented that one of the advantages of IC technology is nighttime paving in that it allows the operator to "see" where he has been.

The concept of intelligent compaction measurement value (ICMV) originates from soil compaction properties, and IC technology is commonly used for soil compaction in QC. This research team asked respondents to name the areas in which they were applying IC technology. Vermont uses IC technology not only for soil but also for HMA, while Alaska adopted it for HMA QC only. No one has used IC technology for QA as shown in Figure 3.4.

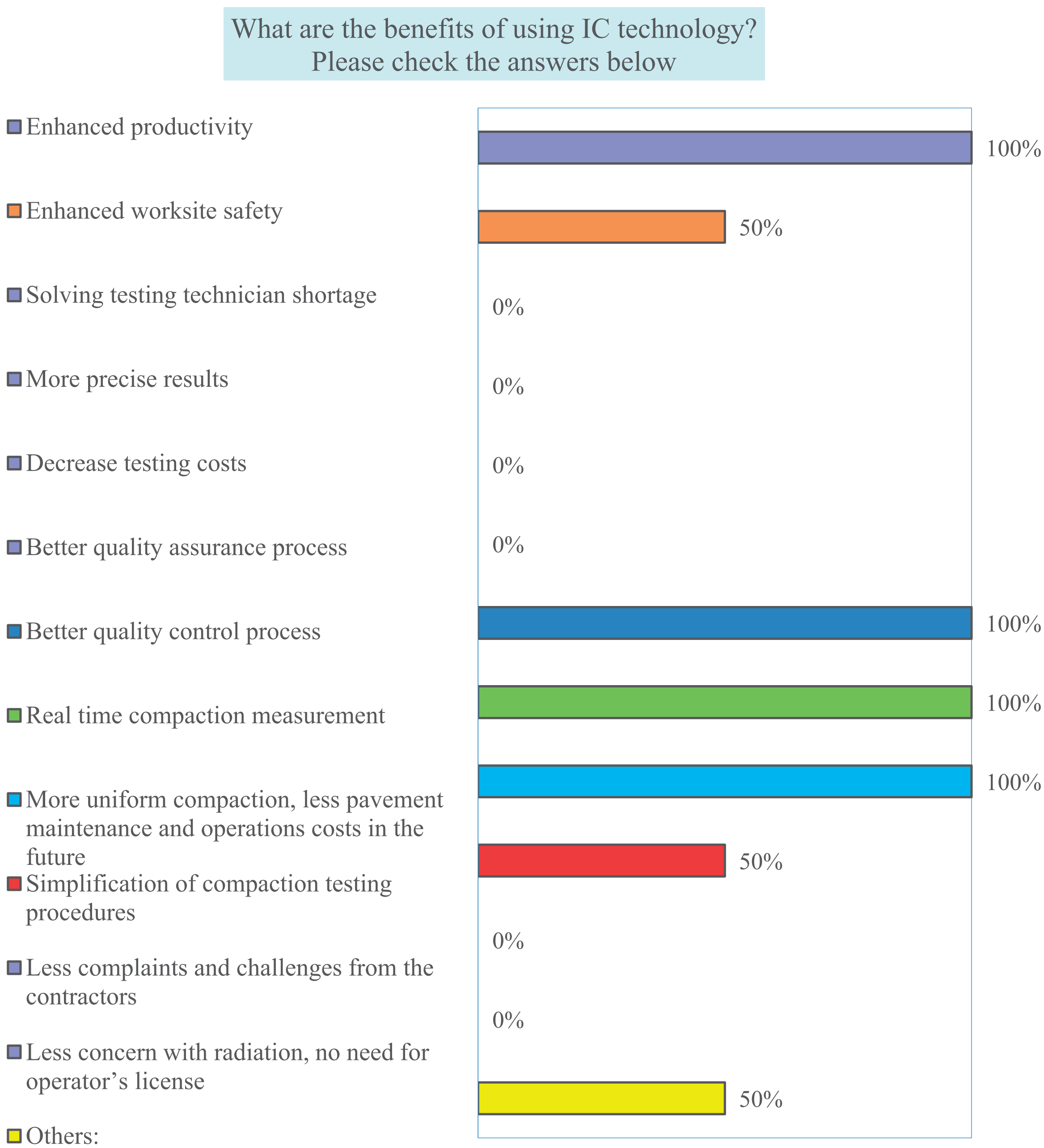


Figure 3.3 Benefits of IC technology.

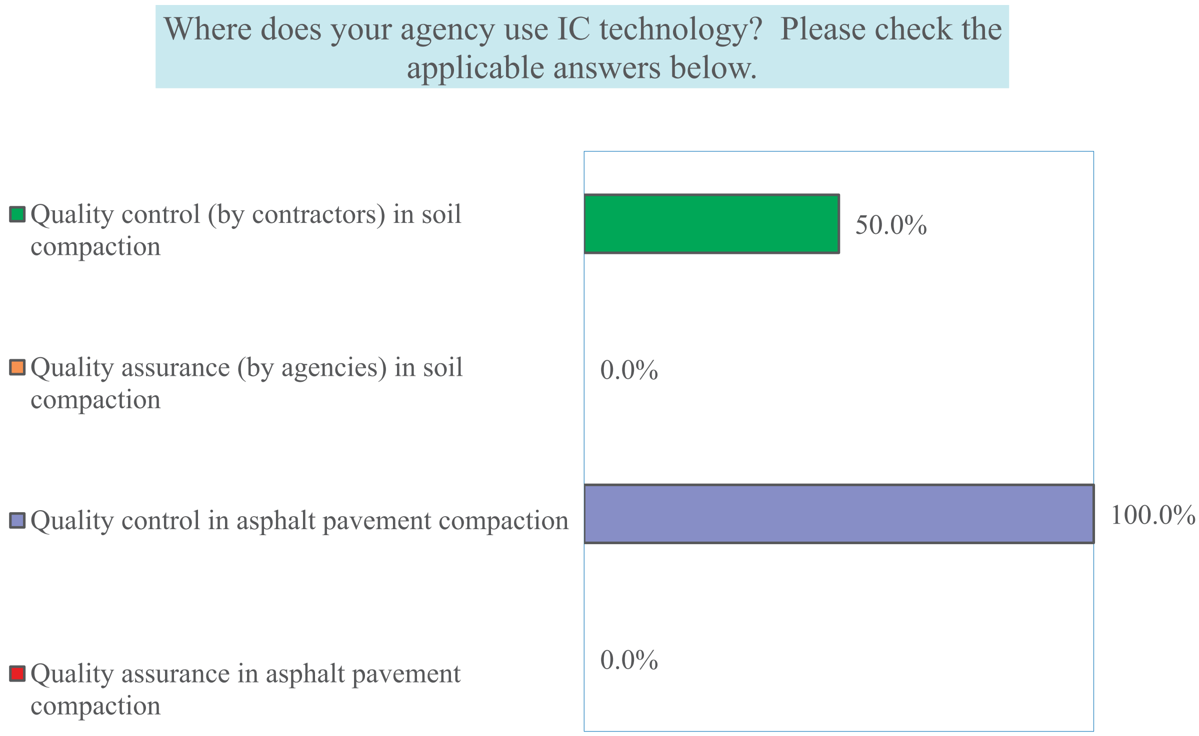


Figure 3.4 Application areas for IC technology.

3.2.2 Group 2: Application of IC Technology

Group 2 includes participants responded that they have not yet adopted IC technology (24 respondents). The next question for this group was "Does your agency plan to formally adopt IC technology in the future?" A total of 22 respondents (out of 24 in this group) answered this question. Respondents that answered "yes" were placed in a subgroup 2-1 (9 respondents), while the remaining 13 respondents were placed under subgroup 2-2 (Figure 3.5).

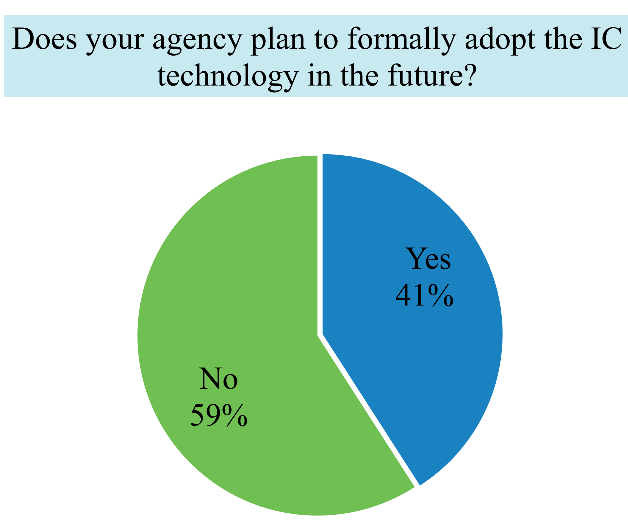


Figure 3.5 Application of IC technology (Group 2).

Figure 3.6 shows the reasons given by Group 2-2 (13 respondents) for not having a plan for IC technology in the future. The main reasons given by 7 respondents (53.8%) are as follows: (1) satisfaction with existing QC/QA procedure, (2) difficulty of adjustments due to the lack of an existing stiffness specification for compaction, and (3) lack of availability of IC equipment from contractors. In addition, six respondents (46.2%) expressed doubts about the accuracy of the results obtained with IC technology.

Respondents in Group 2-1 (9 respondents) who answered that they have a plan to formally adopt IC technology in the future are asked where they plan to apply IC technology (Figure 3.7). A total of 6 respondents (out of 9 in this group) answered that IC technology will be applied in QC in HMA compaction. The QC in soil compaction was next at 44.4% (4 respondents). Several additional comments are provided such as "still determining direction to take" and "not sure". Respondents indicated higher expectations in applying IC technology for HMA than for soil compaction.

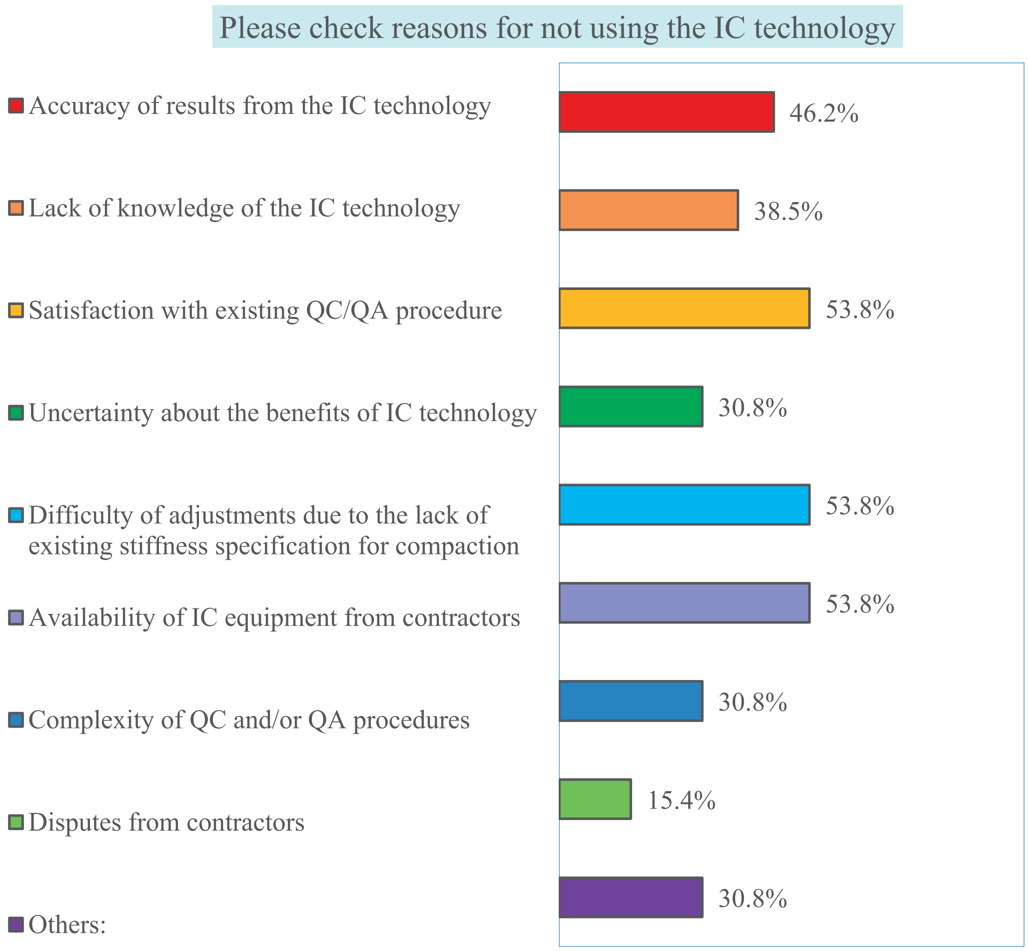


Figure 3.6 Reasons for not using IC technology.

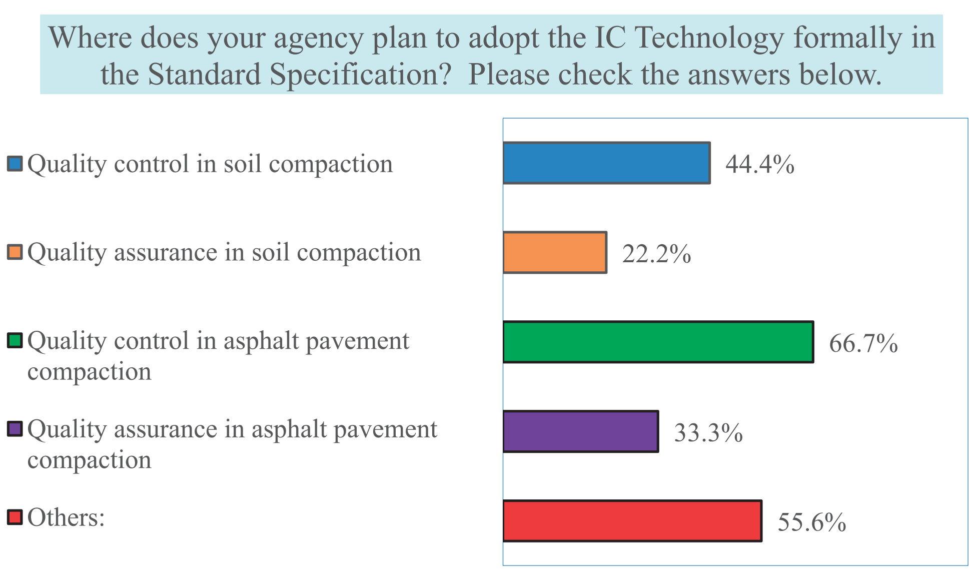


Figure 3.7 Expected application areas for IC technology.

4. TELEPHONE INTERVIEW

4.1 Data Collection for IC Technology

The main purpose of the telephone interviews is to obtain further data from the DOTs in order to understand IC technology in detail. As can be seen in Figure 4.1, the potential interviewees are classified into two groups. Twenty six AASHTO members answered the survey. Among them, the research team selected the leading state DOTs for phone interviews. Based on the first question in the survey, "Does your agency currently adopt IC technology?" Group A is divided into two sub groups. Group A-1 is composed of the DOTs who have adopted IC technology in HMA. Group A-2 refers to the DOTs who have not used IC technology. During the interview, Pennsylvania was added to Group A for a total of three states. All the questions were reviewed by the SAC members. The interviews were based on a set of 19 questions in four different groups as shown in Appendix B.

Meanwhile, the research team was finding it difficult to obtain interviews based on the result of the survey because only three states (Alaska, Vermont, and Pennsylvania) responded that they have adopted IC technology. The three states were an insufficient number to reflect the overall trend of IC technology applications. Therefore, this study decided to add Group B. Group B consists of participants in the field demonstration projects for the research project called "Intelligent Compaction: Quality Assurance for In-Place Density Acceptance," which was conducted between 2012 and 2014. Group B-1 interviewees were the agencies including Utah, Florida, and Maine. Group B-2 participants were the vendors who represented the IC roller manufacturers (HAMM, SAKAI, and Caterpillar). Therefore, eight state agencies and three IC roller vendors participated in this interview. The detailed interview plan and procedure are described in Appendix B.

4.2 Responses to Telephone Interview for IC Technology

The telephone interviews were conducted between June and July 2014 with four groups as mentioned above. The interviewees were mainly divided into two groups. Group A consists of five AASHTO members who responded to the survey. Group B refers to DOTs and IC vendors who participated in the IC demonstration projects between 2012 and 2014.

Table 4.1 shows the summary of the interview. More uniform compaction, less pavement maintenance and night time paving were considered the most benefit of IC technology. These answers were corresponded with the responses from the previous survey. Interestingly, when the survey was conducted, Group A-2 (New Jersey and

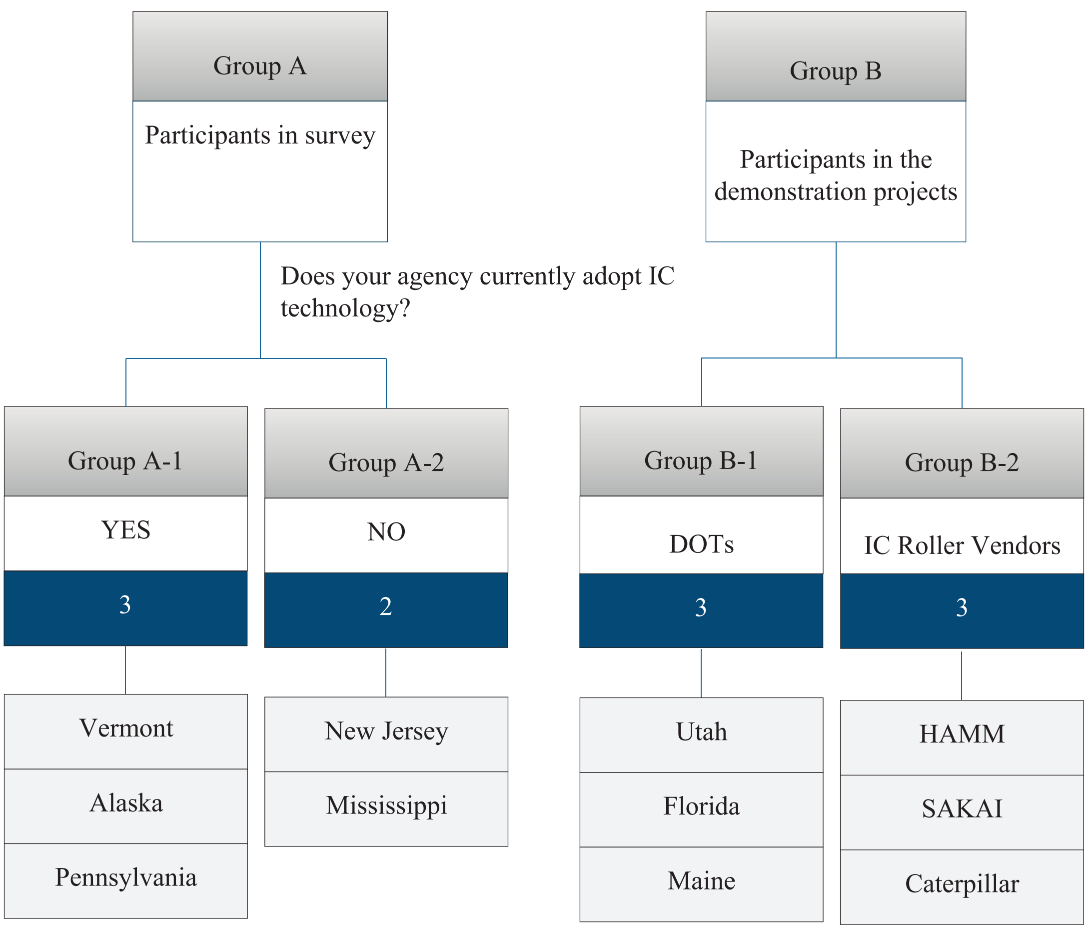


Figure 4.1 Interview plan.

TABLE 4.1
Summary of interview

Questions	Summary
1 The most benefit from IC technology	More uniform compaction, less pavement maintenance Night time paving
2 Whether or not Veda software is used in the implementation	Not yet (transferring the data to the Veda software)
3 IC technology is applied in only QC	Low correlation between in-place density and ICMV for QA No strong results to prove the case for substituting in-place density with the ICMVs
4 The number of contracts after adopting IC for QC	Vermont: two projects Pennsylvania: eight active projects with two pending authorization Utah: three projects
5 Cost-effectiveness (IC operation cost)	Vermont: 0.1% increase in total contract cost Pennsylvania: $20,000 ~ 50,000 (the IC compaction is a small portion of total construction cost) Alaska: $80,000 – two compactors at $4,000 – one compactor with small project Utah: The cost is more than normal compaction roller, but it is worth the money to obtain better quality of compaction operation Maine: The cost is not a problem (similar to Utah)
6 Improvements (concerns)	Not enough justification for QA (no information on density) Training issue (for equipment and data management including software) More demonstration projects are needed to implement IC No relationship between temperature and stiffness Pavement thickness is also issue for ICMV

Mississippi) clarified that they do not have any current plans to adopt IC technology, but they have started to consider it. They have prepared a couple of pilot projects for IC application. In terms of the consideration of the applicability of IC technology for QA in HMA compaction, the respondents mentioned that there are no noticeable results to prove the case for substituting in-place density with the ICMVs. Furthermore, not only the DOTs (Utah, Florida, and Maine) who participated in the field demonstration projects expressed some concerns about the relationship between in-place density and ICMV, but vendors (HAMM, SAKAI and Caterpillar) as well. Most of the states responded to this interview indicated that they found IC technology to be cost effective (Table 4.1). Although using IC rollers can add cost, it does not significantly affect the total cost for the construction project since the IC compaction is a small portion of total construction cost. The advantages of IC technology, including better quality control and uniform compaction, eventually lead to a cost-effective solution.

5. EVLAUTION OF IC DEMONSTRATION DATA FROM US 52

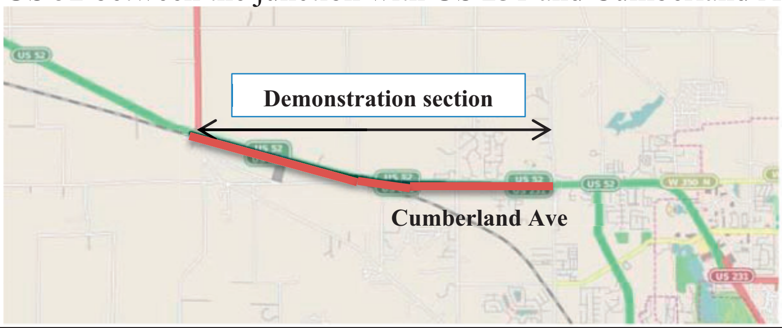
5.1 Data Collection

As mentioned earlier, the Federal Highway Administration (FHWA) conducted a research project (Chang et al., 2013b) to demonstrate IC on US 52 in West Lafayette between 2009 and 2010. Two types of IC vendor equipment (provided by SKAI and Bomag) were used along with non-nuclear gauge (NNG) density, falling weight deflectometer (FWD), and core sampling tests for density. The demonstration was completed and its report is available. However, the objectives of the report differ from that of this study. The report focused on establishing the IC specification and evaluating current IC equipment for QC. This research performed further analysis on additional data from the demonstration on US 52. Five types of data were collected; NNG, core density, temperature, pass count, and ICMV. This research obtained NNG and ICMV data from the Transtec Group, temperature and pass count data were obtained from the example on "Indiana" included in the "Veda" software, whereas core density data was obtained from INDOT. The main purposes of the analysis in this study are (1) to explore the possibility of substituting in-place density with ICMV; (2) to identify factors that affect ICMV; and (3) to refine the data analysis methods. This study evaluated the relationship between ICMV and NNG to identify the possibility of adding ICMV to the INDOT specification for QA. The summary of the IC demonstration on US 52 is presented in Figure 5.1.

5.2 Analysis of Demonstration Data

This study implemented two statistical analyses: (1) linear regression model using bivariate analysis to find the correlation among the variables and (2) a multiple regression model based on multivariate analysis and Analysis of Variance (ANOVA) to identify the interaction between NNG (or temperature) and determination of the pass count.

The variables used for the analysis were core density data, NNG density, Compaction Control Value (CCV), temperature, and pass count. The ICMV developed by BOMAG was an old version so it was not compatible with the Veda software. SAKAI's ICMV named CCV was considered as an ICMV. The consistency of the data collection is an

<table>
<tr><th>Figure</th><th colspan="2">Summary</th></tr>
<tr><td>Location</td><td colspan="2">US 52 between the junction with US 231 and Cumberland Ave in West Lafayette

</td></tr>
<tr><td>Length</td><td colspan="2">5 miles long with two lanes</td></tr>
<tr><td>Date</td><td colspan="2">09.20.2009 ~ 09.24.2009</td></tr>
<tr><td>Pavement structure</td><td colspan="2">The testing pavement was a composite pavement consisting of 6 in. of HMA on the top and 7 in. of concrete pavement; 2 in. of the surface was milled and a 2.5 in. of intermediate HMA layer (19-mm max. nominal aggregate size) and a 1.5 in. HMA new surface layer (9.5-mm max. nominal aggregate size) were placed on top of the surface. (Note: The target layers for IC are illustrated with a box around it.)

1.5 in. HMA Surface course
2.5 in. Intermediate HMA course
New pavement

4 in. HMA course
7 in. Concrete pavement
Existing Pavement</td></tr>
<tr><td rowspan="2">Machine</td><td>SKAI
Double Drum IC roller</td><td>Bomag
Double Drum IC Roller</td></tr>
<tr><td></td><td></td></tr>
<tr><td>SPOT Tests</td><td colspan="2">• NNG
• FWD
• Core density</td></tr>
</table>

Figure 5.1 Summary of IC demonstration on US 52.

important precondition to implement data analysis. When the demonstration was conducted, core density data (19 data points) were collected randomly by INDOT. However, the other data, including NNG, CCV (ICMV from SAKAI), temperature, and pass count, were gathered at the designated locations. Therefore, the core density data were excluded from the data analysis due to the randomness of the data collection.

5.2.1 Linear Regression Model

Linear regression models are commonly used to find the statistical relationship between two variables. The determination of correlation (coefficient determination, R^2) is applied to measure the degree of relationship for two variables. Table 5.1 shows the pairwise correlation. The correlation of NNG and CCV is 0.744, which is attributed the highest value followed by that of pass count and NNG with 0.6772. The analysis shows negative correlations between NNG and temperature as well as CCV and temperature.

Figure 5.2 indicates the normality test along with the histogram, the Q-Q plot, and the goodness of fit. The precondition to performe the multiple regression model is that all data should be normally distributed. A Q-Q plot shows the graphical view of how the data is distributed. If the data points are linearly related, the Q–Q plot will show that the data points follow a straight line. Then a Goodness of Fit Test is conducted to evaluate the result of the normality test by identifying p-value. A p-value with less than 0.05 would indicate that the data is not normally distributed. As it was observed in the results of the nomality test in Figure 5.2, the core density outcome did not follow the normal distribution. Therefore, the results of the core density was excluded from the data analysis due to not only the violation of the nomality test but also the violation of the precondition in the data collection. With the exception of the core density data, the remaining variables were normally distributed.

Lastly, simple linear regression analysis was conducted. This study focused on four compaction response variables: NNG, CCV, temperature, and pass count. Figure 5.3 illustrates the correlation of NNG and CCV according to the pass count (from pass count 1 to pass count 3). The data distribution shows that the values of CCV and NNG gradually rose as the pass count increased. However, the R^2 did not present any pattern depending on the pass count.

TABLE 5.1
Pairwise correlations

No.	Variable	By variable	Correlation	Significant problem (p-value)
1	CCV	NNG	0.7440	<0.001
2	Temperature	NNG	−0.2820	0.0741
3	Temperature	CCV	−0.2441	0.1241
4	Pass count	NNG	0.6772	<0.0001
5	Pass count	CCV	0.4620	0.0024
6	Pass count	Temperature	−0.3728	0.0164

Two different data types exist: all-passes data and final coverage data. While the R^2 for all-passes was equal to 0.55, the value for the final coverage data was 0.377.

The correlation between NNG and CCV was equal to 0.55 in terms of the coefficient of determination in all passes, whereas the correlation related to temperature did not show any determinsitc mathmatical relationship as the cofficients were 0.0596 and 0.0795 for CCV and NNG, respectively (see Figure 5.4).

Temperature was the most important factor affecting the pavement compaction. In pavement engineering, temperature is considered a senstive parameter for determining the quality of compaction. However, the correlations of temperature with other variables, including NNG and CCV, were not observed in this analysis.

5.2.2 Multiple Regression Model

Multiple regressions are used to identify a probabilistic model according to dependent variables. As can be seen from the outcome of the single linear regression model, statistically, the correlations with temperature accounted for a low R^2 in contrast with the correlations between NNG/CCV and NNG/pass count. However, this study considered temperature as one of the variables to determine a multiple regression model since temperature influences the consistency and uniformity of compaction. Table 5.2 shows the results of the multiple regression analysis. The coefficient of determination (adjusted R square) was 0.67. Multiple regression measures the effects of changes in the independent variable on the dependent variable. The null hypothesis (H_0) in ANOVA was that the independent variable has no impact on the dependent variables. Since the p-value (Prob $>$ F) was less than the critical value, as shown in Table 5.2 rejecting the null hypothesis, the suggested multiple regression model was determined to be significantly suitable to the data. For parameter estimates, the significant levels for CCV and pass count were less than 0.05, which means that these independent variables were statistically significant. However, the temperature did not have an effect on the predicted variable (NNG).

The coefficient of the determination between the predicted NNG and the observed NNG showed a high value, 0.69 (see Figure 5.5) as to the accuracy of the model. Also, a residual plot (see Figure 5.6) presents the residuals with the predicted NNG values. If the residual plot is randomly dispersed without any pattern, the multiple linear regression model was appropriate. As a result, the residual plot and predicted NNG graph support that the multiple regression model was deemed appropriate.

There are two different types of variables: numerical variables (NNG, CCV, and temperature) and a categorical variable (pass count). This study conducted ANOVA analysis through the JMP software (pronounced “jump”), as shown in Figure 5.7 to identify the interaction of the numerical and categorical variables. The comparisons of NNG, CCV, and temperature with the pass count shows that each group (pass1, pass2 and pass3) were significantly different. The null hypothesis (H_0) for the ANOVA analysis showed that the means of each group were homogenous.

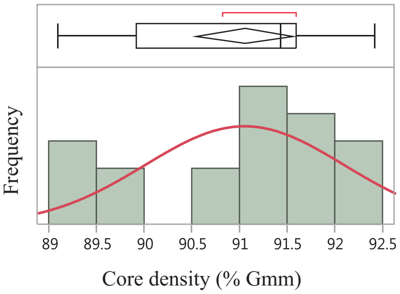
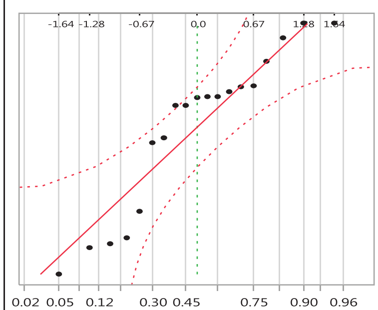
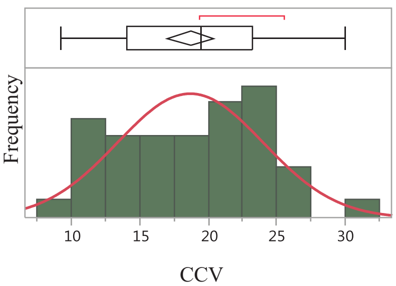
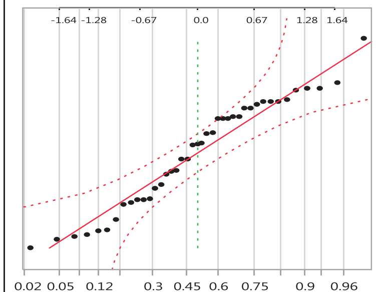
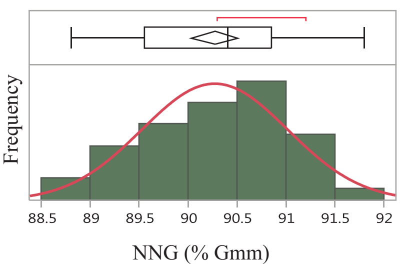
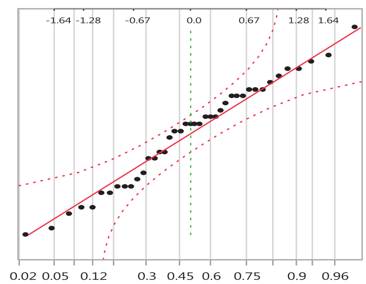
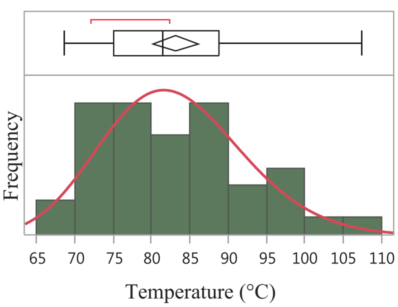
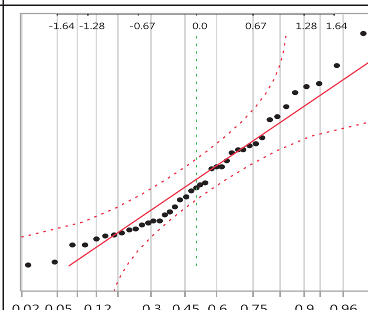
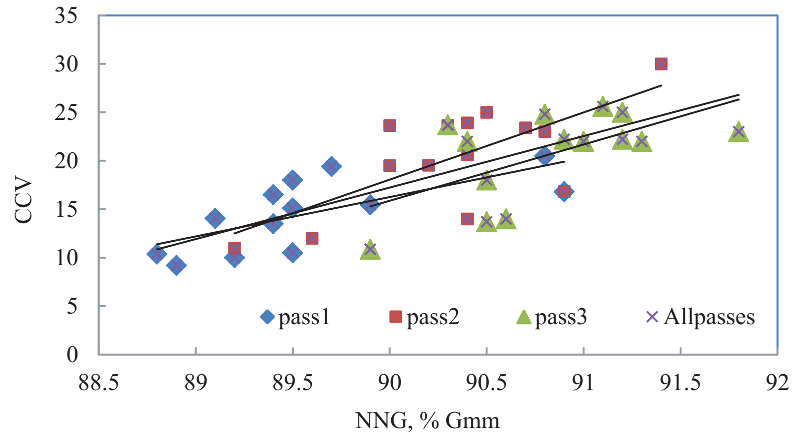
Figure	Histogram	Q-Q plot	Goodness of Fit Test
Core density			p-value: 0.0302 Fail to normally distributed
CCV			p-value: 0.1351 Normally distributed
NNG			p-value: 0.4481 Normally distributed
Temperature			p-value: 0.071 Normally distributed

Figure 5.2 Normality test.

If the p-value was less than 0.05, H_0 was rejected, which reflects that the categorical variable should be considered as an explanatory variable in the multiple regression model. The results of ANOVA analysis showed that the p-values in NNG, CCV, and temperature were less than 0.05 (Significant level). Therefore, the categorical variable affected the estimation of the multiple regression model since the ANOVA analysis indicated a significant interaction between the pass count and the other variables (NNG, CCV, and temperature).

5.2.3 Optimal Compaction Curve

As mentioned in the previous chapter, the main purpose of this research is to explore the application of IC technology in QA. But when the last SAC meeting was held, the question of the application of IC technology in QC was raised. Therefore, optimal compaction curve and Veda analysis present how to apply IC technology in QC by showing analysis of data obtained from the demonstration project on US 52.



pass count	R^2
Pass1	0.486
Pass2	0.499
Pass3	0.377
All-passes	0.55

Figure 5.3 Correlation between CCV and NNG.

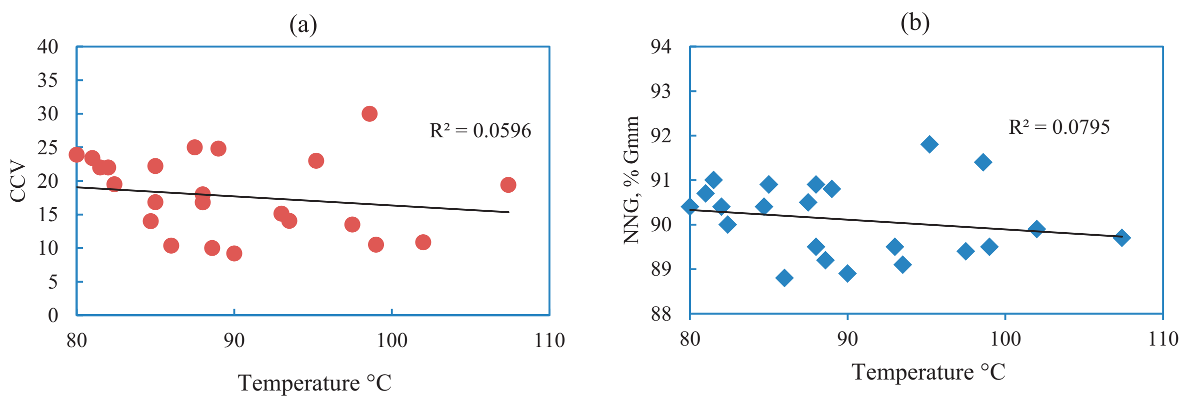


Figure 5.4 Comparison of coefficient of determination: (a) relationship between CCV and temperature (all passes); (b) relationship between NNG and temperature (all passes).

TABLE 5.2
Outcome of the multiple regression model

Regression statistics	
R square	0.694889
Adjusted R square	0.67015
Root mean square error	0.429519
Mean of response	90.26585
Observation	41

Analysis of Variance (ANOVA)

Source	**Degree of freedom**	**Sum of squares**	**Mean squares**	**F ratio**	**Prob > F**
Model	3	15.5462	5.18207	28.0891	<0.0001
Error	37	6.82599	0.18449		
Total	40	22.37219			

Parameter estimates

Term	**Estimate**	**Std error**	**T ratio**	**Prob > |*T*|**
Intercept—NNG (% Gmm)	87.969793	0.76096	115.63	<0.0001
CCV	0.0769225	0.014397	5.34	<0.0001
Temperature (°C)	0.0008943	0.007628	0.12	0.9073
Pass count	0.3894753	0.097827	3.98	0.0003

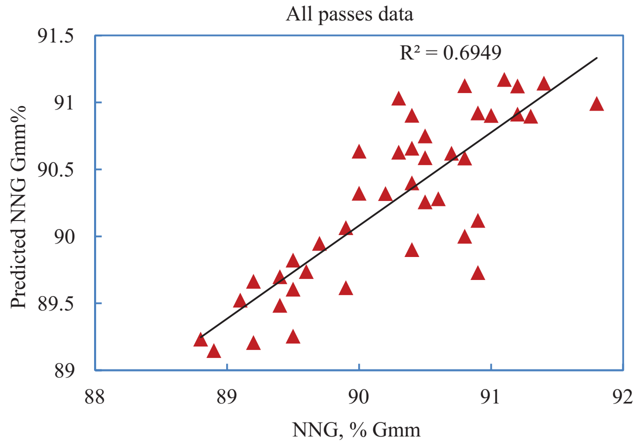


Figure 5.5 Predicted NNG.

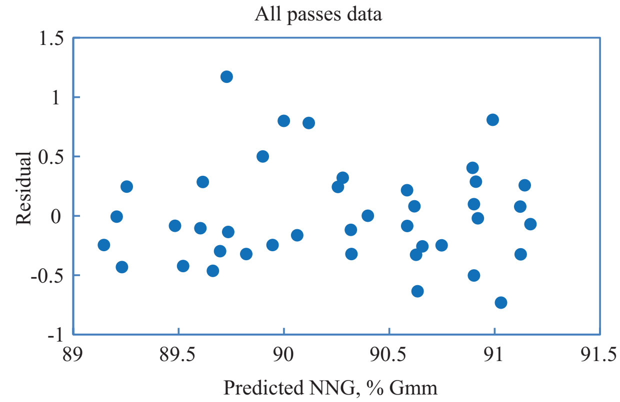
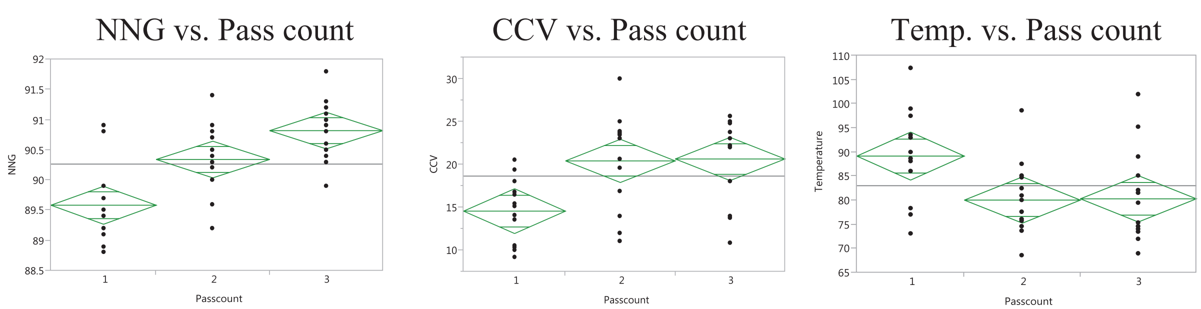


Figure 5.6 Residual analysis.

One of the benefits from the ICMV is to obtain the optimal compaction curve. A test section was required in order to make a decision on the optimal pass count before the original compaction operation. Many states have begun releasing their IC specification for QC in HMA, which stipulates specific test section requirements. Determination of an optimal pass count helps minimize roller overlaps. The optimal pass count is the point when the increase in the ICMV of the material between passes is less than 5% on the compaction curve. The IC compaction curve is defined as the relationship between the ICMV and the roller passes as shown in Figure 5.8. The displacement of pass 1 and pass 2 was equal to 0.086 and displacement of pass 2 and pass 3 was equal to 0.043. The growth of the curve between passes should be less than 0.05, and therefore pass 3 was selected as the optimal pass count.



		Sum of Squares	df	Mean Square	F	Significant level
NNG	Between Group	10.87	2	5.435	3.2380	0.000
	Within Group	11.935	39	0.306		
	Total	22.805	41			
CCV	Between Group	337.800919	2	168.9005	7.9984	0.0012
	Within Group	823.5488929	39	21.11664		
	Total	1161.349812	41			
Temp.	Between Group	752.2433	2	376.1217	4.9013	0.0126
	Within Group	2992.821	39	76.73899		
	Total	3745.064	41			

Figure 5.7 ANOVA analysis.

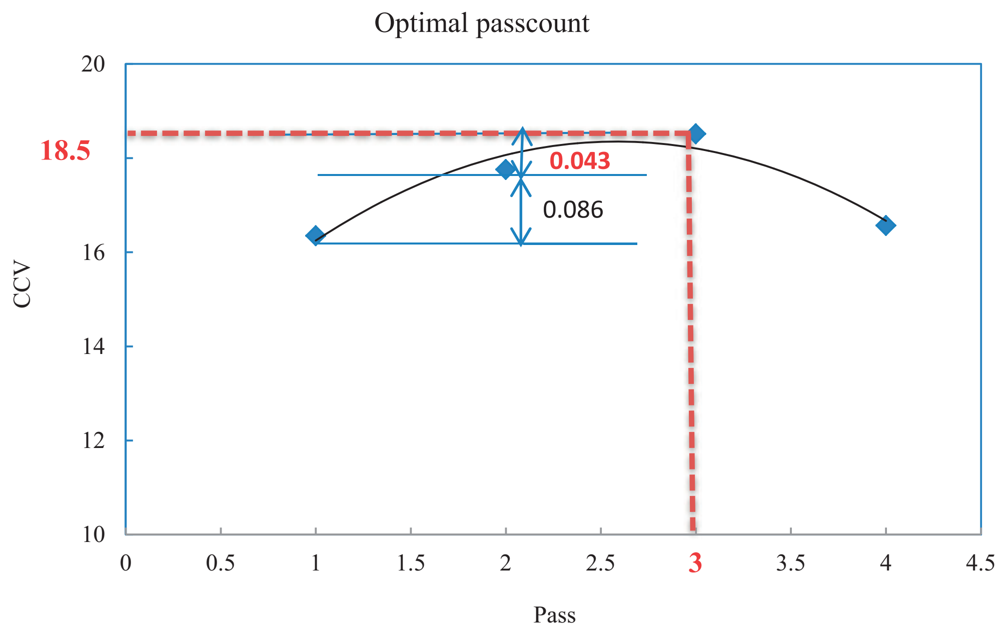


Figure 5.8 Optimal pass count.

5.2.4 Veda Analysis

Veda is software for compaction analysis. Various intelligent compaction machines have their own documentation system and display software. Veda can now import data from the IC compactors and perform standardized data processing. In order to analyze compaction, the standardized data analysis software "Veda" was utilized, which is available at www.intelligentcompaction.com. Figure 5.9 illustrates the Veda outcome of the IC demonstration on US 52. Veda visually shows the results of compaction including location, pass count, temperature, and ICMV. The different colors indicated the number of pass count and temperature and the values of CCV (i.e., the ICMV for SAKAI). For example, the compaction operation was performed three times on the main lane as indicated by the yellow color. However, the orange color for the shoulder indicates that it was compacted only two times. In terms of the compaction temperature, it ranges from 100 °F to 150 °F. The values of ICMV vary widely from 0 to 21 as indicated under ICMV (CCV) in Figure 5.9.

According to the IC construction operation criteria based on the HMA Pavement Quality Control Plan (QCP) provided by FWHA specification (FHWA, 2014), a minimum coverage of 90% (to be determined) of the individual construction area shall meet or exceed the optimal number of roller passes and at least 75% (to be determined) of the IC-designated area shall meet or exceed the target ICMV value. When the IC demonstration on US 52 is applied to the criterion of the coverage of the compaction through Veda, the target ICMV is 18.5, the target coverage is 75% with 50,993 of sample size. The result of the coverage analysis for the IC demonstration on US 52 is "failure" as shown in Table 5.3. The target achieved is 59.57% which does not meet the required standard coverage of 75%. In this case, IC coverage should be investigated by the contractor and the department.

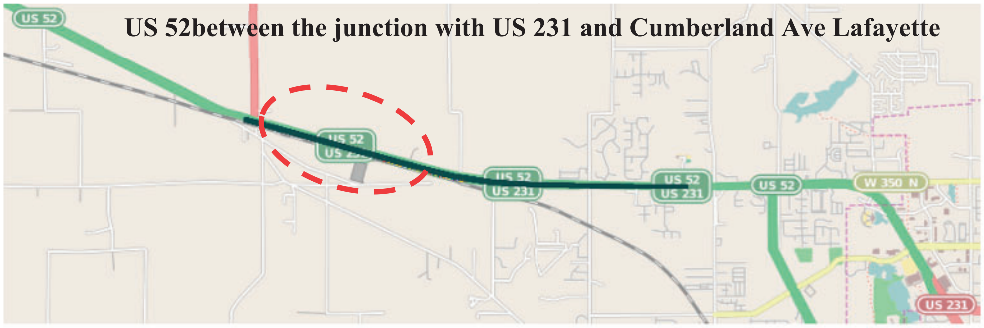
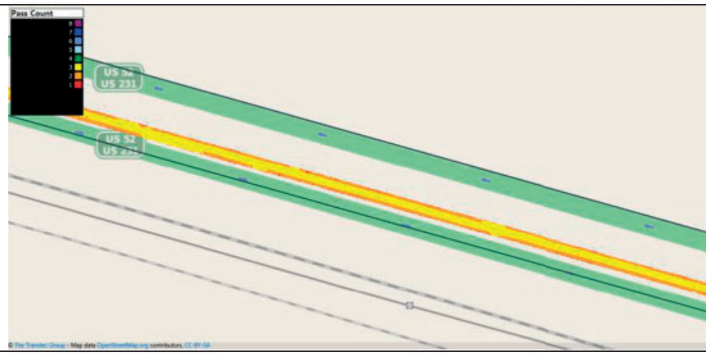
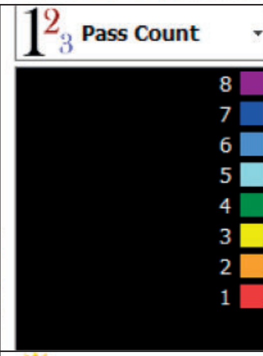
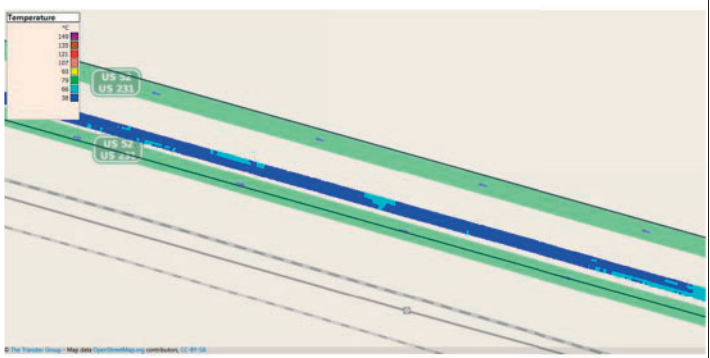
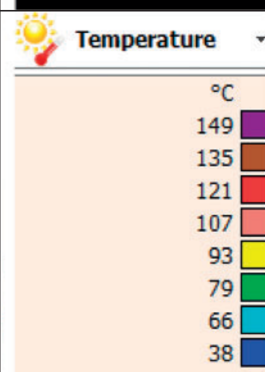
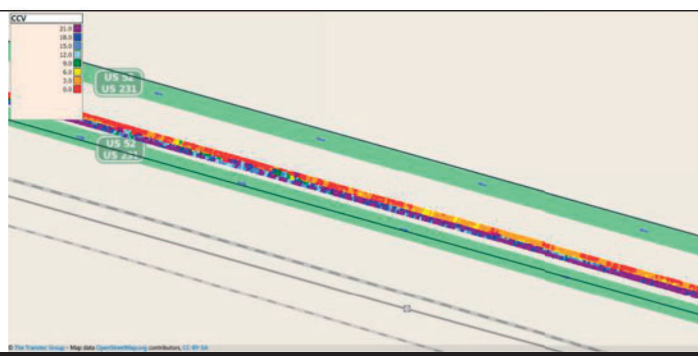
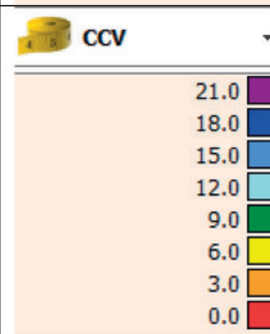
Figure	Compaction outcome of the IC demonstration	
Location		
Pass count		
Temperature		
ICMV(CCV)		

Figure 5.9 Compaction outcome of the IC demonstration (by Veda).

TABLE 5.3
Outcome of coverage (by Veda)

Target		Output		
Sample size	50,993	Output		50,993
Target ICMV	18.5	ICMV	Mean	19.3
			Min	5.5
			Max	43.5
			SD	6.41
% Target coverage	**75**	**% Target achieved**		**59.57**
		Target status		**Failure**

6. CONCLUSION

6.1 Summary

This study aimed to collect information on the application of IC technology in QC/QA projects and the perception of AASHTO members towards the implementation of IC technology. Relevant data was collected using a survey questionnaire followed by phone interviews. This section summarizes the key findings of the project specifically regarding (1) AASHTO members' perception towards IC technology implementation through survey, (2) practical information and recommendation of IC technology through phone interview and (3) data analysis for exploring the possibility of substituting in-place density with IC technology.

6.1.1 Literature Review

"IC technology" provides the following information: (1) the precise location being paved using Global Positioning System (GPS); (2) the framework of the vibratory roller with an auto-feedback system; (3) compaction response data including the speed, number of passes, frequency, temperature, and amplitude from the material being compacted; and (4) intelligent compaction measurement values (ICMVs) utilizing compaction meters or accelerometer (Chang et al., 2011b). Along with the growing interest in IC technology, a possibility has been raised that IC technology will address the issues of the current practice of in-place density test. There is an ongoing project entitled "Intelligent Compaction: Quality Assurance for In-Place Density Acceptance" conducted by FHWA. The purpose of the project is to evaluate the application of IC technology for QA in HMA compaction. Currently four states finished the demonstration projects and published their own reports (Chang et al., 2012a, 2012b, 2013a, 2013b). This study analyzed the results of the four demonstration projects.

- The correlation between core density and compaction response values including ICMV, frequency, amplitude, and temperature was low in all four demonstration projects, which suggests that the compaction values from the IC roller have no significant correlation with the core density.
- The correlation between nuclear gauge (NG) density and ICMV for the final coverage was low, but the correlation for the all-passes count data showed high R^2s with 0.95 in California and 0.7 in Utah. Therefore, it became obvious that the number of compactions (pass counts) is an important parameter.
- The current conclusions were drawn from the four demonstration projects in Ohio, California, Maine, and Utah. More state demonstration projects are being conduct and therefore should be continuously monitored for their results.

6.1.2 Survey

A survey was conducted with AASHTO member states across the country. Twenty-six (26) AASHTO members responded to the survey. The survey results revealed that only two states (Alaska and Vermont) have adopted IC technology, while the remaining 24 respondents with 92% have not used it for QC and/or QA. In addition, 9 respondents (out of 26 respondents) indicated that they have a plan to use IC technology, while 13 respondents said they were not interested in the technology. The reasons for not using IC technology were (1) satisfaction with existing QC/QA procedure, (2) difficulty of adjustment due to the lack of specifications in determining stiffness in HMA, and (3) lack of availability of IC equipment from contractors. According to the comments from the survey, many states have plans to perform field demonstration projects or pilot studies.

6.1.3 Phone Interview

Two sets of interviews were conducted for: (1) application of IC technology and (2) the availability of GPS only application.

The phone interviews for the application of IC technology were performed with eleven interviewees based on the previous survey and current IC demonstration projects conducted between 2012 and 2014. The summary of the phone interview is as follows:

- More uniform compaction, less pavement maintenance and night time paving were indicated to be the benefits of IC technology.
- Group A-2 (New Jersey and Mississippi) answered in the survey that they did not have any plans to adopt IC technology, have started to consider pilot studies for IC technology.
- IC technology is cost effective. Although using IC rollers can add cost, it does not significantly affect the total cost for the construction project since the IC compaction is a small portion of total construction cost.
- The DOTs (Utah, Florida, and Maine) and vendors (HAMM, SAKAI and Caterpillar) who participated in the field demonstration projects expressed some concerns about the relationship between in-place density and ICMV.

The second set of interviews for the availability of GPS only application included Sitech and Trimble. The results are illustrated in Appendix C.

6.1.4 Review of the Demonstration Data

FHWA conducted an IC demonstration on US 52 in West Lafayette, Indiana in September 2009 (Chang et al., 2011b).

Two IC compactors (SAKAI, BOMAG) were used and spot tests including FWD, NNG, and core testing, were performed. The objectives of the data analysis of the demonstration were to validate the possibility of substituting the in-place density with the ICMV. The results of the data analysis are as follows:

- Overall reliable results could not be obtained due to the difficulty in collecting data. Specifically, the core density data were randomly selected while other test data, such as NNG and IC data, were provided at the designated location. Consequently, the core density data were excluded from the data analysis.
- The NNG prediction model showed an R^2 value of 0.67 with statistically significant P-values (less than 0.0001) from the multiple regression model.
- There are two different data types for pass count: final coverage data and all-passes data. According to the ANOVA analysis and multiple comparison analysis, the pass count is an important variable affecting the multiple regression model. Therefore, the selection of pass count data type affects the results of correlations and multiple regression model.
- The optimal pass count would assist contractors in determining the number of passes for the IC roller. In addition, the optimal pass count would show the target ICMV, which can be considered as a criterion to determine the uniformity of compaction in QC.

6.2 Recommendations

1. The application of IC for QA:
   a. Three states (Alaska, Vermont, and Pennsylvania) have used IC technology for QC only based on the survey and the phone interview. In the phone interview, Utah, Florida and Maine DOTs and IC roller vendors including HAMM, SAKAI, and Caterpillar were apprehensive about the relationship between in-place density and ICMV. The analysis of data from the IC demonstration on US 52 indicated that the correlation between in-place core density (% Gmm) and ICMV showed low R^2 values with 0.37 for the final pass and 0.55 for the all passes. Therefore, there is no solid evidence to-date to support the possibility of substituting in-place density with ICMV.
   b. There are several on-going projects studying the application of IC in HMA QA. Therefore, the results of these projects should be closely monitored.
   c. More pilot studies should be conducted to improve the confidence in the relationship between core density and ICMV. Additionally, specific attention must be given to the collection of ICMVs, data from a coring density test, and other field spot tests from the same locations.
2. The application of IC for QC:
   a. The application of IC for QC, IC technology can improve compaction uniformity through compaction curve and compaction coverage analysis. Additionally, the multiple regression model (predicted variable: non-nuclear density) indicated a R^2 value of 0.67 with statistically significant P-values for the independent variables (pass count, temperature, and CCV). Therefore, ICMV can be considered as a criterion to estimate the compaction in QC.
   b. According to the compaction coverage analysis through Veda software, the demonstration on US 52 was a "failure" with a result of 59.57% in the coverage achieved (the required standard coverage was more than 75%). Therefore, this research team recommends that an INDOT IC specification is needed in order to improve compaction coverage and uniform compaction for QC.
3. Use of GPS only application:
   a. The literature review and the phone interview results revealed that the application of Satellite Based Augmentation System (SBAS) does not improve HMA compaction required uniformity of compaction and accurate pass counts. SBAS provides low accuracy levels (39.4 to 118 in.). Also topographic characteristics and weather significantly affect the accuracy level. However, Real-time Kinematic (RTK) supplies high levels of accuracy within 0.5 in. by using a base station.
   b. If only a conventional roller retrofitted with a GPS unit is to be considered then, it is recommended that a Real-time Kinematic (RTK) system be preferred over a SBAS (refer to Appendix C).

6.3 Limitations

The limitations of this study were as follows:

- Out of the 50 state DOTs in the U.S., only 26 state DOTs responded to the survey, which implies that the results obtained from the data analysis might not broadly represent the general opinions of all state DOTs.
- This research team originally invited 30 state DOTs for phone interviews via the review of information from the previous survey. However, only eight state DOTs and three vendors were responded for the phone interviews, mainly due to the low interest of state DOTs in the subject. The small number of phone interviews offered a limited set to draw reliable conclusions.
- For the data analysis, the consistency of the data collection is an important precondition to implement data analysis. When the demonstration was conducted, the core density data (19 data points) were collected randomly with the INDOT procedure, but the other data (NNG, CCV (ICMV from SAKAI), pass count, and temperature) were gathered at designated locations. Therefore, the core density data were excluded from the data analysis due to the different collection method employed.

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APPENDICES

APPENDIX A: SURVEY

Survey of Intelligent Compaction Practice for HMA QC/QA

Intelligent Compaction (IC) is a smart technology of compaction quality measurements in real-time with an in-situ measurement system and compaction feedback controls. Indiana Department of Transportation and Purdue University are studying the possibility of improving the effectiveness of asphalt pavement construction QC (and possibly QA) using the IC technology. Part of the study is to understand the state of the IC practice used by agencies. The survey mainly asks questions about (1) how the states have made use of IC technology; (2) the benefit of applying IC technology; and (3) IC application to the asphalt pavement construction QC/QA. The survey result will be shared with the respondents upon their request.

Please return this questionnaire by February 27, 2014. Thank you for your assistance.

1. Does your agency currently adopt the IC technology for QC and/or QA?

	Yes
	No

Additional comments	

If Yes, please answer questions 2 to 7
If No, please answer questions 8 to 11

2. Does your agency use the IC Technology? Please check the applicable answers below.

	Quality control (by contractors) in soil compaction
	Quality assurance (by agencies) in soil compaction
	Quality control in asphalt pavement compaction
	Quality assurance in asphalt pavement compaction
	None

Additional comments	

3. Does your agency adopt the IC Technology formally in the Standard Specification? Please check the answers below.

	Quality control in soil compaction
	Quality assurance in soil compaction
	Quality control in asphalt pavement compaction
	Quality assurance in asphalt pavement compaction
	None

Additional comments	

4. Does your agency implement the IC technology in regular projects? Please check the answers below.

	Yes
	No

Additional comments	

5. If Yes to Question 6, what are the benefits of using the IC technology? Please check the answers below.

	Enhanced productivity
	Enhanced worksite safety
	Solving testing technician shortage
	More precise results
	Decrease testing costs
	Better quality assurance process
	Better quality control process
	Real time compaction measurement
	More uniform compaction, less pavement maintenance and operations costs in the future
	Simplification of compaction testing procedures
	Less complaints and challenges from the contractors
	Less concern with radiation, no need for operator's license
	Others:

Additional comments	

6. Have you used Intelligent Compaction Measurement Value (ICMV) for asphalt mix quality assurance in conjunction with normal quality assurance criteria?

	Yes
	No
	Not applicable

Additional comments	

7. What assessment properties does your agency measure for the HMA construction quality control and/or quality assurance?

	Not applicable
	In-place density/ In-place air voids
	Smoothness
	Thickness
	Others:

Additional comments	

8. Does your agency plan to formally adopt the IC technology in the future?

	Yes
	No

Additional comments	

9. If Yes to Question 10, does your agency plan to use IC Technology? Please check the applicable answers below.

	Quality control in soil compaction
	Quality assurance in soil compaction
	Quality control in asphalt pavement compaction
	Quality assurance in asphalt pavement compaction
	Others:

Additional comments	

10. If Yes to Question 10, does your agency plan to adopt the IC Technology formally in the Standard Specification? Please check the answers below.

	Quality control in soil compaction
	Quality assurance in soil compaction
	Quality control in asphalt pavement compaction
	Quality assurance in asphalt pavement compaction
	Others:

Additional comments	

11. If No to Question 10, please check reasons for not using the IC technology.

	Accuracy of results from the IC technology
	Lack of knowledge of the IC technology
	Satisfaction with existing QC/QA procedure
	Uncertainty about the benefits of IC technology
	Difficulty of adjustments due to the lack of existing stiffness specification for compaction
	Availability of IC equipment from contractors
	Complexity of QC and/or QA procedures
	Disputes from contractors
	Others:

Additional comments	

General Information

Name	
Position Title	
Agency	
Phone number	
Email Address	

Contact information

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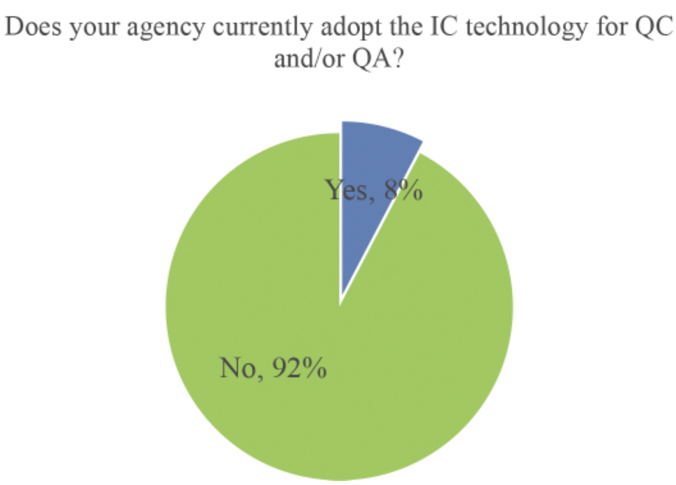
Thank you for your time and effort.

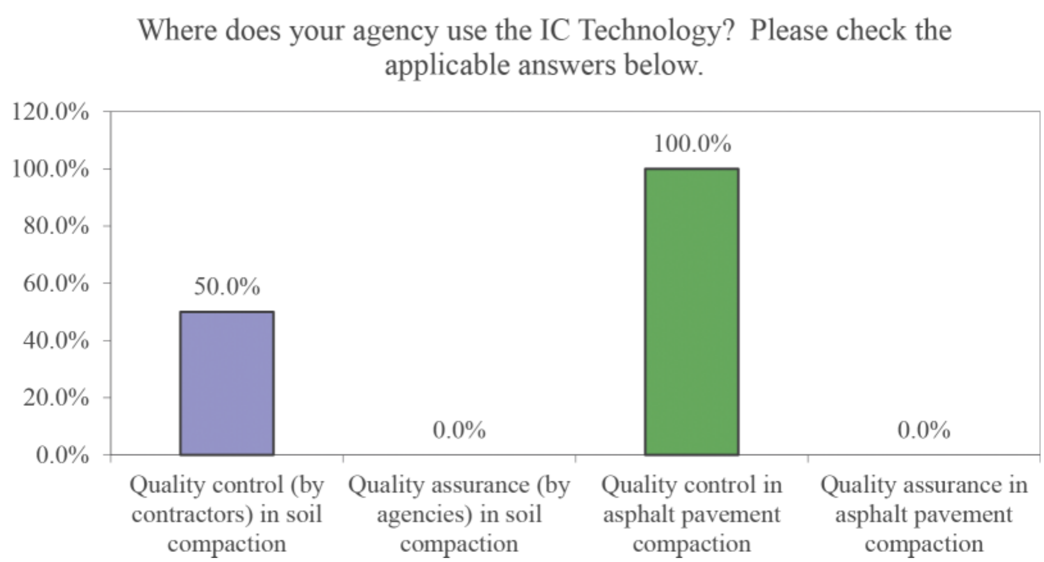
Result of Survey

Group 1 Question 1		
Does your agency currently adopt the IC technology for QC and/or QA?		
Answer Options	Response Percent	Response Count
Yes	7.7%	2
No	92.3%	24
Additional comments		9
answered question		26
skipped question		0

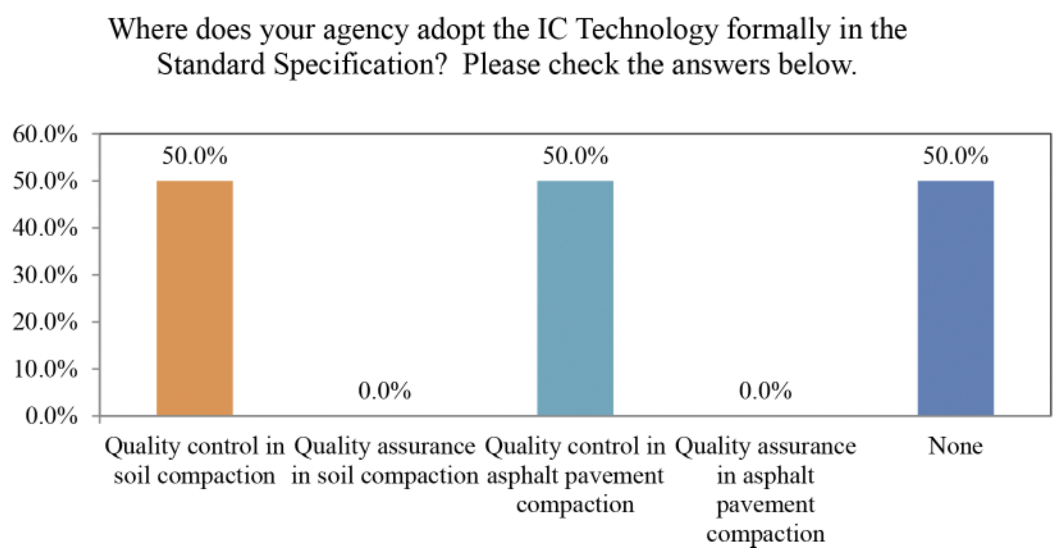


Group 1 Question 1—Additional Comments	
1	Not currently but the IC Roller Visual Display is beneficial for tracking the roller pass counts / pavement mat temperature. Also a valuable QC tool for nighttime paving operations. (Encourage Contractors use IC for QC tool)
2	One demo project done so far; some more may be done coming season
3	It would certainly be allowed for QC but not required.
4	We are going to apply roller path tracking and temperature monitoring system in several projects this summer and it will for QC only.
5	We have conducted a demo project that shadowed our current acceptance process.
6	We have a local university IC research project in progress. A local IC workshop and possible demo will be held 2/25/14.
7	We have not adopted for QC or for QA, but are making efforts to get to that point. Missouri had a demonstration project in the St. Louis area back in late 2010, which gave us a better confidence level and allowed us to reduce the number of QC locations for Nuclear Density Testing by the contractor.
8	We are working on possibly adopting a specification. Expected to be evaluated this summer.
9	Maybe someday, but the state of the art is not there yet.

Group 1 Question 2		
Where does your agency use the IC Technology? Please check the applicable answers below.		
Answer Options	Response Percent	Response Count
Quality control (by contractors) in soil compaction	50.0%	1
Quality assurance (by agencies) in soil compaction	0.0%	0
Quality control in asphalt pavement compaction	100.0%	2
Quality assurance in asphalt pavement compaction	0.0%	0
	answered question	2
	skipped question	24

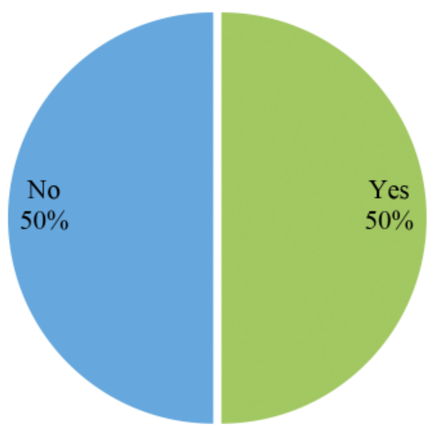


Group 1 Question 3		
Where does your agency adopt the IC Technology formally in the Standard Specification? Please check the answers below.		
Answer Options	Response Percent	Response Count
Quality control in soil compaction	50.0%	1
Quality assurance in soil compaction	0.0%	0
Quality control in asphalt pavement compaction	50.0%	1
Quality assurance in asphalt pavement compaction	0.0%	0
None	50.0%	1
Additional comments		0
answered question		2
skipped question		24

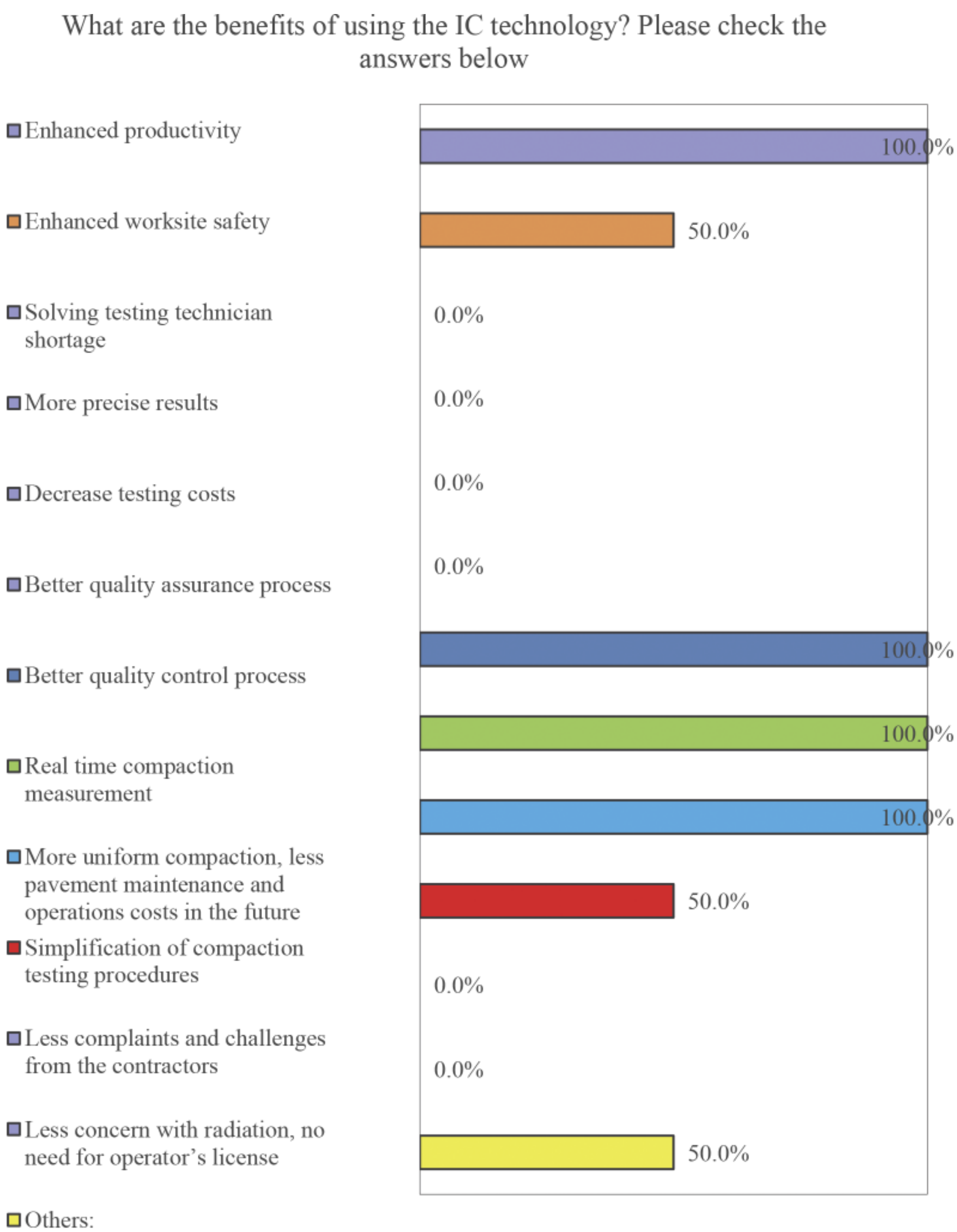


Group 1 Question 4		
Does your agency implement the IC technology in regular projects? Please check the answers below.		
Answer Options	Response Percent	Response Count
Yes	50.0%	1
No	50.0%	1
Additional comments		0
answered question		2
skipped question		24

Does your agency implement the IC technology in regular projects? Please check the answers below.



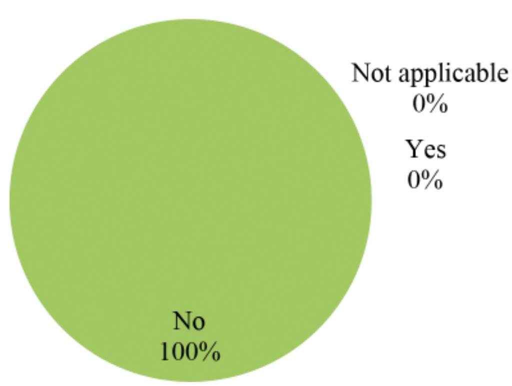
Group 1 Question 5		
What are the benefits of using the IC technology? Please check the answers below.		
Answer Options	Response Percent	Response Count
Enhanced productivity	100.0%	2
Enhanced worksite safety	50.0%	1
Solving testing technician shortage	0.0%	0
More precise results	0.0%	0
Decrease testing costs	0.0%	0
Better quality assurance process	0.0%	0
Better quality control process	100.0%	2
Real time compaction measurement	100.0%	2
More uniform compaction, less pavement maintenance and operations costs in the future	100.0%	2
Simplification of compaction testing procedures	50.0%	1
Less complaints and challenges from the contractors	0.0%	0
Less concern with radiation, no need for operator's license	0.0%	0
Others:	50.0%	1
	answered question	2
	skipped question	24



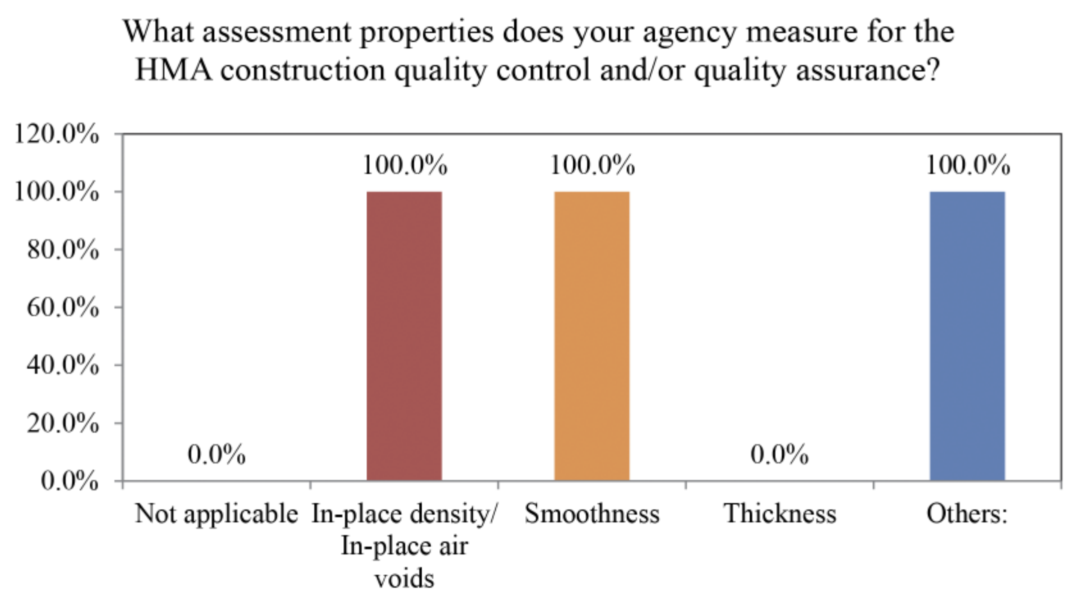
Group 1 Question 5—Additional Comments
Especially for night time paving, operator "sees" where he's been

Group 1 Question 6		
Have you used Intelligent Compaction Measurement Value (ICMV) for asphalt mix quality assurance in conjunction with normal quality assurance criteria?		
Answer Options	Response Percent	Response Count
Yes	0.0%	0
No	100.0%	2
Not applicable	0.0%	0
Additional comments		0
answered question		2
skipped question		24

Have you used Intelligent Compaction Measurement Value (ICMV) for asphalt mix quality assurance in conjunction with normal quality assurance criteria?

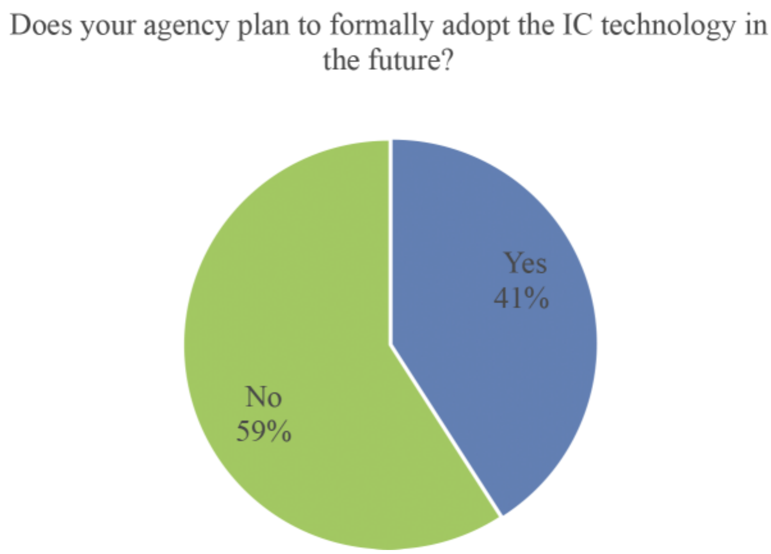


Group 1 Question 7		
What assessment properties does your agency measure for the HMA construction quality control and/or quality assurance?		
Answer Options	Response Percent	Response Count
Not applicable	0.0%	0
In-place density/ In-place air voids	100.0%	2
Smoothness	100.0%	2
Thickness	0.0%	0
Others:	100.0%	2
	answered question	2
	skipped question	24



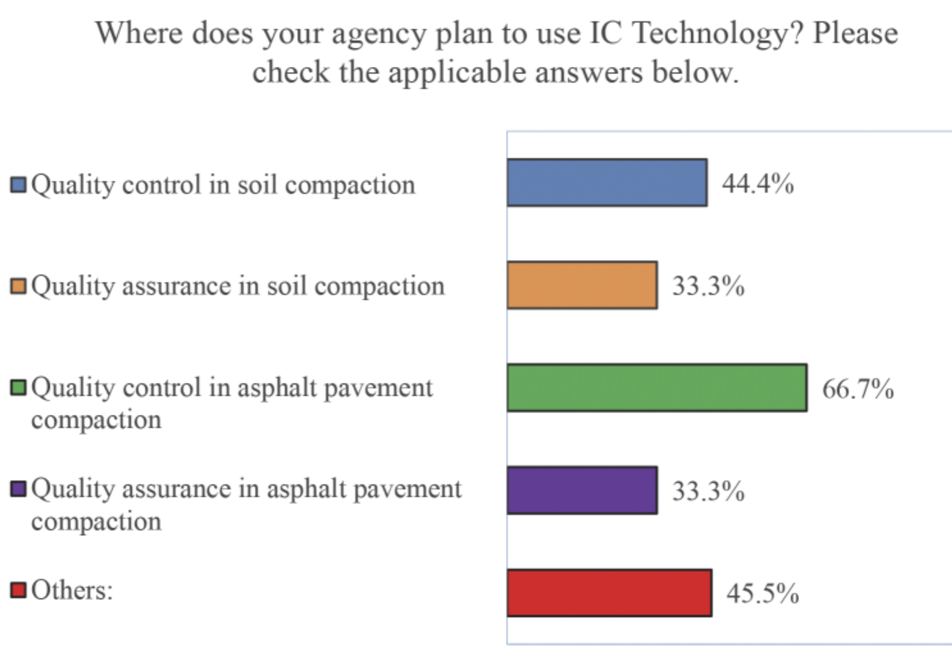
Group 1 **Question 7—Additional Comments**	
1	Binder content, aggregate gradation (in CPF=Composite Pay Factor)
2	Joint Density

Group2 Question2		
Does your agency plan to formally adopt the IC technology in the future?		
Answer Options	Response Percent	Response Count
Yes	40.9	9
No	59.1	13
Additional comments		19
	answered question	22
	skipped question	2
	Total	24



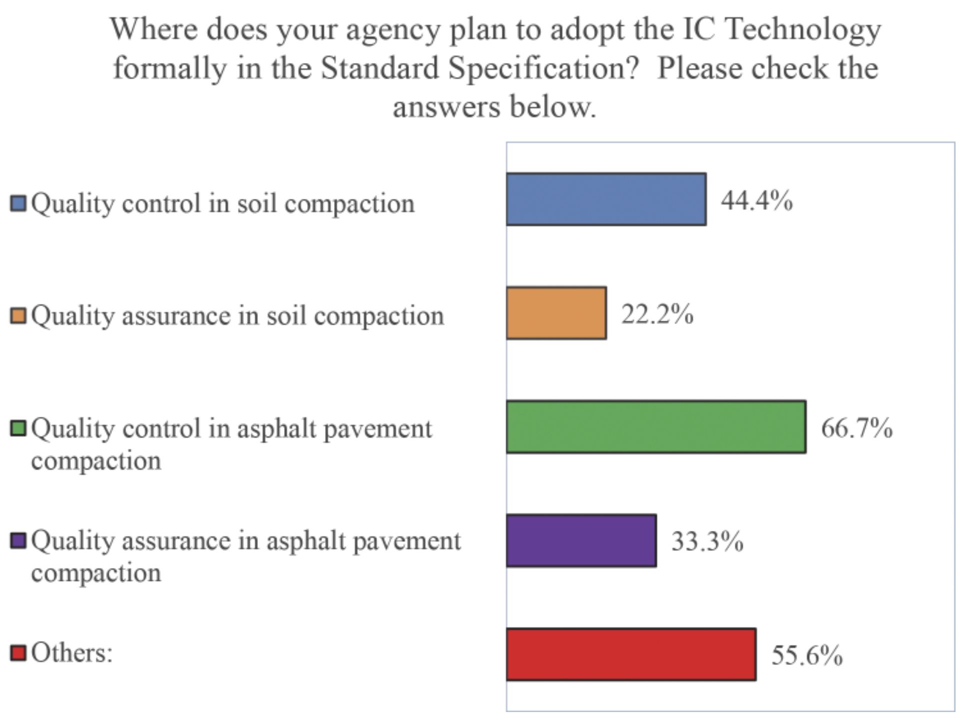
Group 2 Question 2—Additional Comments	
1	Possibly - There is a need for additional projects for the evaluation of IC technology (both for asphalt and earthwork). This will allow the Department and Contractors can gain more experience with IC equipment / software. (Consider evaluating IC on a larger construction project in order to gain more feedback and IC data for review)
2	We have participated in the Pool fund and NCHRP 21-09 studies, we have conducted number of pilot studies , in near future good chances to adopt the system
3	We are researching IC but have no plans to implement at this time.
4	Just in the process of evaluating it
5	No present plans for soils or HMA
6	Base on the results of the testing projects, we may adopt temperature, roller covered area but not density for compaction.
7	Possibly, the technology is still being evaluated.
8	Maybe in 5 to 10 years
9	Maybe, still evaluating it.
10	To be determined - still determining direction to take
11	No plans at this time, but are piloting one project which requires gps equipment to monitor rolling patterns
12	Results of research and demo projects must be evaluated before adoption can be considered
13	We are working with our Missouri Asphalt Paving Association to identify up to 3 projects this summer and work with those contractors to utilize IC on those projects. We are looking at it as a "Proof of Concept" and will not be using it for QA or as basis of payment.
14	Maybe...
15	Possibly, depends on the tests run this summer.
16	We have had demonstration projects, and research projects, and it is generally received favorably, but with some problems to be resolved. There are no current plans to adopt it.
17	Already in the works. We have a draft special provision and 3 projects under construction.
18	something we should explore
19	Possibly

Group 2-1 Question 3		
Where does your agency plan to use IC Technology? Please check the applicable answers below.		
Answer Options	Response Percent	Response Count
Quality control in soil compaction	44.4%	4
Quality assurance in soil compaction	33.3%	3
Quality control in asphalt pavement compaction	66.7%	6
Quality assurance in asphalt pavement compaction	33.3%	3
Others:	45.5%	5
answered question		9
skipped question		15
Total		24



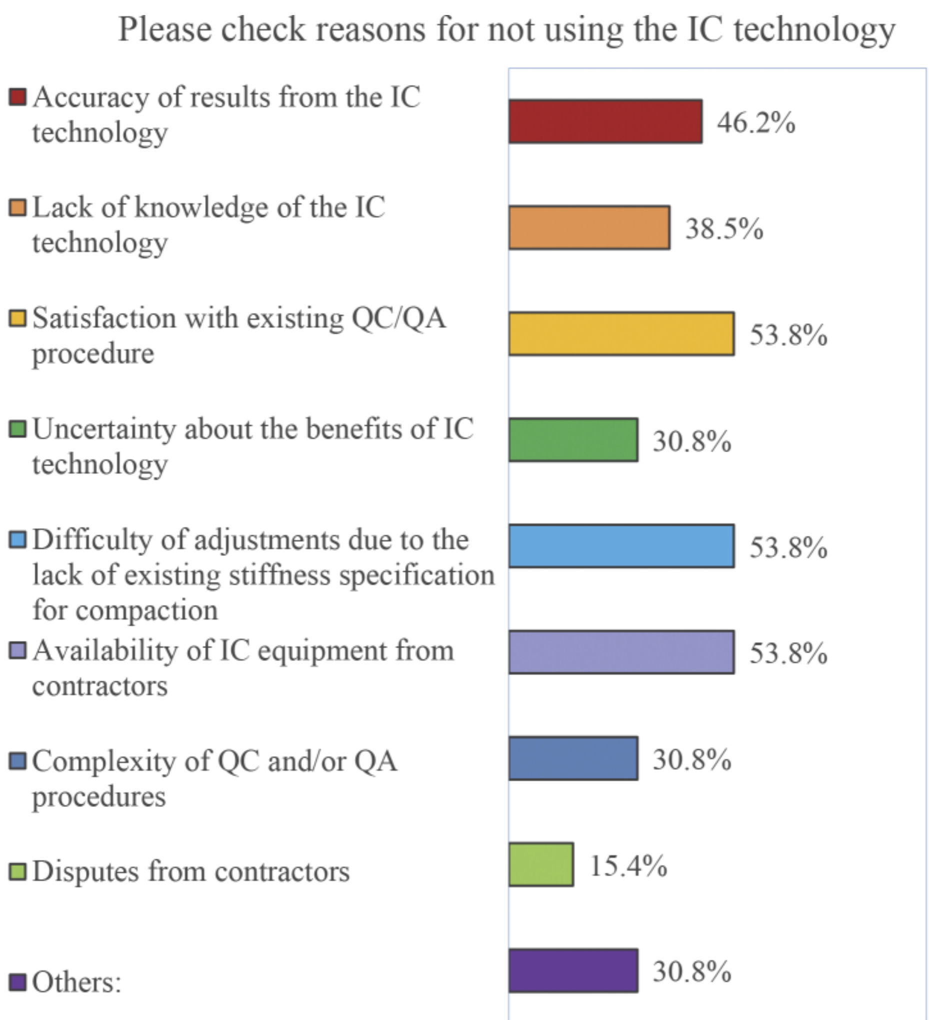
Group 2-1 Question 3—Additional Comments	
1	Plan to allow it for quality control in both areas
2	Possibly on the QC side of soil and asphalt.
3	Still determining direction to take
4	We are working on the Quality Control side for now, however in the future see this as an opportunity of Quality Assurance.
5	not sure

Group 2-1 Question 4		
Where does your agency plan to adopt the IC Technology formally in the Standard Specification? Please check the answers below.		
Answer Options	Response Percent	Response Count
Quality control in soil compaction	44.4%	4
Quality assurance in soil compaction	22.2%	2
Quality control in asphalt pavement compaction	66.7%	6
Quality assurance in asphalt pavement compaction	33.3%	3
Others:	55.6%	5
	answered question	9
	skipped question	15
	Total	24



Group 2-1 Question 4—Additional Comments	
1	None of the above
2	Possibly on the QC side of soil and asphalt.
3	Still determining direction to take
4	We were selected for implementation funding from SHRP2 - Performance specifications and will be working with SHRP2 to develop specifications for the soil compation effort. We have been involved with this SHRP2 (R07) project since June of 2009. It is this SHRP2 project which our St. Louis Intelligent Compaction Demonstration Project was conducted.
5	Not sure

Group 2-2 Question 3		
Please check reasons for not using the IC technology		
Answer Options	Response Percent	Response Count
Accuracy of results from the IC technology	46.2%	6
Lack of knowledge of the IC technology	38.5%	5
Satisfaction with existing QC/QA procedure	53.8%	7
Uncertainty about the benefits of IC technology	30.8%	4
Difficulty of adjustments due to the lack of existing stiffness specification for compaction	53.8%	7
Availability of IC equipment from contractors	53.8%	7
Complexity of QC and/or QA procedures	30.8%	4
Disputes from contractors	15.4%	2
Others:	30.8%	4
	answered question	13
	skipped question	11
	Total	24



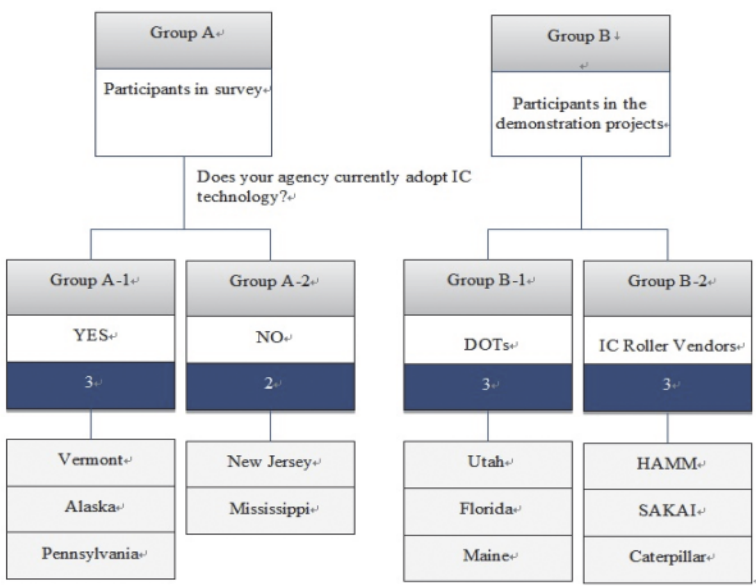
Group 2-2 Question 3—Additional Comments	
1	Training is critical in operation of IC rollers and the analysis of the IC data for both Contractor and Departmental personnel. IC data management and software requires specialized training from roller manufacture and the FHWA IC consultant.
2	More a contractor's responsibility
3	With IDOT's current specifications, we do not method specify how to get density. It is up to the contractor to determine how to optimize density and therefore pay.
4	Inexperience

APPENDIX B: INTERVEIW FOR IC TECHNOLOGY

Interview Outline for IC technology

The potential interviewees are classified into two groups. Group A consists of respondents in the survey, and Group B contains vendors and DOT's who participated in the field demonstration projects from 2012 to 2014. Twenty six AASHTO members answered the survey. Among them, Group A-1 answered "Yes" for the first question, and Group A-2 answered "No" for the question. Group B is made up of the experts who participated in the field demonstration for a research project called "Intelligent Compaction: Quality Assurance for In-place Density Acceptance" from 2012 to 2014. Group B is divided into two groups. GroupB-1 indicates the DOT's, and GroupB-2 indicates the vendors who are involved in the IC rollers.

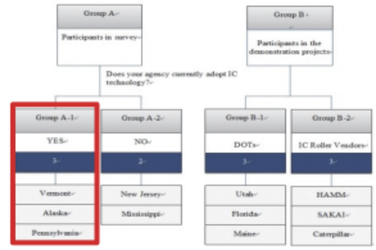
Purpose of the project	To explore the possibility of improving the effectiveness of asphalt mix QC and/or QA by using IC rollers and available data output.
The objective of the interview	To investigate how the states have made use of IC technology after the demonstration projects and how much benefit the states have received by applying IC technology
Interview form	Phone interview
Time	Less than 30 minutes
Participants	Group A: Participants in the IC survey
	Group B: Participants in the IC field demonstration projects from 2012 to 2014



Structure of interview

1. Group A-1

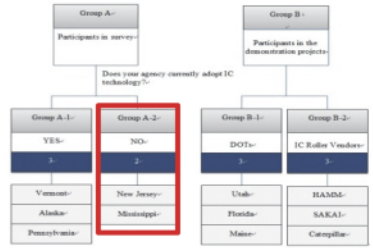
Group A-1 consists of respondents who answered "Yes" for the first survey question "Does your agency currently adopt the IC technology?"



Group A-1		
	Question	Purpose
Q1	When did your agency adopt the IC for QC/QA?	A time for adopting IC technology
Q2	Why/how did your agency adopt the IC for QC/QA? Any quantified benefit since your agency adopted the IC?	Benefits
Q3	How many contracts do you have after adopting the IC for QC/QA?	Current contract
Q4	Is there any contract cost increase due to the IC for QC/QA?	Cost issue
Q5	How do you implement the IC for QC/QA? Do you use Veda software?	Implementation
Q6	What improvements or concerns are needed to use the IC technology for QC? QA?	Improvement

2. Group A-2

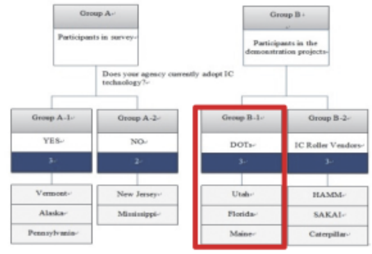
Group A-2 consists of the participants (n=11) who answered that they have not adopted the IC technology and, they do not have a plan to use it in the future.



Group A-2		
	Question	Purpose
Q1	What are your reasons for not using the IC technology now?	The reasons for not using IC technology
Q2	What assessment properties does your agency measure for the HMA construction quality control and/or quality assurance?	Current assessment for HMA construction
Q3	What are the main issues with implementing the IC technology based on your project and research?	Main issues

3. Group B-1

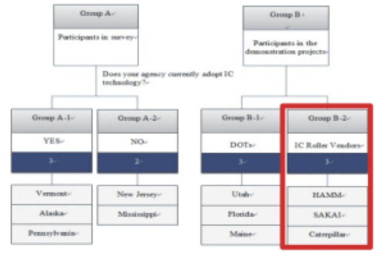
Four DOT's participated in the demonstration for the research entitled "Intelligent Compaction: Quality Assurance for In-place Density Acceptance" from 2012 and 2014. Group B-1 consists of the four DOT's: Utah DOT, Florida DOT, Maine DOT and Utah DOT. They published their final report and implemented the demonstration projects.



Group B-1		
	Questions	Purpose
Q1	Your agency participated in the HMA compaction demonstration. When did you have the demo? How many sites did you have for the demo?	The information of the demonstration projects
Q2	Does your agency currently adopt the IC technology for QC and/or QA? (Do you have any plan to adopt the IC?)	The application of IC technology in QC/QA
Q3	Did you see any attractive benefit of the IC for your agency QC/QA from the demo?	Benefits
Q4	Did you use Veda software to identify the optimal pass count and target ICMV in the demonstration?	Veda software
Q5	Did you see any limit of the IC application to QC/QA?	Limitation of IC application
Q6	What improvements are needed to use IC technology for QC and QA?	Improvements
Q7	Cost-effectiveness for IC technology	Cost-effectiveness

4. Group B-2

Group B-2 indicates the vendors who took part in the demonstration with Group B-1 DOTs from 2012 to 2014.



Group B-2		
	Questions	Purpose
Q1	What are the advantages of using your IC rollers compared to other vendors with respect to technology, application, cost, etc.?	The advantage of IC Roller manufacturer
Q2	How many types of IC rollers do you have? (breakdown roller, intermediate roller and finish roller)	The Model
Q3	Your IC rollers produce ICMV values. How do you interpret your ICMV data with respect to the QC/QA parameters?	The relationship ICMV and in-place density
Q4	Training is critical for operation of IC rollers. Do you have a training program?	Training issue
Q5	When you participated in the demonstration, what were the main problems with implementing IC rollers?	Main issues with implementing IC rollers

Interview Results for IC technology

Group A-1	
1. Question	When did your agency adopt the IC for QC/QA?
Alaska	Last year for QC (2013)
Vermont	Vermont utilizes IC for QC tools(2012)
Pennsylvania	"Adopting IC technology" and "adopting IC technology for QC/QA" is NOT the same thing. PennDOT executives made a decision to adopt IC technology in 2012 I was directed to begin working with it in February/March 2012. I would NOT say that PennDOT has any intention to adopt IC for QC/QA purposes because of the variables mentioned above in your "purpose of the project."
2. Question	Why/how did your agency adopt the IC for QC/QA? Any quantified benefit since your agency adopted the IC?
Alaska	• Night time paving is necessary to use IC technology • Better quality control process • Uniform compaction and less pavement maintenance
Vermont	Major benefit is consistent roller pattern
Pennsylvania	Executive decision The expected benefit is a more uniform compaction resulting in less future maintenance.
3. Question	How many contracts do you have after adopting the IC for QC/QA?
Alaska	• Two projects 2013 and 2014 • Bother are demonstration not real project. • Alaska is also considering IC as QC so try to have more demonstration projects to identify the benefits from IC. • Alaska has a specification for IC/ QC
Vermont	• One project in 2012 • One project in 2014(upcoming)
Pennsylvania	We presently have 8 active projects with 2 pending authorization. Our first IC project was completed in May 2014. The second is scheduled to start later this month.
4. Question	Is there any contract cost increase due to the IC for QC/QA?
Alaska	• The last project spent 80,000 with two compactors (HAMM). • The second project spent 40,000 with one compactor in small project. (IC needs GPS and other device so it is difficult to compare to regular compactors) IC rollers more cost than normal one

Vermont	• Marginal increase but not much • 0.1% of total contract cost The cost of IC equipment is marginal compared to total contract.
Pennsylvania	The cost has been between $20,000 and $50,000 depending on the contract. I have a spread sheet with information pertaining to location, size of projects, overall contract price and IC prices.
5. Question	How do you implement the IC for QC/QA? Do you use Veda software?
Alaska	Contractors submit color coded map and optimal pass count(for example, 95% of coverage is under the optimal pass count)
Vermont	• Using specification. • The previous one we didn't use Veda. • We have a plan to use it upcoming project.
Pennsylvania	We have developed a draft specifications (Step 1.0 and Step 2.0) based on the FHWA guide specs and other states. We are in the process of further editing it and will likely have a version 3.0 available later this summer. This 3.0 version will include revisions based on our recent field experiences.
6. Question	What improvements or concerns are needed to use the IC technology for QC?QA?
Alaska	• Improvement: How do we accept QA after being using IC technology? • Current contractors are reluctant to use new technology so how to encourage them to use it is another concern.
Vermont	• Temperature and roller pattern can be proved in QC • We need to show the relationship b/w ICMV and in-place density first to go forward. • We suspect that ICMV is related to HMA density.
Pennsylvania	Present acceptance criteria are based on density testing of cores extracted from the pavement. IC does not provide density information. Therefore, IC will not be a QA tool for the foreseeable future. IC can certainly be a construction aid; IC may be able to reduce the number of cores drilled *IF* the IC data can demonstrate good pass coverage, good temperature range, and good ICMVs. It might be possible to specify the required number of passes based on the test strip. But you really cannot specify the number of passes in advance, so the contracting office will likely have a fit. It might be possible to specify the acceptable range in temperature to achieve the compaction. Therefore, only passes completed while the temperature was warm enough will count for QA purposes. It might be possible to monitor the standard deviation in the ICMVs; and a good tight data set would give some confidence that perhaps we do not need to drill as many cores as usual – perhaps double the spacing if consistently

	good results are obtained. HOWEVER, this means that the IC data has to be downloaded and analyzed in the field at whatever time of day (or night) that is; and a decision on the number of acceptance cores has to be made on the spot. WHO is going to be reviewing and analyzing this data and making that decision? Also, some systems require an internet connection to access the data stored in the "cloud." Therefore the DOT inspector will need a laptop with an aircard to monitor the work.

Group A-2	
1. Question	What are your reasons for not using the IC technology now?
Mississippi	Mississippi DOT participated in demo in 2009 We potentially use the IC technology in the future. Two reasons to hold the adopting it. First, we had a pilot project. There was no standard for measuring the HMA stiffness. Individual equipment has their stiffness but different values. As well as stiffness of asphalt is related to temperature. There was no correlation b/w stiffens and temperature. Second, there are a lot of opinions for how those data to use acceptance decision. When the contractor collects the IC data, we do not know yet how we can compare that with core-density or nuclear gauge density.
New Jersey	We are not using it now. Because we have a difficulty of cooperation from contractors. We are working on specification of IC now means we will adopt the IC in the future.
2. Question	What assessment properties does your agency measure for the HMA construction quality control and/or quality assurance?
Mississippi	QC/QA mixture property tests : Asphalt Content, VMA, Air void ,In-place density We have used the nuclear density in large projects and core-density in small projects. We have used nuclear and core- density together.
New Jersey	QC : Nuclear density gauge with core to calibrate the NG QA : core density(5cores) and IRI
3. Question	What are the main issues with implementing the IC technology based on your project and research?
Mississippi	Normalized stiffness(standard) We can map using continuous measurement (consistency type measure) which is really great to adopt it. But there are a couple of issues to figure out.
New Jersey	We have to push back to the contractors to adopt the IC rollers

Group B-1	
1. Question	Your agency participated in the HMA compaction demonstration. When did you have the demo? How many sites did you have for the demo?
Florida	One site on I95 in 2012 (small road)
Maine	One site on I95 in 1213
Utah	One site on US 89 in 2012
2.Question	Does your agency currently adopt the IC technology for QC and/or QA? (Do you have any plan to adopt the IC?)
Florida	We are not adopting the IC for QC/QA. We have a plan to do demonstration projects and projects (IC as a primary technology in EC technology) The problem for using IC is that contractors are not positive to adopt the IC. Equipment cost is increasing There is no correlation b/w ICMV and in-place density. The benefit of IC is to achieve the target level of the compaction of uniformity of materials. But we didn't see Uniformity of material in demo.
Maine	We are not adopting it yet. We are working on implementation work. We are not requiring the project. We have a plan to conduct the demonstration and research project. We do not have specification but working on it.
Utah	We have used it case by case. We have not fully adopted IC. Three projects for QC We have a specification The reasons for struggling with using it: We cannot use it as QA. The stiffness value is not equal to density.
3.Question	Did you see any attractive benefit of the IC for your agency QC/QA from the demo?
Florida	Good tool for QC for night time paving The advantages: visual the display with pass count and temperature
Maine	Coverage mapping It is beneficial for night time paving We dint see how stiffness curve help the QC. For QA, less useful for QA I didn't see a good relation b/w ICMV and density test.
Utah	Uniform compaction

4. Question	Did you use Veda software to identify the optimal pass count and target ICMV in the demonstration?
Florida	We didn't. The research team implemented the software. We need training.
Maine	Contractor took the density (NG) for pay adjustment. Contractor didn't use veda. After project, research team gave the optimal pass count and target ICMV
Utah	We didn't use the veda. We are not using it now too
5. Question	Did you see any limit of the IC application to QC/QA?
Florida	Training: using equipment Using management data(including software)
Maine	No limit It is useful technology
Utah	No limit for QC Density is a limit for QA
6. Question	What improvements are needed to use IC technology for QC and QA?
Florida	QA: future phase QC: uniformity mat and visual the display with pass count and temperature
Maine	For QC, I suspect that whether or not stiffness value is going to be appropriate for QA. For soil, stiffness shows good relationship that we want to know. But for pavement, the volume of the matrix affects the stiffness.
Utah	Training is the big issue: Contractor training The questions is how to download the data and how to interpret the data
7. Question	Cost-effectiveness for IC technology
Florida	It's not cost-effective.
Maine	Although the equipment is cost, we would reduce the QC cost in total. Better density test would help contractor reduce pay adjustment.
Utah	Although it costs more we are willing to pay more. Because it shows better product. Rent cost (40,000) will be spent if we use the rollers.

Group B-2	
1. Question	What are the advantages of using your IC rollers compared to other vendors with respect to technology, application, cost, etc.?
Caterpillar	Ruggedness and reliability of the hardware and software. Wireless data transfer is very reliable and seamless. Data integrity. Data is stored on the machine and in the "cloud"
HAMM	1. Ease of set-up and use with OmniSTAR GPS system. Basically it i s an annual subscription you pay for that does not use a land based system. It uses a correction calculation of the GPS-signals via geos tationary reference stations. 2. Correction signal is transmitted via communication satellites to D-GPS receiver on the roller. Takes 5 minutes to hook up. Plug & pla y. 3. Have the option of split screen viewing where you can see two thin gs at once. Mostly you will have pass count on the left and either st iffness or temperature on the right. You can also view just a single screen if you wish but most prefer the split screen. 4. We have the ability to communicate with more than one roller at a time and up to three rollers in the paving train. This is done throug h a Wi-Fi connection. 5. We can transfer the PC Tablet and receiver from one roller to the o ther. It can be between two different soil or asphalt rollers or betwe en a soil and asphalt roller. This makes one system able to be used over various machines without the added cost of another whole sys tem. 6. The viewing screen on our PC Tablet is much larger than any other s and is easier for the operator to see what he and the roller are doi ng.
SAKAI	Accelerometer measures the compaction response quicker.
2. Question	How many types of IC rollers do you have? (breakdown roller, intermediate roller and finish roller)
Caterpillar	CD54B
HAMM	HD+ 90 / HD+ 110 HD+ 120 / HD+ 140
SAKAI	SW880 SW890
3. Question	Your IC rollers produce ICMV values. How do you interpret your ICMV data with respect to the QC/QA parameters?
Caterpillar	Try to establish a correlation with the current measurement method of acceptance/payment. Typically a density specification for either soils or asphalt correlated with a nuclear density gauge, although ICMV's correlate better with other testing devices, such as the Lightweight Deflectometer on

	both soils and asphalt.
HAMM	The calculation that is used to come up with our stiffness value from the information feedback from the accelerometer that is mounted on the left side of the front vibratory drum inside the rubber buffers. $$CMV = C_1 \cdot \frac{A_{2\Omega}}{A_\Omega}$$ Where C_1: a constant (e.g., 300); $A_{2\Omega}$: amplitude at the second order harmonic frequency; A_Ω: amplitude at fundamental frequency.
SAKAI	There are many field demonstration projects to identify the relationship between ICMV (CCV) and In-place density especially Nuclear gauge test to identify the relationship. One project in Idaho showed better results.
4. Question	Training is critical for operation of IC rollers. Do you have a training program?
Caterpillar	We have a basic program for QC people
HAMM	Having a plan to make the specific training manual.
SAKAI	We are responsible for all working including GPS setting and accelerometer and so on. SAKAI is in the process to set up the tanning program now.
5. Question	When you participated in the demonstration, what were the main problems with implementing IC rollers?
Caterpillar	Most problems are related to the proper setup of GPS and positioning systems. Having good satellite reception (clear line of sight to the sky) and loading a proper "calibration file" to establish the desired coordinate system on a given job site.
HAMM	1. Training – The misconception by the State and Contractors that you just put it on the roller and start rolling to collect data. It is called in telligent compaction not smart compaction. 2. Operators understanding how to use the system to help them out. So me like it and some do not. Getting the contractors to understand that they need someone to manage the system and the data you get from it. It is not something we want the roller operators to be in control of. Looking for a QC Manager for the Company to manage the system and understand it.
SAKAI	Setting up the GPS is difficult.

APPENDIX C: INTERVIEW FOR GPS ONLY APPLICATION

Interview Outline for GPS Only Application

Purpose of the project	To explore the application of conventional HMA compactors equipped with GPS.
Interview form	Phone interview
Time	Less than 30 minutes
Participants	Participants: • Sitech • Trimble

	Questions	Purpose
1	Trimble and Sitech have participated in several IC demonstration projects including those conducted in Indiana and Ohio. What is the difference between GPS of IC compactor and your system including CCSFlex or CCS900?	Comparison of IC compactor and CCSFlex or CCS900
2	How many projects for the HMA compaction have been done using CCSFlex or CCS900?	Current state of the application of CCSFlex or CCS900
3	CCSFlex or CCS900 are based on the base station-free Satellite-based Augmentation Systems (SBAS). What is the accuracy level of GPS of SBAS? Are there other options to improve the accuracy level?	Accuracy level of GPS
4	Is CCSFlex or CCS900 cost effective when compared to the IC compactor with a base station? (comparison of cost)	Cost of CCSFlex
5	What are the benefits of CCSFlex or CCS900 with respect to: • Training issues • The difficulty in setting up the unit • Human resource requirements • Printouts (i.e., number of passes)	Availability of CCSFlex or CCS900

Interview Results for GPS Only Application

1. Question	Trimble and Sitech have participated in several IC demonstration projects including those conducted in Indiana and Ohio. What is the difference between GPS of IC compactor and your system including CCSFlex or CCS900?
Trimble	• CCS900 is more commonly used than CCSFlex. • CCS 900 has larger screen and local coordinate system. • CCS900 can load a design and the shape of the road.
Sitech	• CCSFlex and CCS900 are based on a basic configuration using a SBAS. • CCSFlex and CCS900 can be updated to Virtual Reference Station (VRS) or Real-time Kinematic (RTK). • CCSFlex is designed more as a "pass count" solution, though we can add an accelerometer component as well as a temperature component as needed (as in an IC compactor). • CCSFlex can only use a Universal Transverse Mercator (UTM) Coordinate System. • CCS900 can utilize a localization based on State Plane or any other coordinate system the contractor chooses.
2. Question	How many projects for the HMA compaction have been done using CCSFlex or CCS900?
Trimble	• Trimble is involved with many IC projects in 17 States in the U.S.A.
Sitech	• 3 or 4 projects with CCSFlex. • 3 or 4 projects with CCS900.
3. Question	CCSFlex or CCS900 are based on the base station-free Satellite-based Augmentation Systems (SBAS). What is the accuracy level of GPS of SBAS? Are there other options to improve the accuracy level?
Trimble	• SBAS accuracy is 39-118 in. • When the SBAS unit is upgraded with RTK and VRS, it is possible to get high level of accuracy.
Sitech	• SBAS accuracy is 39-118 in. • We can add some code and a GNSS Radio and upgrade to RTK with centimeter level accuracy.

4. Question	Is CCSFlex or CCS900 cost effective when compared to the IC compactor with a base station? (comparison of cost)
Trimble	The cost range varies based on what you want to add from $16,000 to $45,000.
Sitech	• CCSFlex starts around $20,000. • CCS900 starts around $45,000. • The update cost from SBAS to RTK is around $20,000.
5. Question	What are the benefits of CCSFlex or CCS900 with respect to: • Training issues • The difficulty in setting up the unit • Human resource requirements • Printouts (i.e., number of passes)
Trimble	• Training Issues: Simple training within 15 minutes • The difficulty of setting up the unit: – It takes 3 to 4 hours to install. – Some IC rollers like Caterpillar are already equipped with a GPS unit. • Human resource requirements: We don't need an expert to operate. • Printouts: – CCSFlex and CCS900 are capable of printing results (Pass count). – Trimble provides VisionLink® which is web-based application. VisionLink® allows you to review the results quickly.
Sitech	• Training Issue: No positives or negatives here. • The difficulty of setting up the unit: – CCSFlex system creates its own coordinate system (UTM Only). – Accuracy and repeatability are not as good when using a SBAS. • Human resource requirements: Needs an operator. • Printouts : – CCSFlex and CCS900 are capable of printing results. – Information is more limited if using a SBAS solution.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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The recommended citation for this publication is:

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