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Implementation of Intelligent Compaction Technologies for Road Constructions in Wyoming

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IMPLEMENTATION OF INTELLIGENT COMPACTION TECHNOLOGIES FOR ROAD CONSTRUCTIONS IN WYOMING

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ABSTRACT

Conventional test methods for roadway compaction cover less than 1% of roadway; whereas, intelligent compaction (IC) offers a method to measure 100% of a roadway. IC offers the ability to increase compaction uniformity of soils and asphalt pavements, which leads to decreased maintenance costs and an extended service life. This report examines IC technology, how IC quality control and assurance specifications can encourage IC adoption, knowledge and use of IC through survey responses, and benefits and costs of IC. The surveys reveal that a majority of respondents from state departments of transportation have conducted IC demonstration projects, but questions about cost and willingness of policymakers to adopt IC remain a barrier to implementation. The benefit-cost analysis demonstrates that use of IC reduces compaction costs by as much as 54% and results in a $15,385 annual savings per lane mile throughout the roadway's life.

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1. INTRODUCTION

1.1 Overview

The quality of a roadway is related to the quality of the compaction of its pavement and underlying aggregate. State and local officials have used two general techniques to evaluate the compaction of a pavement and soil: stiffness tests or density tests. These tests reveal mechanistic properties of the soil or pavement that are measured at several points along a roadway. Point measurement methods, such as the light weight deflectometer (LWD), nuclear gage test (NG), static plate load test (PLT), and Proctor tests, have been widely used to measure the stiffness, density, or moisture of compacted soils and pavements. Roller-integrated continuous compaction control (CCC) and intelligent compaction (IC), which are distinguished in Section 1.2, have become new methods to gather data about compaction by obtaining stiffness values of the soil in real time. The Wyoming Department of Transportation (WYDOT) currently utilizes point measurement methods to evaluate the compaction of its roadways. Point measurement provide a means for verifying soil compaction; however, this method provides data for less than 1% of a roadway section and requires staff to take field measurements. CCC and IC increase data collection to 100% of the roadway section and reduce the amount of point measurements. For these reasons, adoption and implementation of roller-integrated CCC and IC has the potential to benefit transportation agencies, including WYDOT. Roller-integrated CCC and IC are capable of leading to decreased construction costs and duration, improved long-term pavement quality, and improved documentation. This report demonstrates how adoption and implementation of roller-integrated CCC and IC technologies best benefit the State of Wyoming and other jurisdictions nationally and internationally.

1.2 Background

Research on utilizing roller-integrated CCC and IC in the State of Wyoming commenced in 2013 by researchers at the University of Wyoming in order to develop state-specific quality assurance (QA) guidelines for the implementation of roller-integrated CCC or IC for soil and pavement compaction. "Intelligent soil compaction systems," also known as intelligent compaction (IC), were defined by the National Cooperative Highway Research Program (NCHRP) Report 676 as having three characteristics (Mooney, et al., 2010):

1) Continuous assessment of mechanistic soil properties (e.g., stiffness, modulus) through roller vibration monitoring
2) On-the-fly modification of vibration amplitude and frequency
3) Integrated global position system (GPS) to provide a complete geographic information system-based record of the earthwork site

Characteristics 1 and 3 define roller-integrated CCC, which was first introduced in Europe during the 1970s. Specifications for use of roller-integrated CCC were first introduced in Austria in 1990 and have been endorsed by the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). Characteristic 2 describes an automatic feedback control (AFC) that allows compaction equipment to adjust vibration amplitude and frequency in response to compaction data gathered by the equipment during operation.

CCC and IC technologies on-board compaction equipment yield measurement values (MV) of soil stiffness and modulus from compaction lifts, usually 6 to 12 inches, and their underlying layers up to 5 feet in depth. Collected MVs, in conjunction with GPS, allow for real-time compaction data to be gathered to spatially analyze the compaction levels of soils and pavements. This information is used to determine weak compaction areas and prevent unnecessary over-compaction (Mooney, et al., 2010).

The Federal Highway Administration (FHWA) has led efforts to introduce IC technology throughout the country. In 2008, the FHWA began pilot projects in conjunction with state departments of transportation (DOTs) in Colorado, Florida, Maryland, Minnesota, and North Carolina. Subsequently, several other states have initiated pilot projects through their respective DOTs. Many states are developing or have already developed QA standards for IC. Additionally, the FHWA included IC as part of a second installment of its Every Day Counts initiative, which focuses FHWA resources on developing technologies that decrease project delivery time, improve roadway safety, and help protect the environment (Federal Highway Administration, 2012).

1.3 Problem Statement

Current soil and pavement compaction practices utilize point measurements techniques include tests with a nuclear gage, dynamic cone penetrometer, or LWD. These methods measure approximately one percent of the area being compacted, and the compaction quality of the entire compaction area is evaluated based only on these point measurements. Thus, sufficient compaction quality may not be achieved in several locations within the compaction area, which can lead to reduced long-term pavement quality and increased road maintenance costs. This report investigates how to address these problems by utilizing IC technologies and improving QA standards.

1.4 Project Scope

The goal of this research is to improve pavement quality and safety, decrease road maintenance and construction costs, and decrease road construction duration in Wyoming using IC. Five objectives have been established in order to achieve this goal: to 1) examine current IC technologies and practices, 2) analyze survey results about how other agencies implement IC for soil and pavement compaction, 3) conduct an economic analysis of IC, 4) propose recommendations for QA implementation in Wyoming, and 5) establish future research needs.

1.5 Outline

A literature review was performed (Section 2 and 3) with the goal of evaluating technologies and practices that best benefit Wyoming through learning IC technologies, IC case studies, and QA standards. The literature review examines 1) current IC technologies and practices, 2) current design and construction practices of soil and pavement compaction, 3) current national and state QA guidelines, 4) implementation of IC technologies in compaction practices, and 5) current agency specifications on IC.

A nationwide survey and a Wyoming survey (Section 4) were conducted to complement the literature review and provide information about how research from IC has been implemented. The goal is to understand barriers to adoption of IC, how IC has been implemented, and evaluating the success of IC implementation. The nationwide survey results were analyzed to learn how other transportation agencies perform soil and pavement compaction and to ascertain if and how IC technologies are being utilized. The survey questions address topics such as the current compaction process used, QA specifications enacted, and how IC is integrated into compaction practices. The survey contains a variety or multiple choice and short answer questions. The nationwide survey was available online and sent to transportation agencies throughout the nation. The Wyoming survey was conducted during a WYDOT-sponsored workshop in March 2014.

An economic analysis (Section 5) was conducted to evaluate the short-term and long-term benefits and costs of utilizing IC for compaction of roadways. This includes construction related costs (short-term) and increases to pavement life from benefits to improve compaction (long term). Cost data were obtained from contractors, roller manufacturers, and roller retailers.

Evaluation of the literature review, survey results, and economic analysis helps to develop recommendations for QA implementation and establish future research needs in Wyoming (Section 6). Recommendations were established to 1) facilitate the implementation of IC technology in Wyoming, 2) suggest the benefit/cost analysis of its implementation, and 3) highlight potential changes to current construction practices.

2. LITERATURE REVIEW ON SOIL COMPACTION

2.1 Overview

This section highlights the findings about soil compaction from the literature review. The purpose of this review is to present and analyze various CCC and IC technologies, QA options incorporating CCC and IC, and current practices of CCC and IC. The analysis is used to develop survey questions for transportation agencies and a recommendation for types of demonstrations to be conducted in Wyoming, which are discussed in Section 4 and Section 6, respectively. This section includes the background of IC, types of IC rollers, how MVs are generated, how MVs relate to point measurement compaction tests, types of QA options using IC, case studies that evaluate QA options, and roadway compaction specifications used by various transportation agencies.

2.2 Background of Intelligent Compaction

2.2.1 History

Mooney and Adam (2007) have documented the history of roller-integrated CCC, which should be referred to for more detail. Dr. Heinz Thurner, a Swedish Highway Administration official, introduced the first roller-integrated CCC by instrumenting a 5-ton-tractor drawn Dynapac vibratory roller with an accelerometer. The research began in 1974, and the following year Dr. Thurner and his partner Ake Sandstrom founded Geodynamik to advance the technology. Geodynamik introduced the compaction meter value (CMV) in 1978 and, working in conjunction with Dynapac, has offered it commercially since 1980. Several companies have introduced compactometers with CMV, including Ammann, Caterpillar, and Ingersoll Rand. Bomag introduced its proprietary Omega value and Terrameter in 1982. Bomag added the E_{vib} value in the late 1990s, which is a measure of dynamic soil stiffness (Kröber, Floss, & Wallrath, 2001). Sakai introduced its compaction control value (CCV) in 2004 (Scherocman, Rakowski, & Uchiyama, 2007). The advancement in compaction technology allowed for Austria, Germany, and Sweden to establish QA specifications for CCC during the 1990s. ISSMGE has endorsed Austrian specifications for CCC (Mooney, et al., 2010).

2.2.2 Technology

CCC is described as having two components: continuous assessment of mechanistic soil properties and integrated global position system to provide a complete geographic information system-based record of the earthwork site. IC includes an additional component, which is the ability to adjust the amplitude and frequency in real time based on the mechanistic properties of the soil. Instrumentation is placed within the roller to gather data on the vibration of the roller with regard to its amplitude and frequency. The information received is translated into a roller MV, which is discussed further in Section 2.3. The MVs are transmitted to a computer on board the compactor, which also plots the MV in real time to a geographical location on a map from a GPS unit (Mooney, et al., 2010).

Geodynamik created the first instrumentation used to generate MVs as discussed in Section 2.2.1. The company used a mechanically implemented two-piece clamshell eccentric mass assembly within the drum. This drum would create two eccentric masses that would combine to create a maximum eccentric mass moment m_oe_o, where m_o is the mass of the weight within the drum and the e_o is related to the distance of the weight from the center of the drum. This occurs when the roller is driven in one direction with frequency Ω (rad/s). The eccentric mass moment and frequency would create a maximum time-varying centrifugal force F(t). This force can be generated theoretically using Eq. 2.1, where *t* is time in seconds. F_{ev}, which is used by Bomag in its variocontrol roller with counter-rotating eccentric masses, is the vertical component of the eccentric force $m_o e_o \Omega$ (Mooney, et al., 2010).

$$F(t) = m_o e_o \Omega^2 \cos(\Omega t) = F_{ev} \cos(\Omega t) \tag{2.1}$$

The roller amplitude A was calculated using Eq. 2.2 on the basis of the eccentric mass moment and the drum mass m_d.

$$A = \frac{m_o e_o}{m_d} = \frac{F_{ev}}{m_d \Omega^2} \tag{2.2}$$

Servo-controlled rollers have allowed IC to occur more easily. Servo-controlled rollers have the ability to automatically adjust the vibratory amplitude and frequency to improve roller performance. Ammann/Case, Bomag, and Dynapac IC rollers have the ability to automatically adjust vertical vibration force when operating conditions are not optimal. Furthermore, Bomag and Amman/Case rollers can reduce the eccentric force amplitude as the user-defined roller threshold MVs are reached.

The recommended on-board GPS unit should be real-time kinematic, which generally exhibits better accuracy than satellite differential GPS. Horizontal accuracy is approximately 0.98 inch, and vertical accuracy is 1.46 inch; however, the MV resolution in the direction of the roller is between 0.66 feet and 3.3 feet. The resolution is recommended to be no less than 10 times the accuracy of the GPS unit being used. The MV resolution in the roller's direction of travel is a spatial average of data received within the MV resolution area. Resolution parallel to the drum is approximately 6.6 feet, which is approximately the width of the roller's drum. The resolution parallel to the drum is an average of the MVs from the overlap of roller passes with an overlap of approximately 0.3 feet on sequential passes (Facas & Mooney, 2010).

GPS positioning errors occur by 1) offset of the GPS receiver to the drum center, 2) data averaging during calculation of the roller MV while the roller is moving, and 3) the roller's travel direction. The error from offset can be remedied by calculating the offset distance of the GPS receiver into the software of the on-board IC computer. The software should also be designed to factor in the roller's travel direction. Errors resulting from data averaging occur because the MV occurs at the end of the reporting resolution area. The software must be programmed to account for this error, adjusting the location of the MV to the center of the resolution area (Facas & Mooney, 2010).

2.2.3 Equipment

IC equipment is typically attached to smooth drum rollers or sheep's foot rollers; however, sheep's foot rollers have displayed large MV variability during repeatability studies and are less favored for use in CCC and IC. Most rollers are retrofitted with the IC and GPS equipment. The IC equipment, which includes a sensory processing unit and display as depicted in Figure 2.1, allows for generation of MVs that are mapped using GPS equipment. Table 2.1 contains roller models that are capable of generating MVs for soils (The Transtec Group, Inc., 2013). Figure 2.2 is an example of vibratory rollers that can be outfitted with roller-integrated CCC/IC systems.

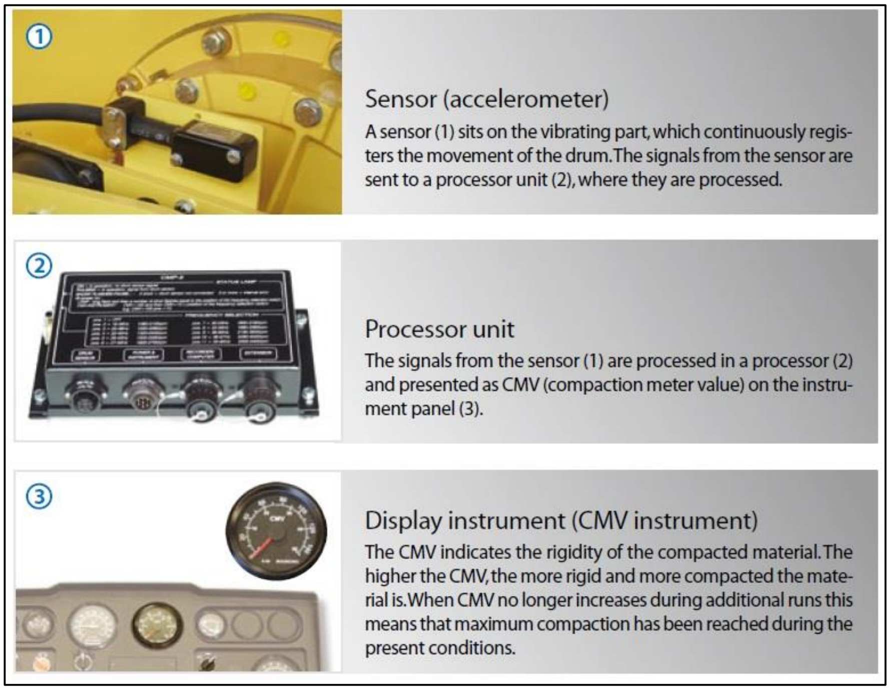

Figure 2.1 Roller-integrated CCC System by Dynapac (Dynapac, 2013)

Figure 2.2 Vibratory Rollers for Roller-Integrated CCC/IC

Table 2.1 List of IC Equipped Roller Models for Soil Compaction

Vendor	Model	Model No	IC-MV	Software
Ammann/Case	ACEplus	SV	K_b	ACEplus
Bomag	VarioControl	BW213-4BVC	E_{vib}	BCM05
Caterpillar	AccuGrade	CS44-CS78 CP54-CP74	CMV, MDP	AccuGrade, VisionLink
Dynapac	DCA-S	CA 152-702	CMV	DCA-S
HAMM(Wirtgen)	HCQ		HMV	HCQ
Sakai	CIS	SW850-SW900	CCV	AithionMT
Volvo	Trimble retrofit		CMV	SiteVision, VisionLink

IC-MV: Intelligent compaction measurement values; a generic term for all IC measurements
ACEplus: Ammann Compaction Expert – Plus DCA – S
K_b: Ammann soil stiffness value
GPS: Global Positioning System
E_{vib}: Vibration Modulus
CMV: Caterpillar and Dynapac Compaction Meter Value
MDP: Caterpillar Machine Drive Power
CIS: Sakai Compaction Information System
CCV: Sakai Compaction Control Value
DCA: Dynamic Compaction Analyzer
HCQ: HAMM Compaction Quality
HMV: HAMM Measurement Value

2.3 Measurement Values

2.3.1 Generation of Measurement Values

As noted in Table 2.1, the manufacturers of roller-integrated CCC that generate MVs are Dynapac, Caterpillar, Hamm, Volvo, Sakai, Ammann/Case, and Bomag. Currently, Dynapac, Caterpillar, Hamm, and Volvo rollers generate the CMV. The CMV value is the ratio of vertical drum acceleration amplitudes at the operating vibration frequency. Sakai uses the CCV, which is the algebraic relationship of multiple vertical drum vibration amplitudes, including fundamental frequency, multiple harmonics, and subharmonics. Ammann/Case rollers generate a stiffness value k_b. The k_b value takes into consideration the vertical drum displacement and the drum-soil contact force. Bomag rollers generate an E_{vib} value that is generated similar to the k_b value (Mooney, et al., 2010).

2.3.2 Relationship to Roller Operation and Site Conditions

Roller MVs correlate well with conventional measurement tests, such as the plate load test (PLT) and lightweight deflectometer (LWD), due to the dependence of MVs on soil stiffness. However, the generation of MVs is also affected by operating factors and site conditions. The amplitude, frequency, speed, and direction of the vibratory roller are examples of operating factors that MVs are dependent upon. Soil heterogeneity and lift characteristics are site conditions that affect MVs.

The measurement depth was affected by the amplitude of vibratory rollers. NCHRP Report 676 concluded through case studies that the each increase of 0.1 mm of amplitude corresponded to an increase of 3 cm of depth (Mooney, et al., 2010). Depending on the soil characteristics, the change in measurement depth had an impact on MVs. The dependence of MVs on measurement depth is discussed later in this section. The dependence of MVs solely on amplitude was unpredictable, but a correlation existed between the MV-amplitude dependence and soil type. Granular soils demonstrated a positive MV-amplitude dependence; whereas, cohesive soils demonstrated a negative roller MV-amplitude dependence. Due to the high unpredictably of the effect of amplitude on MVs, constant amplitude is recommended while conducting QA.

The effect of roller MVs as a function of frequency was tested with Sakai and Ammann/Case rollers. MVs depend on roller frequency due to the partial loss of contact with the soil. Sakai rollers experienced a higher loss of contact when the frequency was set to 20 Hz, compared with 25 Hz (Mooney, et al., 2010). Due to the MV dependence on frequency, constant frequency is recommended while conducting QA.

The Sakai and Dynapac rollers displayed a decrease in MV with increasing speed. The roller speed relationship in Sakai and Dynapac rollers occurs because a partial loss of contact with the soil is reduced with the vibration energy spread over more soil at higher speeds. Constant roller speed is recommended during QA with Sakai and Dynapac rollers (Mooney, et al., 2010).

Rollers are typically used in forward and reverse directions. MVs for each direction were taken for Ammann, Bomag, Dynapac, and Sakai rollers. Discrepancies between the MVs for each direction were “subtle” for each of the rollers (Mooney, et al., 2010). The MVs of each driving direction should be measured at the site and compared to determine the amount of discrepancy.

Soil heterogeneity can greatly affect MVs, which can vary by 100% due to the variability in transverse soil stiffness. LWD testing is recommended across the drum lane to evaluate the soil heterogeneity. If QA is dependent on repeated passes, then the passes should be conducted over the same area of soil.

The soil characteristics of the lift and the soil underlying the lift can also affect MVs. IC equipment measure at depths between 2.7 and 4.0 ft and an area from 0.1 to 0.3 ft in front of and behind the drum. Measurement depth varies linearly at a rate of 1.2 in for each 0.04-in change in vibration amplitude. The generation of MV based on the measurement of the depth is affected by the lift and layer thickness, relative stiffness of layers underlying a lift, vibration amplitude, and drum-to-soil interaction (Mooney, et al., 2010). The ratio of lift stiffness to sub-lift stiffness greatly affects MVs. MVs were especially unreliable measures of soil stiffness, with up to 50% variability, when 6-in lifts of stiff soil were placed above less stiff sub-lift soil.

In order to capture the mechanistic soil properties of a lift, a method was developed to calculate the lift stiffness while accounting for sub-lift materials. This method involves forward modeling and inverse analysis using finite element (FE) and boundary element (BE) methods. Forward modeling utilized FE and BE to predict the expected MVs for individual lifts. The inverse analysis technique utilized FE and BE to calculate MVs for a lift in real time; however, the calculation process proved timely, requiring between 2.5 and 7.5 minutes to calculate MVs. Empirically based regression models were established from BE results to allow for real-time calculation of MVs. Three models were developed that successfully predicted FE and BE results with less than 3% error for 99% of the data (Mooney & Facas, 2013). The lift calculation method is available to commercial equipment producers for integration into IC software. MV variability still existed in small lifts, typically six inches, which contained greater stiffness than the underlying sub-lift soil.

2.3.3 Relationship to Conventional Methods of Testing

The ability for roller-integrated CCC and IC to be used for QA rests on its ability to predict several mechanistic properties of soils. A series of test beds with differing soil types, moisture contents, and underlying soil properties were tested in several states as discussed in Section 2.5. The soil material was broken into three groups: non-granular subgrade, granular subgrade, and granular subbase/base. Regression analysis was performed on all the MVs produced by IC equipment. These MVs were compared to results obtained from conventional testing methods, including dry unit weight, the California Bearing Ratio (CBR), LWD, PLT and resilient modulus (M_r). A series of comparisons revealed that correlations were possible to dry unit weight, CBR, LWD, PLT, and M_r. The correlations were possible with a simple linear regression analysis when the test beds had homogenous soil, stiffer underlying layer support, and constant operation settings.

Correlation values between MV and conventional results did fall out of the range of significance on several test beds. Lack of correlation is attributed to several factors such as sub-lift soil heterogeneity, varying moisture content, narrow range of measurements, transverse heterogeneity, and variation in machine operating parameters. Averaging MVs across the drum width, performing multiple regression analysis on soil properties, and maintaining constant operating parameters can decrease variability and increase correlation of MVs and conventional results. Operating rollers at lower amplitude settings, between 0.028 and 0.043 inch, can increase correlation. Correlation increased to levels of significance (R^2>0.5) between MVs and the results from dry unit weight (γ_d), CBR, LWD, PLT, and M_r when the effects of moisture content, lift thickness, sub-lift properties, and operation parameters were accounted for by using multiple regression analysis. Table 2.2 contains correlation values when adjusted for multiple regression analysis between MVs and LWD, PLT, and CBR tests (Mooney, et al., 2010).

Table 2.2 Typical Range of $R^2_{adjusted}$ Values for Multiple Regression Analysis

Material	γ_d	Modulus (LWD & PLT)	CBR
Non-granular subgrade	0.6 - 0.8	0.2 - 0.6	0.3 - 0.7
Granular subgrade	-	0.5 - 0.7	-
Granular subbase/base	0.4 - 0.8	0.6 - 0.9	0.4 - 0.8

2.4 Quality Assurance

QA options and guidelines for subgrade and base layers have been detailed in NCHRP Report 676 and are summarized in this section. The report established six options for QA, which exist within three general methods of testing. The first method involves using point measurements to identify the locations with the lowest MVs. The second method involves achieving a percent change in MVs over sequential measurement passes. The third category uses calibration areas to establish target values (TV) for MVs for an evaluation area. Table 2.3 briefly summarizes each option, which is discussed in the following subsections. Guidelines for the QA options include considerations during a measurement pass for roller operation parameters, evaluation areas, calibration areas, and documentation. A separate QA option evaluating compaction uniformity using semi-variograms, which was not detailed in NCHRP Report 676, is discussed at the end of this subsection.

Table 2.3 Description of QA Options (Mooney, et al., 2010)

QA Option	Description
Option 1	Point measurements on least compacted area based on MVs
Option 2a	Comparing percent change in mean MV between consecutive passes
Option 2b	Comparing percent change in MV at a location between consecutive passes and requiring a certain percentage of locations to have a percent change lower than a set target value
Option 3a	Establishing an acceptable correlation between MV and point measurement on a calibration area to create TVs
Option 3b	Establishing a TV based on the mean MV when the percent difference in MV consecutive passes on the calibration area is less than or equal to 5% on 90% of the calibration area
Option 3c	Establishing an acceptable correlation between MVs and lab-determined properties on the calibration area to create TVs

2.4.1 QA Guidelines

Several guidelines are recommended while performing any of the QA options. The guidelines for operating parameters, evaluation area, and calibration area allow for more uniformity while performing measurement passes, allowing for more consistency in the generation of MVs. Documentation of each measurement pass should include pre-established types of information. This information should include the roller MV, three-dimensional position with time stamp and GPS quality, vibration amplitude, vibration frequency, travel speed, driving direction, automatic feedback control setting, indication of jumping, vibration setting, and pass sequence (Mooney, et al., 2010).

Operating parameters during measurement passes can have a profound effect on the generation of MVs. The amplitude, frequency, roller speed, and direction are aspects of operation that should be carefully set and monitored during measurement passes. Consistency with these aspects of operation allow for more accurate roller repeatability checks. Amplitude between 0.7 and 1.1 mm with a tolerance of ±0.2 mm, frequency between 28 and 32 Hz with a tolerance of ±2 Hz, and roller speed between 1.9 and 3.4 mph are recommended. Roller MVs should not be collected during startup, stopping, and turning.

The MVs received from a measurement pass should be checked for validity using repeat measurement passes and checking the MV consistency between forward and reverse driving directions. MVs should be verified by a second roller pass on a test strip within the evaluation area. The percent difference in the mean MV over the test strip should be less than 5%, and the maximum standard deviation of the MVs should be less than or equal to 10%. MVs should be checked for positioning between travel modes. An obstacle should be placed on the test strip perpendicular to the direction of the roller’s travel with the roller passing it once in each direction. The mapping of the obstacle in each direction is used to indicate if there is a discrepancy in the mapping locations between the driving directions. The positioning of the MVs is accepted if the position error is less than one-half the reporting resolution.

Guidelines for selecting evaluation and calibration areas are established to provide for more consistent MVs. Lengths for evaluation area are typically between 330 to 1,640 feet. Soil heterogeneity should be minimized, avoiding a change in borrow material or transitions from a cut to a fill section. The calibration test bed should have a minimum width of the roller’s width and a length of 100 feet. Minimum calibration areas are ideal when soil homogeneity exists. Larger calibration areas should be used with increased soil heterogeneity. The calibration area should be constructed similarly to the evaluation area, including the material type, material placement procedure, moisture conditioning, and lift thickness.

IC instruments on the roller must provide sufficient documentation during measurement passes. NCHRP Report 676 recommends the following parameters be documented during measurement passes: MV, three-dimensional position with time stamp and GPS quality, vibration amplitude, vibration frequency, travel speed, direction, automatic feedback control setting, jumping indication, vibration setting, and pass sequence.

2.4.2 QA Option 1

Option 1 utilizes roller-integrated CCC to locate the least compacted soil locations. These locations are then tested using point measurement methods. Locations with a length less than 10 feet should not be tested. The evaluation area is acceptable if the point measurements meet the required point measurement specifications. This option assumes that a positive correlation exists between soil compaction and MVs. Heterogeneous soils should be examined further to see if this option is appropriate.

2.4.3 QA Option 2a

Option 2a is a comparison of the mean MV from two consecutive roller measurement passes. The percent difference in the mean ($\%\Delta\mu_{MV_i}$) between measurement passes is given by Equation 2.3. The QA is accepted if the recommend percent difference in mean is 5% or less.

$$\%\Delta\mu_{MV_i} = \left(\frac{\mu_{MV_i} - \mu_{MV_{i-1}}}{\mu_{MV_{i-1}}}\right) \times 100\% \quad (2.3)$$

2.4.4 QA Option 2b

Option 2b is a comparison of the percent change in MV ($\%\Delta MV$) at a location between consecutive passes and requiring a certain percentage of locations to have a percent change lower than a set target value. Equation 2.4 provides the percent change in MV. It is recommend that between 80% and 95% of the locations have a percent change in MV that is less than two times the standard deviation of the percent change in MV. QA using this option requires a process to transform the spatial MV data in to a comparable grid for each measurement pass. This process has not proven to be reliable and requires careful consideration of the methodology if utilized.

$$\%\Delta MV_i = \left(\frac{MV_i - MV_{i-1}}{MV_{i-1}}\right) \times 100\% \quad (2.4)$$

2.4.5 QA Option 3a

Option 3a starts with developing a correlation between point measurements and MVs on a calibration area. A minimum of five measurements should be taken for each compaction level: low, medium, and high. Generally, the coefficient of determination between the point measurement and MVs should be greater than or equal to 0.5 (i.e.$R^2 \geq 0.5$). When the correlation is established, MV corresponding to the correlated point measurement value is used to create a TV. Typically, this can be achieved with a single-variable regression; however, multivariate regression may be necessary to achieve the required coefficient of determination to account for varying soil properties and different measurement depths. Acceptance is met when a certain percentage of MVs in the evaluation area are equal to or greater than the TV. The recommend acceptance percentage is between 80% and 95%.

2.4.6 QA Option 3b

Option 3b requires establishing a TV as the mean MV for the evaluation when the percent difference in MV between consecutive passes on the calibration area is less than or equal to 5% for 90% of the calibration area. Acceptance is met when the TV is achieved on the evaluation area.

2.4.7 QA Option 3c

Option 3c is aimed at developing a correlation between laboratory soil property value, such as the resilient modulus (M_r) as a function of moisture contents and dry unit weights, and field-measured MVs on a calibration area. This option enables the establishment of a target MV using the laboratory soil test. First, a standard Proctor test is performed to determine the maximum dry unit weight and its optimum moisture content of the soil. Using this soil information, dry unit weight and moisture content ranges should be specified by the reviewing agency. Second, a series of laboratory resilient modulus tests are performed in accordance with the standard protocol used by the state agency at the specified range of moisture contents. A correlation of M_r as a function of soil dry unit weight and moisture content is then established. Third, a relationship is established between field-measured roller MVs and moisture and dry unit weight that are determined using the spot test methods. Forth, a multiple regression model is established between MVs and the field measurements at the respective moisture and dry unit weight. This model would be used to predict the laboratory soil property values based on the field measurements. TVs are established based on the laboratory tests and desired soil properties. Pad foot rollers are not recommended for this QA option.

2.4.7 Semi-Variogram

A semi-variogram is a geostatistical analysis method that can be used to analyze the uniformity of soil and pavement compaction. While this QA option is helpful for visualizing uniformity characteristics of soil or pavement and is becoming more prevalent, its use has extended only to academic literature and has not been integrated into QA specifications by state DOTs. A brief description of this QA option is listed below. More information is available in the referenced article by Vennapusa, White, and Morris.

A semi-variogram plot has a $\gamma(h)$ value on the y-axis and a separation distance of h along the x-axis as depicted in Figure 2.3. The $\gamma(h)$ is defined as half the average squared differences of data values that have a separation distance of h. Two sets of data are plotted: the exponential semi-variogram, represented by the smooth curve, and the experimental semi-variogram plot, modeled by the circles in Figure 2.3. The exponential semi-variogram represents the theoretically uniform compaction model and the circles represent the data obtained from MVs. Acceptance is related to the distance between the exponential and experimental plots. Set acceptance standards were not recommended by the authors but a “goodness-of-fit” value can be assigned to demonstrate sufficient compaction uniformity.

Three parameters to be aware of when reading a semi-variogram are the range (R), Sill ($C+C_o$), and nugget (C_o). The range represents the distance at which the separation distance from zero to the plateau of the exponential semi-variogram. The sill represents the plateau height of the exponential semi-variogram plot, which is nearly equal to the data’s variance. The nugget describes the sampling error in the data, where the exponential semi-variogram theoretically should pass through the origin without any error (Vennapusa, White, & Morris, 2010).

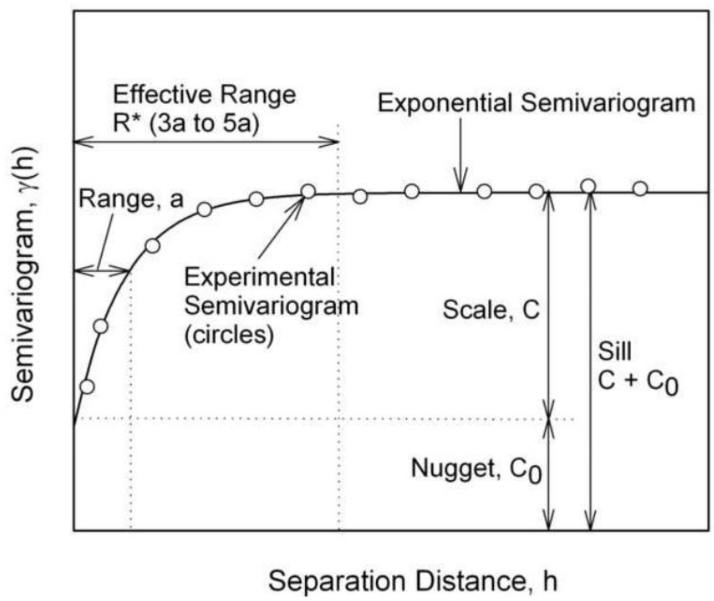

Figure 2.3 Example of a Semi-Variogram (Vennapusa, White, & Morris, 2010)

2.5 Case Studies

Several case studies have been conducted to evaluate the QA options described in Section 2.4. Table 2.4 shows the six case studies outlined in the NCHRP Report 676. Each of the studies tested at least one QA option. Additional case studies from Texas are included in but were not a part of NCHRP Report 676.

Table 2.4 Case Studies and Options Tested (Mooney, et al., 2010)

State	I.D. No.	Options Tested	Material
Colorado	CO34	1, 2a, 2b, 3a	Granular Subbase
Florida	FL15	1, 2a, 2b	Granular Subbase
Florida	FL19	3a	Aggregate Base
Florida	FL23	1, 2a, 2b, 3a, 3b	Granular Subgrade
North Carolina	NC20	1, 3a	Granular Subgrade
Minnesota	MN10	3c	Nongranular Subgrade

2.5.1 Colorado

2.5.1.1 Test Bed CO34

The case study on CO34 took place on a 40-foot wide by 1,000-foot long evaluation area of granular subbase. AASHTO soil type A-4 was excavated and soil type A-1-a was used as fill material. The evaluation and calibration areas were compacted using a Dynapac IC roller. The target soil dry-unit weight (γ_d) was set at 100% of the maximum ($\gamma_{d\text{-}max}$). A target moisture content (w) was not used for quality control because rock content was greater than 50% by weight. A Zorn lightweight deflectometer (LWD) was used to determine the modulus, and a nuclear gauge was used to determine the dry unit weight. The lift depth was 12 inches. QA options 1, 2a, 2b, and 3a were evaluated, while only options 2a and 2b met the QA standards based on the NCHRP recommendations.

Option 1 required that all the point measurement tests in the weakest areas met the required $\gamma_{d\text{-}TV}$. The six point measurements failed to meet the γ_d-TV requirements. The use of 100% as the $\gamma_{d\text{-}TV}$ was stricter than the existing Colorado standards. A standard that was lower, yet within acceptable practices, would have increased the amount of passing point measurements.

Option 2a required that the percent change in the mean MV ($\%\Delta\mu_{MVi}$) between roller passes be 5% or less. Acceptance was met on pass six, which had a $\%\Delta\mu_{MV}$ equal to 4.1%. Option 2b required that 80% of the evaluation area have MVs with a percent change in consecutive measurement passes less than two times the standard deviation of the MVs from a repeatability test. A nearest neighbor interpolation method was used to create fixed grids. Acceptance was met on pass six with 81% of the evaluation area passing. Use of this method displayed great variability of MVs on consecutive roller passes with percent changes ranging from a decrease of 50% of the original MV to an increase of 75%. Variability was attributed to limitations in comparing MVs between measurement passes using the fixed grid evaluation method.

Option 3a required that correlations between point measurements and MVs be established on the calibration area. The Dynapac compactor provides MVs in the form of compaction meter values (CMV_D). An acceptable correlation of R^2 equal to 0.52 between the γ_d and CMV_D was established. The correlation between the LWD modulus and CMV_D was not acceptable at R^2 equal to 0.39. This was attributed to soil heterogeneity and a stiffer calibration area than evaluation area. Based on the measured γ_d, the MV-TV was set at CMV_D equals 48. It was required that 90% of the evaluation area meets the MV-TV. The standard was not met with only 3% of the evaluation area meeting the MV-TV.

2.5.2 Florida

2.5.2.1 Test Bed FL15

The case study on FL15 took place on a 40-foot wide by 200-foot long evaluation area. The lift was 12-inches thick consisting of nine inches of granular subgrade: AASHTO soil type A-3 and three inches of bed ash. A Sakai CCC roller was used for compaction, and point measurements were taken with a nuclear gauge and Prima LWD. QA Options 1, 2a, and 2b were tested options, where 2a and 2b met the QA standards.

Option 1 had a γ_d-TV equal to 98% of the maximum γ_d. None of the six point measurements in the weakest areas indicated by the MVs met the γ_d-TV; though, the measurements would have met the standard if the γ_d-TV had been equal to 94% of the maximum γ_d. Consideration of a less strict TV was suggested for future use. Also, a positive correlation did not exist between the MVs and point measurements indicating that lower MVs did not necessarily correspond to lower compaction. Option 1 is effective when MV and point measurement have a significant positive correlation.

Option 2a required that $\%\Delta\mu_{MVi}$ be 5% or less. Acceptance was met on pass nine, which had a $\%\Delta\mu_{MV}$ equal to 3.0%. Option 2b required that 80% of the evaluation area have MVs with a percent change in consecutive measurement passes less than two times the standard deviation of the MVs from a repeatability test, which was 10% in this case study. Nearest neighbor interpolation was used to create a fixed grid of MVs for each pass. Acceptance was met as 92% of the evaluation area achieved less than a 10% $\%\Delta\mu_{MV}$ between consecutive passes.

2.5.2.2 Test Bed FL19

The case study on FL19 took place on a 30-foot by 917-foot evaluation section. The calibration area was 8 feet by 100 feet. The lift consisted of a 6-inch aggregate base: AASHTO A-1-b- over a stabilized subgrade layer. A Dynapac IC roller was used for compaction, and the γ_d-TV was set at 98% of the maximum γ_d. Point measurements from a nuclear gauge, CBR, and LWD were correlated to MVs. Option 3a was evaluated and was not accepted.

The γ_d-TV could not be achieved on the calibration area so inverse regression approach with an 80% prediction interval (i.e., 80% of observations in evaluation area must fall within the prescribed MV-TV range) was used to determine acceptance. Only 68% of the MVs in the evaluation area fell within the prescribed MV-TV range. The result was less than the 80% required and did not meet acceptance. It was noted that a significant correlation did not exist on the evaluation area, where it had on the calibration area. This was due to soil heterogeneity in the underlying layer, which was confirmed by point measurement tests. It was recommended that soil heterogeneity be studied in greater detail to ascertain what level of homogeneity is needed to utilize this option.

2.5.2.3 Test Bed FL23

The case study on FL23 also was conducted in Florida with a 36-foot by 825-foot evaluation area and a 7.2-foot by 180-foot calibration area. The task was to cut 0.6 to 1.0 feet of an existing embankment of subgrade material: ASSHTO A-1-b. Compaction of the scarified subgrade was completed by a Case IC roller. The γ_d-TV was required to be greater than or equal to 95% of the maximum γ_d. QA options 1, 2a, 2b, 3a, and 3b were evaluated, and options 1, 2a, and 2b were accepted.

Forty point measurements were taken to check for acceptance based on Option 1. All 40 point measurement met the 95% γ_d-TV, and the evaluation area was accepted. The point measurement yielded an MV range of 97% to 109% of the maximum γ_d. The point measurements were taken after pass 6.

Option 2a required that $\%\Delta\mu_{MVi}$ be 5% or less. Acceptance was met on pass three, which had a $\%\Delta\mu_{MV}$ equal to 3%. Option 2b required that 90% of the evaluation area have MVs with a percent change in consecutive measurement passes less than 5%. Kriging, which is accounted for the exponential spatial variation of points in all directions, was used to compare MVs from consecutive passes. Acceptance was met on pass 5 with 94% of the area less than the 5% $\%\Delta\mu_{MV}$ relative to the previous pass.

Option 3a required that a correlation be established between point measurements and MVs on the calibration area. The correlation was achieved using inverse regression with an 80% prediction interval. The MV-TV was required for 90% of the evaluation area while only 20% of the evaluation area achieved the MV-TV, and thus, acceptance was not met. When testing for γ_d using point measurements, it was found that all the point measurements passed. The LWD modulus tests indicated that only 28 of 40 tests passed. This reflects that the soil in the evaluation area based on γ_d was much closer to acceptance than that indicated by the MVs and LWD modulus. Comparing the calibration area and evaluation area, point measurement tests revealed that the calibration area had lower CBR profiles for the underlying support conditions.

Option 3b requires that the TV to be established based on the mean MV when the percent difference in MV consecutive passes on the calibration area is less than or equal to 5% on 90% of the calibration area. The MV-TV was established after the fifth pass on the calibration area. However, the results were inconclusive, because the calibration area was determined to not be representative of the evaluation, as tested during Option 3a.

2.5.3 North Carolina

2.5.3.1 Test Bed NC20

The case study on NC20 took place on a 60-foot by 1640-foot evaluation area consisting of granular subgrade. The section was compacted with a Sakai CCC roller on the silty sand subgrade: AASHTO A-2-4. A calibration area of 60 feet by 300 feet was overlaid onto the evaluation area. A balloon density tester was used to measure the dry unit weight on the evaluation area, and a nuclear gauge was used to measure the dry unit weight on the calibration area. Additionally, an LWD was used to measure the modulus on the calibration area.

Option 1 required that point measurements from the weakest areas indicated by MVs were equal to or greater than 95% of the maximum dry unit weight. The dry unit weight range of the point measurements was 100% to 102% of the maximum dry unit weight. Acceptance was met based on the target value of 95%. However, a significant positive correlation between the MVs and point measurements was not obtained with R^2 equal to 0.21. Therefore, option 1 should be used with caution, and additional testing is recommended without a significant positive correlation between MVs and point measurements.

Option 3a required that 90% of the evaluation be equal to or greater than the MV-TV, which was established based on tests on the calibration area. A measurement pass revealed that 93% of the area was equal to or greater than the MV-TV; however, the significant correlations between the nuclear gauge results and MVs did not exist as discussed in option 1. A significant correlation existed between the LWD modulus and MVs and was used to develop the MV-TV. It is recommended that QA should not be performed without a significant correlation between the QA required dry unit weight and MVs.

2.5.4 Minnesota

2.5.4.1 Test Bed MN10

The case study on MN10 was used to illustrate the application of option 3c. Acceptance of the evaluation area was not tested. The test bed was filled with a non-granular subgrade material: AASHTO A-6, which was supported by a relatively stiff and homogeneous subgrade layer. The subgrade layer was controlled in three sections with differing moisture contents prior to compaction. The sections contained the optimum moisture content and 3% above and below optimum moisture content. Moisture content was varied to evaluate the effects of moisture on MVs. A pad foot Bomag IC roller was used for compaction.

Option 3c requires a specified percent of the evaluation area meet MV-TV established by correlating point measurements from the field to MVs and laboratory data. The dry unit weight from field measurements and MVs did not have a significant correlation with R^2 equal to 0.37; however, the adjusted coefficient of determination (R^2_{adj}) was equal to 0.54 when multiple regression analysis was performed to account for the effects of moisture content. After relating field MV measurements to laboratory measurements for the resilient modulus, the resilient modulus is then used to predict the MV and establish the MV-TV. An acceptance envelop was then established as a combination of the MV-TV, a moisture content within 2% of optimum and the 90% saturation curve. Variations of moisture content must be accounted for when establishing MV-TVs to provide better relationships between MVs and measurements taken by hand. In this case, the moisture content accounted for the difference between a not significant and significant relationship.

2.5.5 Indiana

2.5.5.1 TB1 (White, Vennapusa, & Gieselman, 2011)

Test Bed 1 was located along SR-25 in West Lafayette, Indiana. A smooth single-drum roller was used to compact a granular embankment. The objective of the project was to investigate the effect of the roller's vibration amplitude on soil density, modulus, and strength. MVs generally increased with an increase in the number of passes with minimal decompaction occurring on the last pass—approximately 1% and 3% of the MVs for an amplitude of 1.80 mm and 0.90 mm, respectively. The decompaction resulted in a lower CBR values that were greater for the lower amplitude and approximately the same for the higher amplitude value.

2.5.6 Texas

Texas DOT conducted soil compaction projects on seven test beds in 2008, which were not included in NCHRP Report 676. Compaction was performed with a Case/Amman padfoot roller and Case/Amman smooth drum roller. The values for the data for the smooth drum roller are presented in this section based on the recommendation in NCHRP Report 676 to use smooth drum rollers for better MV consistency. The compacted tests beds included a clay subgrade, lime-stabilized subgrade, and flex base material. A variety of in-situ test methods were used to compare data to MVs, and data consisting of LWD, PLT, dry unit weight, CBR, and FWD correlations are presented for each type of test bed material. Table 2.5 contains the coefficient of determination for each material layer type (Chang, et al., 2008).

Table 2.5 Coefficients of Determination for MVs and In-situ Tests in Texas

	Clay Subgrade	**Lime-Stabilized Subgrade 1**	**Lime-Stabilized Subgrade 2**	**Flex Base Material**
LWD	0.10	0.45	0.37	0.25
PLT	0.67	0.51	-	0.48
Υ_d	-	0.37	-	-
CBR	0.37	0.72	-	-
FWD	0.75	0.64	0.73	0.37

"-" denotes data not available

While a positive correlation exists with all the in-situ tests and MVs, a majority of the coefficients of determination do not meet statistical significance. FWD and PLT correlate better with MVs; however, coefficients of determination from LWD and MV data never meet statistical significance. Several factors can lead to lower values, which are discussed in Section 2.3. Values can be improved if multiple regression analysis and accounting for underlying soils are taken into consideration when calculating correlation values.

2.6 Currently Adopted Specifications

The QA specifications for soil compaction in this section are outlined on a state-by-state basis. The specifications include CCC/IC, QA options, and traditional point measurement methods.

2.6.1 Colorado

Colorado DOT has developed specifications for the compaction of subgrade and base courses. Subgrade requirements are detailed in Section 203 of the Colorado DOT 2011 Specifications Book, and base course requirements are discussed in Section 304 (Colorado Department of Transportation, 2013).

Subgrade with AASHTO soil types A-2-6, A-2-7, A-4, and A-6 through A-7 shall be compacted to within 2% of the optimum moisture content per Section 203. All other soil types shall be compacted to a relative compaction described by in Table 2.6 (Colorado Department of Transportation, 2013). AASHTO T-99 requires the use of a 5.5-lb (2.5-kg) rammer, and AASHTO T-180 requires the use of a 10-lb (4.54-kg) rammer to obtain the optimum moisture content and maximum density, which is described in more detail by Colorado DOT's Colorado Procedure 23-10.

Table 2.6 CDOT Relative Compaction Requirements for Subgrade

AASHTO Soil Classification	AASHTO T-99 Minimum Relative Compaction (Percent)	AASHTO T-180 Minimum Relative Compaction (Percent)
A-1	100	95
A-3	100	95
A-2-4	100	95
A-2-5	100	95
All Others	95	90

Aggregate base course shall be compacted with a width of 6 inches to within 95% of the maximum density determined by AASHTO T 180 as described in Section 304. The aggregate base course shall be counted by ton of weight or cubic yard of volume as specified by contract. Measuring moisture content and density is governed by Colorado DOT's Colorado Procedure 25-12 and Colorado Procedure 80 (Colorado Department of Transportation, 2013). These procedures allow for point measurements to be taken using a rammer, sand cone method, or nuclear gauge for both subgrade and base courses.

2.6.2 Utah

Utah DOT has developed specifications for the QA of the base course. The base course requirements are detailed in Section 02721 of the UDOT 2012 Standard Specifications Book. UDOT requires testing for dry density, moisture content, and soil gradation.

Utah DOT requires that the maximum dry density and optimum moisture content be calculated using AASHTO T-180, which utilizes a 4.54-kg rammer to determine soil properties. Base courses for use in the pavement section must have an average measured density of 97% of the maximum dry density and no single density test can be below 94%. Moisture content must be within 2% of the optimum moisture content. Moisture content and dry density can be measured per the UDOT minimum sampling and testing requirements. A nuclear gauge (AASHTO T 310) is specified to obtain dry density, and evaporative drying (AASHTO T-255) is specified to obtain moisture content (Utah Department of Transportation, 2012).

2.6.3 Florida

Florida DOT defines specifications for subgrade, subbase, and base layers accordingly. The subgrade, subbase, and base layers must achieve a minimum of 98% of the modified Proctor maximum density. Shoulders must have a minimum of 95% of the maximum density. The density shall be measured using a 10-lb (4.54 kg) rammer per Section 160-4 and Section 200-7 of the Florida DOT Standard Specifications for Road and Bridge Construction 2014, which was adapted from AASHTO T-180.

2.6.4 Wyoming

Wyoming DOT allows the moisture content of the subbase and base layers to fall between 4% below and 2% above optimum moisture content per Section 301 of Wyoming DOT's Standard Specifications for Road and Bridge Construction 2010 Edition. The subbase and base layers must have a minimum soil density of 95% of the maximum dry density determined in accordance with AASHTO T-180. Soil density and moisture content can be determined by the sand cone method, nuclear gauge method, or Proctor tests as described in the Wyoming DOT Materials Testing Manual.

2.6.5 Texas

Texas DOT requires that the density and moisture content of the subgrade and the base layers be tested with quality control and quality assurance testing. Methods for testing the subgrade density and moisture content are conducted using Texas DOT Designation TEX-114-E. The density and moisture content must meet specific ranges based on the measured plastic index (PI) of the soil as summarized in Table 2.7. The required density and moisture content are compared with the maximum dry density and optimum moisture content determined by Proctor tests. The density of the base layer must meet the maximum density. The density of the base layer can be tested using a rammer, soil compactor analyzer, and Proctor tests.

Table 2.7 Soil Density and Moisture Content Requirements for Texas DOT

Plastic Index	Percent of Max. Dry Density	Moisture Content
PI up to 15	98% or more	-
PI above 15 and up to 35	98 - 102%	At or above optimum
PI above 35	95 - 100 %	At or above optimum

Draft IC specifications have been developed for the Texas DOT by the Transtec Group, a private engineering firm contracted by the FHWA to coordinate the implementation of IC throughout the nation. The IC specifications require that the dry unit weight is 100% of the target maximum dry unit weight and that the moisture content is within 1% of the optimum moisture content. The procedure for compaction involves the IC roller's MVs compared with dry unit weight and moisture content along a control strip for each layer. The control strips must have minimum length of 500 feet. The IC roller is used for compaction and conventional tests are used for at least three locations along the control strip.

After the control strips are performed, the state's engineer will determine MVs that are acceptable for compaction target values. The IC roller then compacts the specified area. Preliminary acceptance is achieved when the target values are met. Final acceptance is met if no more than one of five samples tested using conventional methods is below the target density. If there is one test that failed to meet the target value, the density must not be below 3 pcf of the target density. Compaction of the area must be done again if final acceptance is not met. All samples must be conducted using conventional methods and be taken within 24 hours of compaction by the IC roller.

2.6.6 Iowa

Iowa DOT requires that the subgrade and subbase layers achieve within a specific range of dry unit weights and moisture contents, which are detailed in the Iowa DOT Standard Specifications for Highway and Bridge Construction (2012). The subgrade and subbase layers must have a dry unit weight of at least 95% of the maximum dry unit weight and be within 6% of the optimum moisture content as determined by standard Proctor tests. Acceptable tests for determining the moisture content are oven drying per ASSHTO T-265, pan drying per AASHTO T-265 (open burner), microwave drying per ASTM D-4643, and nuclear gauge. Acceptable tests for determining the dry unit weight are nuclear gauge, a drive cylinder per ASTM D-2937, rubber balloon per ASTM D-2167, and sand-cone per ASTM D-1556.

2.6.7 Minnesota

Minnesota DOT Materials Lab Supplemental Specifications for Construction (2014) establishes QA standards for subgrade and base layers. The specifications delineate ranges for moisture content and dry unit weight required for acceptance. The subgrade moisture content must be between 95% and 102% of the optimum moisture content, which is determined using modified Proctor tests as described in the Minnesota DOT Grading and Base Manual (2013). The subgrade density, which is also measured by Proctor tests, is required to be the maximum density (Minnesota Department of Transportation, 2013).

2.6.8 California

Caltrans Standard Specifications published in 2010 establishes compaction measurement requirements for subgrade and base courses. Measurement takes place using a nuclear gage as described in California Test 231. The optimum moisture content and maximum dry unit weight are determined by volume-to-weight data described in California Test 216. The subgrade and base are required to be 95% of the maximum dry unit weight. Also, the finished surface cannot vary more than 0.08 of a foot below the established grade.

2.7 Summary

This section covers IC history, technology, equipment, case studies and current QA specifications for various state DOTs. Table 2.8 contains a summary of the information from the case studies. Correlations between MVs and conventional compaction methods were generally better for PLT and FWD tests and did not correlate as well with LWD tests.

Table 2.8 Summary of Case Studies

	QA Acceptance Met						
Case	**QA1**	**QA2a**	**QA2b**	**QA3a**	**QA3b**	**QA3c**	**Notes**
CO 34	No	Yes	Yes	No	-	-	R^2_{LWD}= 0.37; $R^2_{\gamma d}$= 0.52
FL 15	No	-	-	-	-	-	
FL 19	-	-	-	No	-	-	
FL 23	Yes	Yes	Yes	No	No	-	
NC 20	Yes	-	-	Yes	-	-	R^2= 0.21; correlation value low
MN 10	-	-	-	-	-	-	R^2= 0.37; R^2_{adj}= 0.54
Indiana	-	-	-	-	-	-	Research purposes
Texas	-	-	-	-	-	-	R^2= 0.10 - 0.75

The case study from Texas also revealed information about the correlation values developed for different types of soils or soils that are treated differently. Table 2.9 contains a list of the correlation values for clay soil, lime-treated soil, and flex base materials.

Table 2.9 MV Correlation to Conventional Tests by Soil Type (Chang, et al., 2008)

Soil Type	R^2
Clay Subgrade	0.10 - 0.75
Lime-Treated Subgrade	0.37 - 0.73
Flex Base	0.25 - 0.48

3. LITERATURE REVIEW ON ASPHALT COMPACTION

3.1 Overview

The purpose of this section is to present and analyze how various CCC and IC rollers are applied to asphalt pavements. Several aspects of asphalt compaction related to soil compaction are discussed in this section. These aspects include different equipment types, different correlations between roller MVs and conventional tests, and an additional QA option. Also, case studies of CCC and IC on asphalt pavements are included. Conclusions of the literature review on soils described in Section 2 as well as pavement in this section are included.

3.2 Equipment

The equipment used for compaction of asphalt pavements utilizes dual-drum smooth rollers instead of single-drum rollers. The equipment is manufactured by the same companies as the single-drum rollers. Table 3.1 summarizes roller models for asphalt pavement compaction (The Transtec Group, Inc., 2013). The dual-drum rollers are equipped with the same technology as the soil compactors discussed in Subsection 2.2.3. The technology generates the same MV values, measuring the stiffness of the asphalt pavement. Dual-drum rollers are also equipped with temperature sensors to measure the asphalt temperature. The asphalt's temperature has an effect on the stiffness and can be used in formulae to adjust the MVs into comparable terms data using regression analysis methods. The MVs are then related to properties of the asphalt, which are discussed in Section 3.3.

Table 3.1 List of IC Equipped Roller Models for Asphalt Pavement Compaction

Vendor	Model	Model No	IC-MV	Software
Bomag	AsphaltManager	BW190AD-4AM	E_{vib}	BCM05
Caterpillar	AccuGrade	CB44B,CB54B CD44B,CD54B	CMV	VisionLink
HAMM(Wirtgen)	HCQ	HD+90/ HD+110 HD+120/HD+140	HMV	HCQ
Sakai	CIS	SW850/ SW880/SW890	CCV	AithionMT

IC-MV: Intelligent compaction measurement values; a generic term for all IC measurements; E_{vib}: Vibration modulus; CIS: Sakai Compaction Information System; CCV: Sakai Compaction Control Value; HCQ: HAMM Compaction Quality; and HMV: HAMM Measurement Value

3.3 Measurement Values

MVs are generated in the same manner as soil compaction, which is discussed in Section 2.3. Asphalt pavement compaction differs in its relationships to MVs, which generally require correlations based on coring of the pavement. The techniques for measuring the density differ from those used in soils. The basis of acceptance for a roadway asphalt pavement is defined by the density of a pavement to its maximum density. The maximum density is obtained by taking cores of the asphalt pavement with test conducted within two days of coring. The maximum density can be obtained in accordance with AASHTO T-209. Many state DOTs use a volumetric process, such as AASHTO T-209, to measure the cores and relate the constructed asphalt pavement density to the maximum density. Next, the densities obtained from the volumetric tests are related to roller MVs to establish a correlation, whereby its degree of fitting is evaluated based on the coefficient of determination. If the coefficient of determination is significant enough, the MVs can then be used for relating various QA options. Several in-situ methods have also been identified for measuring asphalt density and modulus in several case studies presented in Section 3.5. These tests include light weight deflectometers (LWD), nuclear gauge (NG), non-nuclear gauge (NNG), falling weight deflectometer (FWD), and portable seismic pavement analyzer (PSPA) (Chang, et al., 2011).

3.4 Case Studies

Several case studies have been conducted to evaluate the effectiveness of IC rollers on asphalt compaction. Certain case studies on pavement have evaluated QA options as described in Section 2.4 and Section 3.4. Other case studies evaluate the consistency of the rollers' temperature sensors with other non-roller temperature devices, the correlation values with the MVs from the subbase layers, and correlations to specific in-situ tests.

3.4.1 Minnesota

A FHWA-sponsored test took place on Route 4 in Kandiyohi County and mapped the hot mix asphalt (HMA) base course and wearing course. The subbase was also mapped for further investigation related to the quality of the asphalt courses. The case study was performed in June 2008 and utilized a Sakai SW880 double-drum vibratory roller. The goal of the case study was to monitor the consistency of the roller's temperature sensors. Also, the relationships of asphalt MVs and the subbase conditions as well as correlations to in-situ testing were evaluated. The correlations to in-situ testing are established in accordance with Option 3a. However, this case study did not establish target values (TV) to evaluate the acceptance of asphalt compaction.

The findings from the case study demonstrated that temperature readings from the roller's sensors were consistent with temperatures from thermal cameras placed at the test site (Chang, et al., 2011). Also, the MVs from the subbase and HMA base layers were found to have a coefficient of determination (R^2) equal to 0.69, which is higher than the required 0.5, indicating a correlation of significance. This indicates that MVs on pavement layers are related to the compaction quality of the underlying layers. Strong correlations were found between the MVs and lab density measurements with an R^2 equal to 0.99 when MVs were calculated using a 3.3-foot average radius. NG data and MV data had an R^2 equal to 0.90. The authors of the study noted that the correlations were developed using a limited number of data points: four for the lab density and five for the NG.

3.4.2 Mississippi

The FHWA-sponsored test took place on US 84 in Wayne County in July 2009. A Sakai double roller was utilized to measure the HMA base layer. MVs from the subbase were also measured. The goal of the project was to familiarize Mississippi DOT officials and contractors with the technology. FWD and NG density readings were taken to correlate with the MV data. The correlations were the principal information gained from the demonstration with no specific QA option being tested. Correlations for the FWD and MVs on the HMA were found to have an R^2 equal to 0.75 while a low correlation was achieved between MV and NG readings. The low correlation was attributed to the variability of layer thickness, variations in HMA temperature, and roller operating variables (i.e., amplitude, frequency).

3.4.3 Indiana

The FHWA-sponsored test took place on US 52 between US 231 and Cumberland Ave in Lafayette, Indiana. The test took place in September 2009 and utilized both Sakai and Bomag double-drum rollers. The test consisted of milling 2 inches of existing HMA then compacting a 2.5-inch HMA base layer followed by a 1.5-inch HMA surface layer. The compaction was completed above an existing 7-inch layer of HMA underlain by 6 inches of concrete.

The purpose of the test was to introduce IC to INDOT officials and contractors. The test also included correlations studies between MVs and in-situ tests. The Sakai MVs and non-nuclear gauge tests had an R^2 equal to 0.48, which was near the level of significance. The correlation between Bomag MVs and FWD tests as well as core densities did not result in a R^2 near or above a level of significance. The lack of correlation was attributed to 1) no temperature adjustment on Bomag MVs, and 2) MVs represent all pavement layers, including the existing pavement while the in-situ tests are mostly influenced by the newly laid HMA layers.

3.4.4 Utah

The FHWA-sponsored tests took place on US 89 in American Fork on August 6 through August 9, 2012. The tests were organized into three adjacent test beds and were tested with Sakai and Hamm IC rollers. The Sakai roller was equipped with a GPS system that was supported by a hand-held Trimble to obtain real time kinematic precision (RTK) of 2 to 4 cm. The Hamm roller utilized an OmniStar HP signal with a RTK precision between 5 and 10 cm (Chang, Xu, & Rutledge, 2012). Compaction was performed on asphalt base courses on all test beds.

A nuclear gauge and core samples were used to obtain asphalt density. These values were compared to roller MVs. The first test bed was used to determine correlations between roller MVs and operational and site conditions. On the second test bed, the Hamm roller MVs had an adjusted R^2 equal to 0.33 when comparing to core densities while the Sakai roller MVs had a higher adjusted R^2 of 0.48 when multivariate regression was used for establishing the correlation. Analysis shows that the correlation values were mostly affected by the roller frequency for the Hamm roller and asphalt temperature for both rollers. The insignificant correlation values were attributed to the uncertainty of positioning measurements and unusual rolling patterns. The third test bed, which utilized the Hamm roller, contained significant correlations between roller MVs and nuclear gauge density measurements with an adjusted R^2 of 0.92. Analysis demonstrated that no single factor, such as temperature or operating parameters, had a large statistical influence on the correlation (Chang, Xu, & Rutledge, 2012).

3.4.5 New York

The FHWA-sponsored test took place on US 219 near the village of Springville. The test performed between May 17 and May 22, 2009, using a Sakai double-drum roller. An HMA base, second lift HMA base, and HMA binder course were compacted. The purpose of the test was to demonstrate the IC roller's ability to improve roadway compaction to New York State DOT officials and contractors. The test revealed that MVs collected from underlying layers using a single-drum roller correlated to MVs in asphalt layers using a dual-drum roller. However, NG and NNG density results did not correlate well with MVs. The weak correlation was attributed to temperature variation, roller passes, roller amplitude, and roller frequency (Chang, et al., 2011).

3.4.6 Maryland

The FHWA-sponsored test took place on eastbound US 340 in Frederick County from July 20 to July 24, 2009. The test consisted of grinding an existing HMA layer and compacting an overlay of stone matrix asphalt. Sakai and Bomag rollers were used for compaction. The purpose of the project was to demonstrate the ability of IC rollers to improve roadway compaction to Maryland State Highway Administration officials and contractors. Correlation between Sakai MVs and in-situ densities were conducted. MVs and NG tests results demonstrated an insignificant correlation with an R^2 equal to 0.20.

The weak correlation was attributed to temperature variation, roller passes, roller amplitude, and roller frequency.

3.4.7 Texas

The FHWA-sponsored test took place on Farm-to-Market Road 1281 between 0.3 and 3.301 miles east of Interstate 10 in El Paso County. A new two-inch layer of HMA was constructed by milling the existing asphalt layer and introducing 4% by weight cement to the top 4 inches of existing granular base. The test utilized a Sakai double-drum roller to compact the new HMA layer. Two tests beds, TB 01A and TB 02A, were analyzed for compaction. Correlation values were calculated between MVs and in-situ densities using FWD, NNG, and portable seismic pavement analyzer (PSPA). MV and density correlations in TB 01A had an R^2 equal to 0.75 with the FWD, 0.68 with NNG, and 0.91 with PSPA. However, the correlation studies were concluded based on only five measurements. The coefficient of determination between MVs and PSPA on TB 02A was equal to 0.48 for the six measurements (Chang, Xu, & Rutledge, 2012). Although three out of the four R^2 values were significant, more data measurements are necessary to draw a conclusive correlation study.

3.4.8 California

The demonstration project was conducted in Solano along a 1.26-mile section of eastbound I-80 in September 2013. Compaction of HMA was performed with Caterpillar, Bomag, and Hamm IC rollers on three test bed sections. Compaction took place on a 3-inch intermediate course for each test bed. Correlations between core densities, NG, FWD, and MVs were conducted. Correlations between NG data and core densities were low with an R^2 value of 0.08. MVs from all three compactors demonstrated a similar or lower correlation with core density. Correlations between FWD data and MVs were also low with an R^2 value of 0.16. However, the correlation between MVs and NG were substantial with R^2 values of 0.96 and 0.97 for the Hamm and Bomag IC roller, respectively. The reported low correlation between NG and core densities was unknown, causing NG data and, subsequently, MVs to be unreliable.

3.5 Currently Adopted Specifications

In this section, the QA specifications for asphalt compaction are outlined in a state-by-state basis. The specifications include IC QA options, and traditional point measurement methods. A group of neighboring states were chosen (Utah and Colorado) and other states were chosen based on their progress with IC case studies and specifications.

3.5.1 Utah

Utah DOT requires that cores of the asphalt be retrieved; the asphalt density is measured based on UDOT Specification 02741 (Utah Department of Transportation, 2012). The core densities must be at least 93.5% of the theoretical maximum specific gravity as obtained from AASHTO T-209. An exception to this requirement exists for thin layer asphalt overlays, which must have a minimum core density of 92.5% of the theoretical maximum specific gravity.

3.5.2 Colorado

Colorado DOT requires that the specific gravity of the asphalt be equal to at least 92% of the theoretical maximum specific gravity per Section 401.17 of the Colorado DOT Standard Specifications Manual (Colorado Department of Transportation, 2013). The density of the asphalt can be measured by two methods. The first method is taking cores of the asphalt and measuring the density through a volumetric approach outlined in Colorado Procedure 44. In the second method, asphalt density is obtained from an NG test per Colorado Procedure 81.

3.5.3 Florida

Florida DOT uses 6-inch diameter cores, NG, or other devices for measuring density with a frequency of one test per 1,500 feet of pavement. The requirement is established in Section 330 of the Florida DOT Standard Specifications for Road and Bridge Construction (2014). The standard specifications do not outline specifications for IC.

3.5.4 Wyoming

Wyoming DOT has five roadway designations for density testing of pavements as listed in Section 401 of the Wyoming DOT Standard Specifications for Road and Bridge Construction. Minimum core densities, which are tested using a volumetric method, of 92% of the voidless unit weight are required by Designation II, which is a road designation that has the most specified requirement (Wyoming Department of Transportation, 2010).

3.5.5 Texas

Texas DOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (2004) has density requirements for dense-graded HMA and cold-laid HMA. Density is measured by taking cores and using a volumetric method, which is specified by Texas Test Procedure Tex-207-F. Dense-graded HMA must have a density equal to 96% of the maximum density. A tolerance of 1% is permitted. Cold-laid HMA must have a density between 91% and 94%. Cold-laid HMA must also have a moisture content no greater than 1% as tested by Texas DOT Test Procedure Tex-212-F.

3.5.6 Iowa

Iowa DOT requires that cores are taken to calculate the specific gravity. A volumetric method is used to calculate the specific gravity, which is then related to the maximum specific gravity. Section 2303 of the Iowa DOT Standards for Highway and Bridge Construction (2012) specifies that the contractor must achieve a specific gravity between 91.5% and 96.5% of the maximum specific gravity for at least 50% of the samples taken for each lot. Payouts are related to the percent of samples achieving the specific gravity requirements. Certain types of roadways with less intense use, such as non-high-speed ramps, non-interstate roads used for fewer than 12 months, and state park roadways, must have a minimum specific gravity of 92% of the maximum specific gravity.

3.5.7 Minnesota

Minnesota DOT Materials Lab Supplemental Specifications for Construction (2014) requires a volumetric measurement of cores from the asphalt pavement to be taken per Section 2360.3. The specifications require that the cores have a minimum relative specific gravity depending whether the pavement is a wear course and the percent of voids. A wear course must have a specific gravity of 92% of the maximum specific gravity.

3.5.8 California

Caltrans Standard Specifications published in 2010 establishes compaction measurement requirements for HMA (Caltrans, 2010). The requirements specify that density of the HMA be between 91% and 97% of the maximum theoretical density. The density is measured using California Test 375, which correlates nuclear gage density readings to core sample densities. The moisture content of the HMA must be a maximum of 1% as determined by California Test 226 or 370, which are oven or microwave drying methods, respectively.

3.6 Intelligent Compaction Specifications

FHWA has been promoting IC via its Every Day Counts initiative. The initiative supports local workshops, demonstration projects, development of standard IC specifications, and additional technical assistance for state and local governments to implement IC. State and local transportation agencies are seen as the catalyst to adoption of IC because they provide contractors with quality control/quality assurance (QC/QA) specifications for compaction of roadways. Quality control is referred to as the method for testing compaction parameters, such as density and moisture content, by construction crews to verify the quality of the roadway; whereas, quality assurance is referred to as the validation of quality control methods and data through additional compaction testing.

A literature review on current state DOTs' draft IC specifications indicates that state and local transportation agencies continue to require conventional compaction testing methods even if IC guidance is provided for roadway soil and pavement compaction (The Transtec Group, Inc, 2014). For example, Caltrans uses a combination of nuclear gauge readings and core sampling for pavement QC/QA; however, its draft IC specifications are not used system-wide. Similarly, Minnesota has created draft specifications and has conducted several field demonstrations over the past decade; however, permanent specifications for soils and pavement have not been integrated into their standard specifications manual. Texas, Michigan, and Iowa have developed special provisions for soils, but do not include QC/QA parameters for acceptance and use IC for research purposes or for demonstrating the technology.

Currently, 18 states are drafting or have adopted IC QC/QA specifications and special provisions based on information gathered from the DOT survey described in Section 4 and the Transtec Group (The Transtec Group, Inc, 2014). Eight states, shaded in black, are opting to provide draft specifications for both soils and pavements, while 10 states, shaded in dark gray for soils and light gray for pavement, are drafting specifications for either soils or pavements. More states are expected to begin drafting QC/QA specifications as more workshop and field demonstrations are scheduled (The Transtec Group, Inc, 2014). Figure 3.1 displays the types of IC QC/QA specifications drafted by states. These draft specifications range from special provisions to comprehensive specifications to be used for statewide roadway construction (The Transtec Group, Inc, 2014).

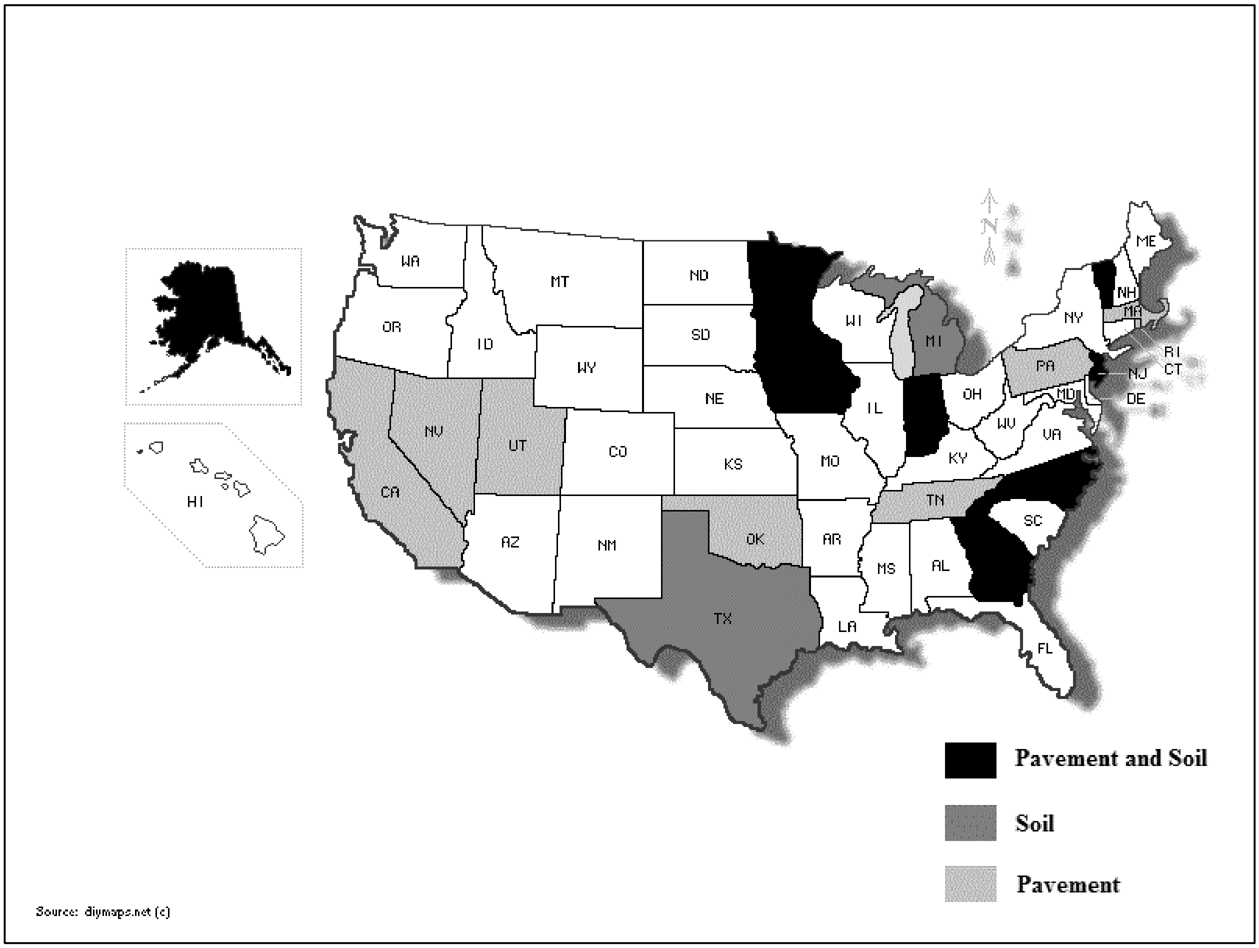

Figure 3.1 IC QC/QA Specifications by States

The specifications detail requirements for GPS data, documentation, test sections, and construction QC/QA. The two types of outcomes for the specifications involve reporting compaction value results for QC/QA and/or providing documentation of IC data for demonstration purposes. For soils, specifications used for QC/QA involve acceptance based on a percent difference in measurement values (MVs) between roller passes and/or correlation of IC MVs with in-situ point measurements to establish IC target values. Georgia, Indiana, North Carolina, and Vermont require correlations from test trips between in-situ point measurements and MVs. Georgia also required an optimal pass number established when there was a less than 5% change in MVs. The remaining states' IC specifications did not provide more detailed QC/QA specifications for soils (The Transtec Group, Inc, 2014).

For pavements, most states have QC/QA specifications that establish a target number of roller passes by a percent difference in MVs followed by establishing target values for MVs based on correlations of nuclear gauge or core samples on a test section. The exceptions to these specifications are Iowa, Nevada, Utah, and Rhode Island, which do not detail a method or requirements for compaction values (The Transtec Group, Inc, 2014).

3.7 Summary

This section included information about the IC equipment, case studies, and specifications for asphalt. The case studies and review of specifications sections revealed that IC can have statistically significant correlations and that states are preparing IC QA specifications. The case studies displayed a wide range of correlation values, and a summary of these values are contained in Table 3.2. Current DOT specifications require core sampling or NG testing for QA.

Table 3.2 Coefficient of Determination Between MVs and Conventional Tests

	Conventional Compaction Testing					
Case	**Cores**	**FWD**	**NG**	**NNG**	**PSPA**	**Notes**
California	-	0.16	0.96	-	-	
Indiana	-	-	-	0.48	-	
Maryland	-	-	0.20	-	-	
Minnesota	0.99	-	0.90	-	-	Only 5 cores samples
Mississippi	-	-	0.75	-	-	
New York	-	-	-	-	-	Not statistically significant
Texas	-	0.75	-	0.68	0.91	
Utah	0.48	-	0.92	-	-	Multiple regression for cores

Based on the case studies provided in the Section 2 and this section, the findings regarding the efficacy of IC are as follows:

1) The correlations values between MVs and in-situ tests from the soil and asphalt case studies appear promising but inconsistent.
2) Several factors led to poor correlations, which are noted in each case study; however, strong correlations were demonstrated in many case studies.
3) For IC to become a viable process for contractor use and QA implementation, consistent correlation values of at least 0.5 must be achieved. Correlation between soil MVs and in-situ tests appear to be more consistent, while correlations with asphalt pavements are much less consistent.
4) Correlation data will benefit greatly from the finite element (FE) and boundary element (BE) real-time analysis that account for prior layer compaction (Mooney & Facas, 2013). Application of the FE and BE methods to pavement compaction must also be theoretically established, which has been established for soils by Mooney and Facas (Mooney & Facas, 2013). MVs from pavements can then be compared to underlying MVs from soil layers to analyze their effect on pavement compaction.
5) The case studies on soils in Section 2 take into account the soil types and their effects on the MVs. During pavement compaction, temperature data, pavement moisture, and other factors are considered for their effects on MVs. However, conclusive data for the effect of each parameter on an MV have not been demonstrated for pavements. Further development about how factors such as soil type, operating parameters, and site conditions could help provide better information about how to apply IC.
6) A guide for adjusting MVs based on soil types, climate conditions, and soil heterogeneity would be beneficial for technicians and engineers analyzing MVs in soils and pavements to obtain better correlation values. The guide should also include optimal operating parameters for a given soil or pavement condition that includes amplitude, frequency, and roller speed. These operating parameters have been well defined for soils than pavement, but they still require refinement for both material types.

4. IC WORKSHOP, WYOMING AND NATIONAL SURVEYS

4.1 Overview

This section discusses studies from two surveys that were conducted to better understand how IC is understood and used by practicing engineers. The first survey was conducted with practicing engineers in Wyoming and is referred as the "Wyoming survey." The second survey was conducted with DOT officials throughout the nation and is referred as the "national survey." The methodology is described in Section 4.2 while the Wyoming and national survey findings are described in Sections 4.3 and 4.4, respectively.

The Wyoming survey of professionals was developed by the authors to understand the current knowledge of IC among professionals and how IC is being applied. The survey was conducted in March 2014 for public and private officials attending the Intelligent Compaction Data Management workshop sponsored by the FHWA in conjunction with the Wyoming Department of Transportation (WYDOT) and the Wyoming Local Technical Assistant Program (WY LTAP). The workshop included an overview of IC technology, types of IC QC/QA programs, and how to use VEDA software with QC/QA data. Figure 4.1 is a photo of the workshop.

Figure 4.1 IC Data Management Workshop in Laramie, WY

4.2 Methodology

Both surveys were geared toward practicing engineers who already have or are likely to come into contact with IC during their professional practice. The Wyoming survey was distributed in paper format and contained 21 questions as included in Appendix B. The questions were aimed at gauging participants' knowledge and perceptions of IC.

The national survey was conducted from September to October 2014. The survey was presented to likely candidates in every state DOT throughout the nation, including the District of Columbia. The survey was sent and conducted electronically via SurveyMonkey®. The national survey focused on aspects of practice as several DOTs have had experienced performing IC projects in their respective states. The survey asked about participants' knowledge of IC, current QC/QA methods, usage of IC, drafted QC/QA specifications for IC, and cost data for IC. The survey was structured to allow applicants to answer questions that were applicable to their level of experience with IC. For example, a person responding that they had not conducted IC demonstrations project in their state were not asked technical questions about the results from IC demonstrations. Therefore, the survey ranged from nine questions to 18 questions based on a person's responses. A sample of the national survey with total 18 questions is included in Appendix C

4.3 Wyoming Survey Results

The objective of the Wyoming survey was to understand how much knowledge private and public professionals practicing in Wyoming have about IC. The survey questioned respondents about their familiarity with IC, technical knowledge they may have, perceptions of IC, and their opinion about IC's future role in Wyoming. There were 79 total respondents, of which 69 were employed by WYDOT, seven by private firms, and three by local governments. Results for every question are located in Appendix B.

The survey results revealed that respondents were receptive to the idea of intelligent compaction but had a limited knowledge of and concerns about IC. Fifty-one percent of respondents said that they had heard of IC prior to the workshop. Figure 4.2 contains what respondents considered their primary sources of information about IC. A majority of respondents indicated that the FHWA was a primary source of information, which is considered a result of FHWA's promotion of IC and the prompting of respondents to learn about IC leading up to the FHWA-sponsored workshop. One respondent indicated in a later section that his agency owns an IC roller for use in landfill construction. None of the other 78 respondents had experience with IC rollers; however, 13 respondents noted interest in utilizing one for their company or agency.

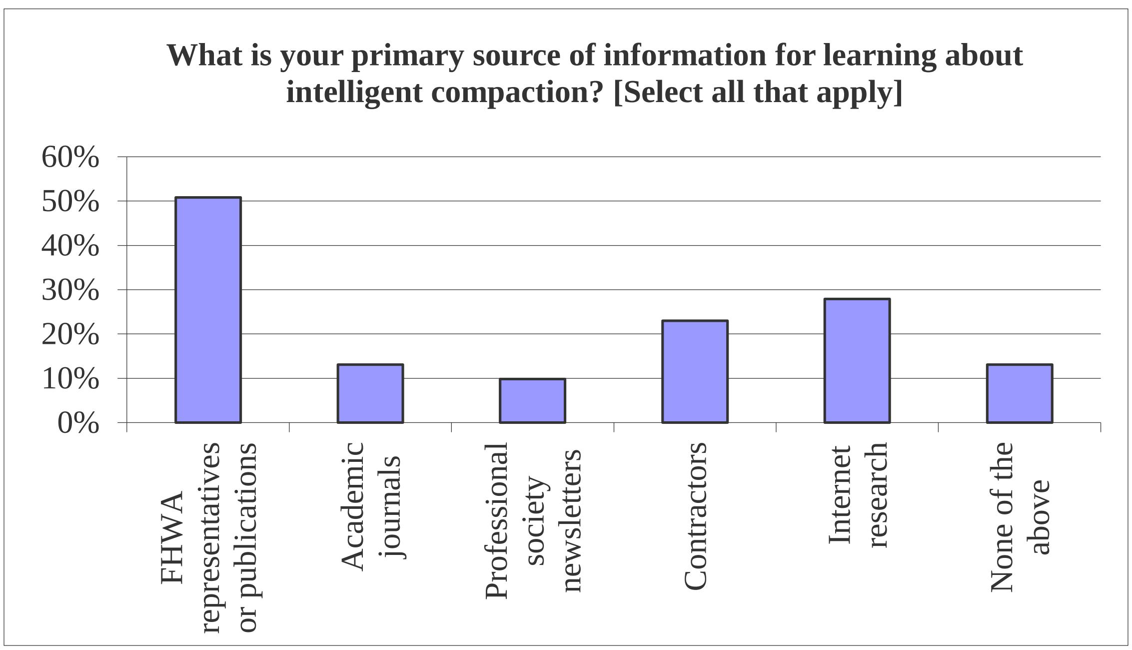

Figure 4.2 Results for Primary Source of IC Information from Wyoming Survey

The lack of experience with IC rollers was indicated by the respondents' desire to conduct a field demonstration. The highest percent of responses with familiarity of aspects to any single aspect of IC in Question 6 was 42%. Of the respondents, 58% indicated that a field demonstration would help them learn about IC, and 79% of respondents thought that a field demonstration would help facilitate implementation of IC in Wyoming. Among many concerns with IC, Table 4.1 indicates that the most notable concern was cost. However, 56% of the respondents did not know the effect of IC on the overall cost of compaction jobs while 16% believed that the cost will be decreased using IC. Concerns about costs could be related to the limited amount of independent research conducted between the costs of IC compared to conventional compaction. More information about benefits and costs of IC is available in Section 5. Despite the concerns listed in Table 4.1, 70% of respondents thought that IC should be adopted in Wyoming while 26% were not sure, and 4% did not respond. Adoption of IC standards only increased interest in IC and no respondents indicated that they would not use IC if provided the option in a state standard.

Table 4.1 Results for Concerns with IC from Wyoming Survey

Do you have any concerns with intelligent compaction? [Select all that apply]

Answer Options	**Response Percent**	**Response Count**
Cost	33.3%	24
Reliability of data	26.4%	19
Reliability and durability of technology	19.4%	14
Not a specified quality control/assurance method	22.2%	16
Lack of operator ability and/or time and cost to train operators	22.2%	16
Unfamiliar with technology	20.8%	15
There are no concerns	19.4%	14
Other		9
answered question		**72**
skipped question		**7**

The survey reveals that the next steps toward implementation are providing an economic justification and an IC field demonstration for public and private sector stakeholders in Wyoming. The field demonstration should incorporate QC/QA methods used by other states and outlined in FHWA specifications, which provide a refined model for use of IC. A field demonstration can also be used by researchers to verify the results of other demonstration projects, advance IC technologies, and explore new applications of IC.

4.4 National Survey Results

The purpose of the national survey is to understand DOTs' knowledge of IC, if IC is being used by DOTs, how IC is being used, and what outcomes DOTs have had with IC. More specifically, the national survey was divided into four types of questions:

1) DOT knowledge and use of IC
2) Current DOT QC/QA methods
3) Types of QC/QA methods used for IC
4) Short-term and long-term costs associated with IC

As mentioned previously, respondents were asked only the questions that were applicable to their experience with IC. This means that the number of respondents for certain questions may be lower than the total number—32—of survey respondents. Also, respondents were given an opportunity to indicate that they were "not sure" of an answer or that the question was "not applicable" to them. Also, respondents were allowed to answer "other" and fill in a comment for most questions. These types of responses are indicated during the discussion of each question where they are considered pertinent information. Results for each question are located in Appendix C. Figure 4.3 displays the state DOTs that responded to the survey shaded in gray.

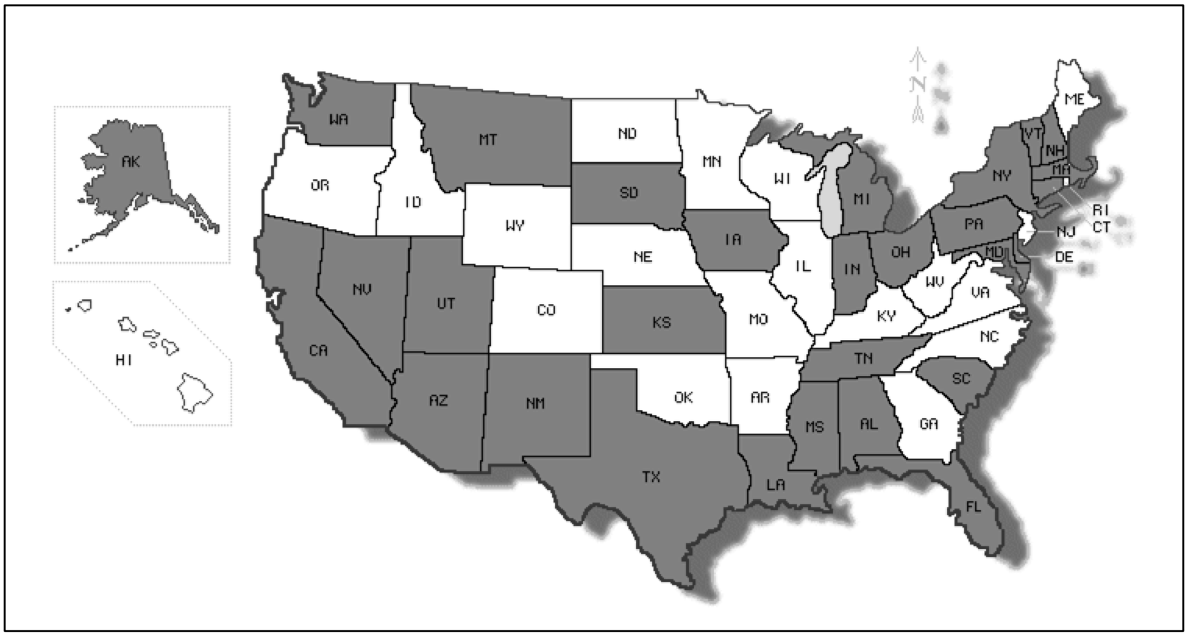

Figure 4.3 Map of State DOT Respondents Shaded in Gray

4.4.1 DOT Knowledge and Use of IC

Four questions in the survey were presented to understand where DOT representatives receive their information about IC (Question 2), the aspects of IC that they are familiar with (Question 3), concerns about IC (Question 4), and the number of IC demonstrations conducted (Question 7). The results for Question 2 are listed in Table 4.2. The highest number of responses was for "FHWA representatives or publications." This is most likely due to the funding of workshops for state DOTs by the FHWA. Also, four respondents that choose the "other" option specifically specified that the pooled fund projects sponsored by the FHWA were a source of information. The results from this question emphasize FHWA's vital role in promoting IC, where it may have been a collective action problem for states to otherwise undertake individually.

Results for Question 3 are listed in Table 4.3. The responses reveal that the technology as well as the operation of rollers is fairly well understood by the respondents. QC/QA standards and costs and benefits of IC are less well understood. The lower response rate for QC/QA standards can be related to the types of demonstration projects that have occurred in several states. Many states have opted to demonstrate the ability of IC rollers to document roller passes and provide information but not necessarily act as a QC/QA tool. The benefit from using IC rollers for this purpose lies in their ability to reduce the amount of time a roller is operating by avoiding redundant passes and providing a more orderly visual representation of rolling pattern to the operator. Also, operation of rollers and roller technology can be more readily understood by reading literature on performance and case studies; however, it may be more difficult for those DOTs that haven't had demonstration projects to understand the costs and QC/QA aspects of IC.

Table 4.2 Primary Source of Information for Learning IC (Results for Question 2)

What is your primary source of information for learning about intelligent compaction? [Select all that apply]		
Answer Options	**Response Percent**	**Response Count**
FHWA representatives or publications	90.3%	28
Academic journals	19.4%	6
Professional society newsletters	3.2%	1
Contractors	19.4%	6
Internet research	35.5%	11
None of the above	6.5%	2
Other (please specify)		11
answered question		**31**
skipped question		**1**

Table 4.3 Aspects of IC Familiarity (Results for Question 3)

Which aspects of intelligent compaction is your agency familiar with? [Select all that apply]		
Answer Options	**Response Percent**	**Response Count**
Operation of intelligent compaction rollers	76.7%	23
Technology used during intelligent compaction	90.0%	27
Cost and benefits	50.0%	15
Quality Control and Assurance Standards	56.7%	17
None of the above	6.7%	2
Other (please specify)		5
answered question		**30**
skipped question		**2**

Question 4 gauges concerns of DOTs with IC, which are listed in Table 4.3. The two largest concerns dealt with policymaker approval for quality assurance and lack of staff knowledge to confirm data. The first concern may be due to the recent introduction of IC as a tool for QC/QA, which was comprehensively documented for soils by Mooney, et al. (2010) and for asphalt by Chang, et al. (2011). As indicated by the responses to Question 7, several states are still being introduced to IC with 11 out of 32 respondents indicating that their state has held multiple IC demonstrations and 12 have conducted only one demonstration. The low number of states with experience using IC on multiple occasions can also explain the lack of staff knowledge. When a demonstration project does occur, FHWA representatives and roller manufacturers are training a limited number of DOT officials on how to use the IC. FHWA has sponsored Intelligent Compaction Data Management classes in more than 30 states in order to increase staff knowledge about how to use IC for QC/QA; however, that knowledge must be practiced using first-hand data. It is expected that DOT staff knowledge will increase as more demonstration projects occur and IC adoption becomes more prevalent. It is worth noting that four respondents selecting "other" had concerns with ICMV correlations to conventional tests. This is a valid concern, and considerations about site conditions and historical correlation values must be taken into account when applying IC to a given road section. This is discussed in more detail in Section 2.3.

Table 4.3. Concerns with Using IC (Results for Question 4)

Does your agency have any concerns with the use of intelligent compaction for soil or pavement materials? [Select all that apply]		
Answer Options	**Response Percent**	**Response Count**
There are no concerns	10.3%	3
Cost	31.0%	9
Reliability of data	34.5%	10
Ability to have it approved as a quality assurance technique by policymakers	41.4%	12
Less strict than current quality assurance methods	17.2%	5
Lack of staff knowledge to confirm data	41.4%	12
Unfamiliar with technology	20.7%	6
Other (please specify)		11
answered question		**29**
skipped question		**3**

4.4.2 Current DOT QC/QA Methods

This section of the survey contained two questions: QC/QA methods for subgrade, subbase, and base (Question 5); and QC/QA methods used for pavement (Question 6). Figure 4.4 contains the responses for Question 5 and Figure 4.5 for Question 6.

All respondents except one indicated that they use nuclear gauge for QC/QA. Proctor tests were the next more common followed by sand cone tests. Nuclear gauge and core sampling were the most common methods used for QC/QA on pavements. Three respondents, Alaska, Indiana, and Texas, indicated that IC can be used for QC/QA for soils. Two of those respondents, Indiana and Texas, indicated the use of IC for QC/QA on pavements as well. Refer to Section 2.7 for soils and Section 3.7 for pavements for more information about IC QC/QA specifications.

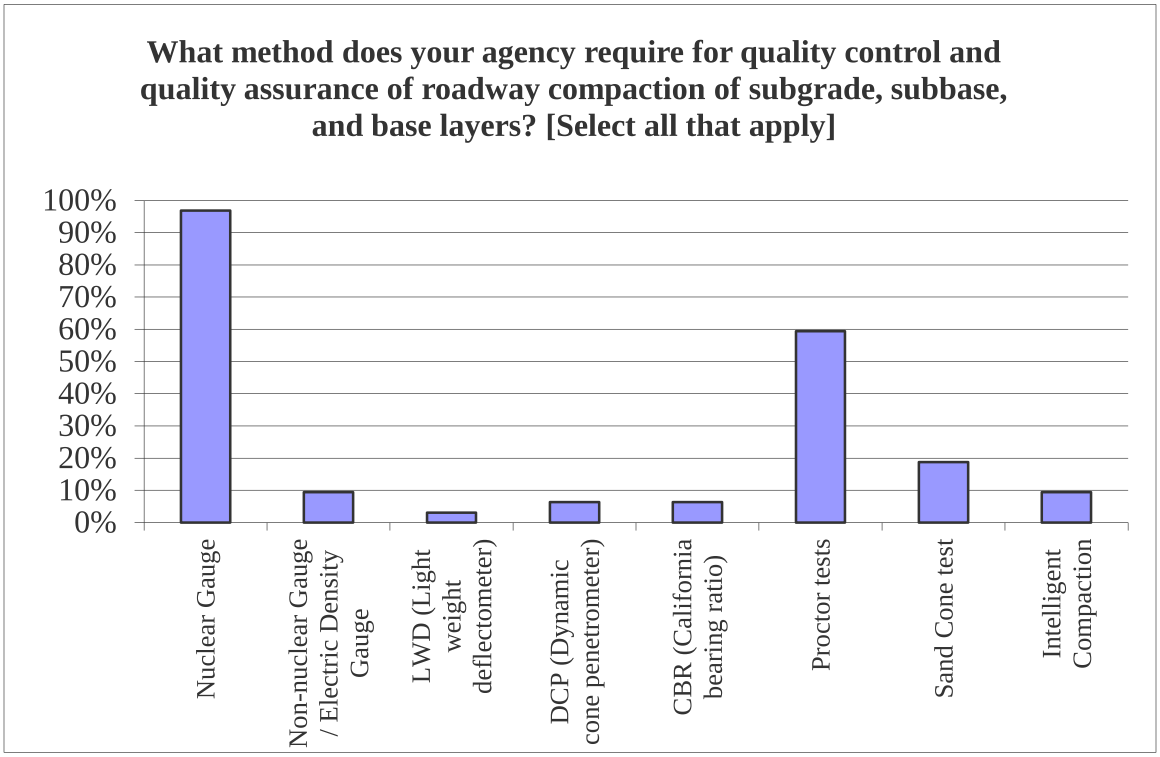

Figure 4.4 Methods for QC/QA of Subgrade, Subbase, and Base Layers (Results for Question 5)

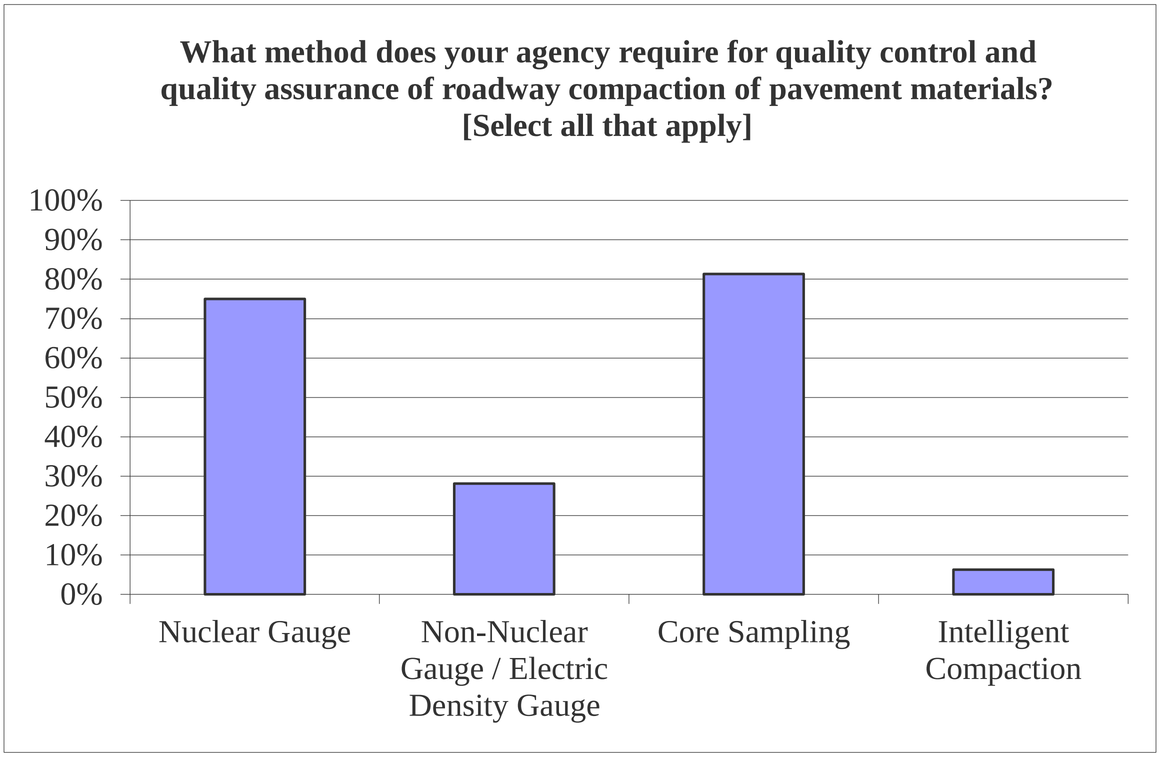

Figure 4.5 Methods for QC/QA of Pavement Materials (Results for Question 6)

4.4.3 Types of QC/QA Methods Used for IC

Five questions were presented to understand how IC QC/QA has been implemented. The questions provide information about the drafting and adoption of IC QC/QA specifications (Question 9), the method of IC QC/QA (Question 10), use of IC automatic feedback (Question 11), IC operating parameters for measurement passes (Question 12), and correlation of IC data to conventional tests (Question 13).

Table 4.4 IC QC/QA by Agency (Question 9)

Has your agency ever drafted quality control or quality assurance standards for intelligent compaction? [Select one]		
Answer Options	**Response Percent**	**Response Count**
Yes, quality assurance standards for intelligent compaction have been adopted	14.3%	3
Yes, draft standards have been completed and are awaiting adoption	19.0%	4
Yes, we are in the process of drafting standards	23.8%	5
No, but we plan on drafting standards	4.8%	1
No, and we do not plan on drafting standards at the current time	38.1%	8
Other (please specify)		11
answered question		**21**

Question 9 in Table 4.4 involved the current state of IC QC/QA in the DOT. Among the 21 responses gathered, seven of the respondents have QC/QA standards for IC that have been adopted or are awaiting adoption. Five respondents are in the process of drafting standards, and nine respondents have not drafted standards. The 12 respondents answering that their DOT was either drafting standards or had drafted standards were prompted to answer questions pertaining to their IC QC/QA standards.

Question 10 asked about the type of IC QC/QA methods that are used. Table 4.5 lists the results. Note that a respondent may indicate more than one method of QC/QA. The most common QC/QA method is to correlate in-situ testing with IC-MVs, which is described as the Option 3 series in Section 2.4. This was followed by establishing a number of passes with the intelligent compaction roller and testing the weakest soil or pavement areas indicated by intelligent compaction, which is Option 1 in Section 2.4. One respondent answering "other" commented that, while there was no specific IC QC/QA method, the use of IC was a "good tool to track coverage of rollers and number of passes." This response speaks to IC's ability to improve rolling pattern efficiency and, in effect, save time during roller compaction.

Table 4.5 IC QC/QA Methods for Compaction (Results for Question 10)

If your agency has or is drafting quality control or quality assurance standards for intelligent compaction, what quality control or quality assurance methods does you agency utilize for intelligent compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
Number of passes with intelligent compaction roller	41.2%	7
Testing weak soil / pavement areas indicated by intelligent compaction roller	41.2%	7
Percent difference of compaction values from intelligent compaction roller within a given area / uniformity testing	11.8%	2
Correlation of in-situ testing with intelligent compaction values	58.8%	10
Not sure	17.6%	3
Other (please specify)	29.4%	5

When asked in Question 11 about whether auto feedback was allowed during measurement passes, the largest response was "No." These responses are in line with recommendations from NCHRP Report 676, which does not recommend auto feedback to occur while performing a measurement pass. Table 4.6 lists the responses.

Table 4.6 Automatic Feedback Use (Question 11)

If your agency has or is drafting quality assurance standards for intelligent compaction, does your agency allow for automatic feedback to adjust compaction parameters during compaction? [Select one]

Answer Options	Response Percent	Response Count
Yes, but it is not required	11.8%	2
Yes, and it is required	17.6%	3
No	35.3%	6
Not Sure	35.3%	6

Question 12 involved the requirements for operating parameters for measurement passes. NCHRP Report 676 recommends constant amplitude and frequency during measurement passes in order to increase MV accuracy; however, only three respondents explicitly indicated those parameters for measurement passes. Other responses can also encompass constant amplitude and frequency parameters, but that decision may be left up to a project manager or roller operator. This may occur due to lack of knowledge about MV accuracy due to operating parameters or a reliance on construction teams to carry out IC data retrieval. The responses for Question 12 are listed in Table 4.7.

Table 4.7 Operating Parameters Required for IC Measurement Passes (Results for Question 12)

If your agency has or is drafting quality control or quality assurance standards for intelligent compaction, does you agency require operating parameters for measurement passes? [Select one]

Answer Options	**Response Percent**	**Response Count**
Yes, measurement passes should be conducted at constant drum amplitude and frequency	14.3%	3
Yes, measurement passes are determined on a project-by-project basis	14.3%	3
No, but the contractor is required to report the operating parameters for the measurement pass	19.0%	4
No, the contractor determines the parameters and does not have to report the operating parameters	9.5%	2
Not Sure	23.8%	5

During the case study section, several in-situ tests were correlated to IC-MVs on test sections of soil or pavement to establish target values (TVs). Responses to Question 13 revealed that nuclear gauge tests were the most commonly correlated tests with IC-MVs followed by core density. This mirrors the case studies sections in Section 2 and Section 3, which include several correlations to nuclear gauge tests and core density on asphalt pavements. Table 4.8 contains the responses for Question 13. Percentages were not included due to the high combined number of respondents noting "not applicable," "not sure," or "other."

Table 4.8 In-situ Test Required for IC correlation (Results of Question 13)

If your agency uses correlations, which in-situ test values are required to be correlated to intelligent compaction values? [Select all that apply]

Answer Options	**Response Count**
Nuclear Gauge	10
Non-nuclear Gauge / Electric Density Gauge	1
Dynamic cone penetrometer data	3
Falling weight deflectometer data	2
Lightweight deflectometer data	2
California bearing ratio	0
Dry unit weight	3
Moisture content	4
Core density (for pavements)	5
Not applicable	7
Not Sure	1
Other (please specify)	4

4.4.4 Short-term and Long-term Costs Associated with IC

The survey contained three questions related to benefits and costs on a short-term basis (Question 15) and a long-term basis (Question 16 and Question 17). All the respondents that answered Question 15 indicated that bid or in-house compaction costs increase due to the use of intelligent compaction. These responses are listed in Table 4.9. Twenty-two of the 32 respondents indicated that they were “not sure” about the short-term costs or that the question was “not applicable” to them. Of these 22 respondents, 18 had conducted no more than one demonstration project and one respondent was “not sure” how many demonstration projects had been conducted. While several DOTs have conducted IC demonstrations, these demonstrations are often conducted with the financial support of the FHWA. Cost data are not necessarily collected or analyzed after a demonstration, especially during the first demonstration projects where the goal is to introduce DOT officials to IC technology. Conversely, eight of the 10 respondents indicating an increase in short-term costs had conducted more than one demonstration, and the other two respondents had conducted one demonstration project.

Table 4.9 Changes in Costs Utilizing IC (Results for Question 15)

What changes in bid costs or in-house costs does your agency incur with compaction services utilizing intelligent compaction? [Select one]

Answer Options	Response Percent	Response Count
An increase in cost	31.3%	10
About the same cost	0.0%	0
A decrease in cost	0.0%	0
Not sure	34.4%	11
Not applicable	34.4%	11
answered question		**32**
skipped question		**0**

Section 5 contains an analysis of short-term costs and demonstrates that there is a reduction in cost when using IC. This is due to the decreased amount of QC/QA in-situ testing required and time savings from more efficient roller patterns. It is noted that these are under conditions where roller operators have been trained to use IC equipment, technicians are trained to efficiently perform QC/QA, and engineers understand how to analyze QC/QA data. Demonstration projects, especially the initial projects, are expected to hold an increased cost due to the training requirements associated with IC technology.

Long-term benefit and cost data were less available with only three respondents—from Alaska, Texas, and Utah—indicating that they had information (Question 16). Of these respondents, the respondent from Texas, who noted that Texas DOT had conducted eight IC projects in the past six years, indicated with a qualitative response that IC projects had “higher benefits than costs.” The sample size of this single response is too low to be conclusive, but it does support the conclusions in Section 5 that long-term benefits of IC are higher than the costs. On the other hand, nine respondents, who do not have the long-term cost data, are planning to assess the long-term cost benefit of IC or eager to obtain this information from other independent agencies.

5. ECONOMIC ANALYSIS

The FHWA has cited reduced construction and maintenance costs as a feature of IC rollers (Federal Highway Administration, 2011); however, limited benefit-cost data are available to validate this claim. This is echoed by Wyoming professionals, who indicated that the cost of IC was their largest concern, and state DOTs, which responded that cost was a concern. To address the prominent concern of cost, a framework for a benefit-cost analysis was developed based on costs for construction of a roadway and savings from improved compaction uniformity over the pavement lifecycle. The framework is illustrated using two case studies: a thick (2- to 4-inch) asphalt overlay, and a new roadway section that includes soil and pavement layer compaction. The methodology to obtain cost data includes two specific cost cycles: construction and roadway life. Definitions for each cycle are included in Section 5.1.1. The summation of the cycle costs are to be compared between two compaction methods: conventional compaction and testing versus IC compaction. Sensitivity analysis is also provided for each case study in order to further analyze costs where there are few data points for inputs.

5.1 Methodology

The methodology used for analysis takes into account construction costs and roadway lifecycle costs as two separate time periods. Definitions for the time periods and compaction types are presented first. The framework for analyzing the differences between the conventional and intelligent compaction types is then presented for each time period.

5.1.1 Definitions

The definitions below provide an outline for types of costs that would be defined within each time period and type of compaction.

Construction Cycle Cost: The construction cycle includes the time period that begins with the preparations for conducting roadway compaction. This encompasses the costs for rollers, labor to operate the rollers, and conducting QC/QA testing.

Roadway Lifecycle Cost: The roadway lifecycle means the expected service life of the roadway. The costs per year for conventional compaction and IC are calculated based on the capital cost of the roadway improvement divided by the service life of the roadway in years. Pavement maintenance costs are not considered because the type of maintenance is highly dependent on the transportation agency and roadway characteristics.

Conventional Compaction and Testing: Conventional compaction means any method of compaction used by contractors to perform roadway compaction and subsequent QC/QA methods that do not use a roller equipped with on-board stiffness or density measuring devices. QC/QA data are obtained by in-situ field tests.

IC Compaction: IC compaction means the compaction of a roadway section by use of a device, such as one defined in the FHWA QC/QA sample specifications for IC, attached to a roller that allows for the measurement of soil stiffness. Generally, this includes the use of an accelerometer, GPS unit, and on-board computer to aid roller operators in compaction efforts. QC/QA data are obtained from the roller and is analyzed by a QC/QA technician or engineer (Federal Highway Administration, 2014).

5.1.2 Framework

The comparison between the two compaction methods comprises a summation of the costs from the two cost cycles over similar construction lengths and roadway lifecycles. The summed costs for each time period are compared to each other independently. In order to illustrate the framework, a project type and size must be chosen. The first case study, described in Section 5.2, is a project with a thick, one-lane mile asphalt overlay. The second case study, described in Section 5.5, is a new construction of a one-lane mile section, which includes subgrade compaction. This framework not only can be applied to new road construction but also can be applied to different types of roadway improvements, including reconstructions, so long as the data for each type of improvement are gathered and used accordingly.

The calculation of costs is based on QC/QA Option 3a when using IC, which is described in Section 2. Option 3a was used for this analysis because it is the most commonly implemented QC/QA option based on responses from DOTs as listed in Table 4.4 within Section 4.4.3. Cost differences between compaction methods using QC/QA Option 1 can be taken from Figure 5.6 in Section 5.3.

Construction Cycle: Construction costs regarding roller equipment and labor for conventional compaction are gathered using pricing data from contractors. The costs are set as an hourly rate so that they can be used for different types of projects if necessary. A rate of compaction for construction crews can also be obtained from the contractors. The rate should yield an area per unit time period, for example, 6,000 square feet per hour. This allows for calculation of the amount of time that it would take a construction crew to complete the type of work that is being analyzed. This amount of time is then multiplied by the roller equipment and labor costs for each type of compaction as illustrated by Equation 5.1.

$$\text{Construction Cost} = (\text{Compaction Time in Hours}) \times [(\text{Roller Cost per Hour}) + (\text{Roller Operator Cost per Hour}) + (\text{GPS Cost per Hour})] + [(\text{QC/QA Cost per Area}) \times (\text{Area})] \quad (5.1)$$

Construction costs for IC were calculated based on a reduced amount of time to perform roller operations and the cost of an IC roller. The IC roller cost may be available from contractors, but if it is not, it should be obtained from IC roller manufacturers. The roller manufacturer chosen for a specific analysis should be based on similarities to the conventional roller used, such as setup (drum roller number and type), weight, and vibratory characteristics. In order to calculate the number of hours for compaction using IC, a 30% reduction in the number of hours it would take a conventional roller is applied, which is given by Equation 5.2. The reduction was based on the number of roller passes from IC rollers compared with conventional rollers to perform similar compaction work as observed by Briaud and Seo (Briaud & Seo, 2003). The test section area, used for QC/QA purposes, must be added into the amount of time needed for compaction using the IC roller. The total time required for compaction of the test area and the roadway section is then multiplied by the hourly rates for labor and equipment to obtain the cost as demonstrated in Equation 5.3.

$$\text{IC Hours} = (\text{Conventional Compaction Hours for Roadway Section} + \text{Conventional Compaction Hours for Test Section}) \times (100\% - \text{IC Efficiency }\%) \quad (5.2)$$

$$\text{Cost per Line Item} = (\text{Hourly Rate of Line Item Cost}) \times (\text{Hours}) \quad (5.3)$$

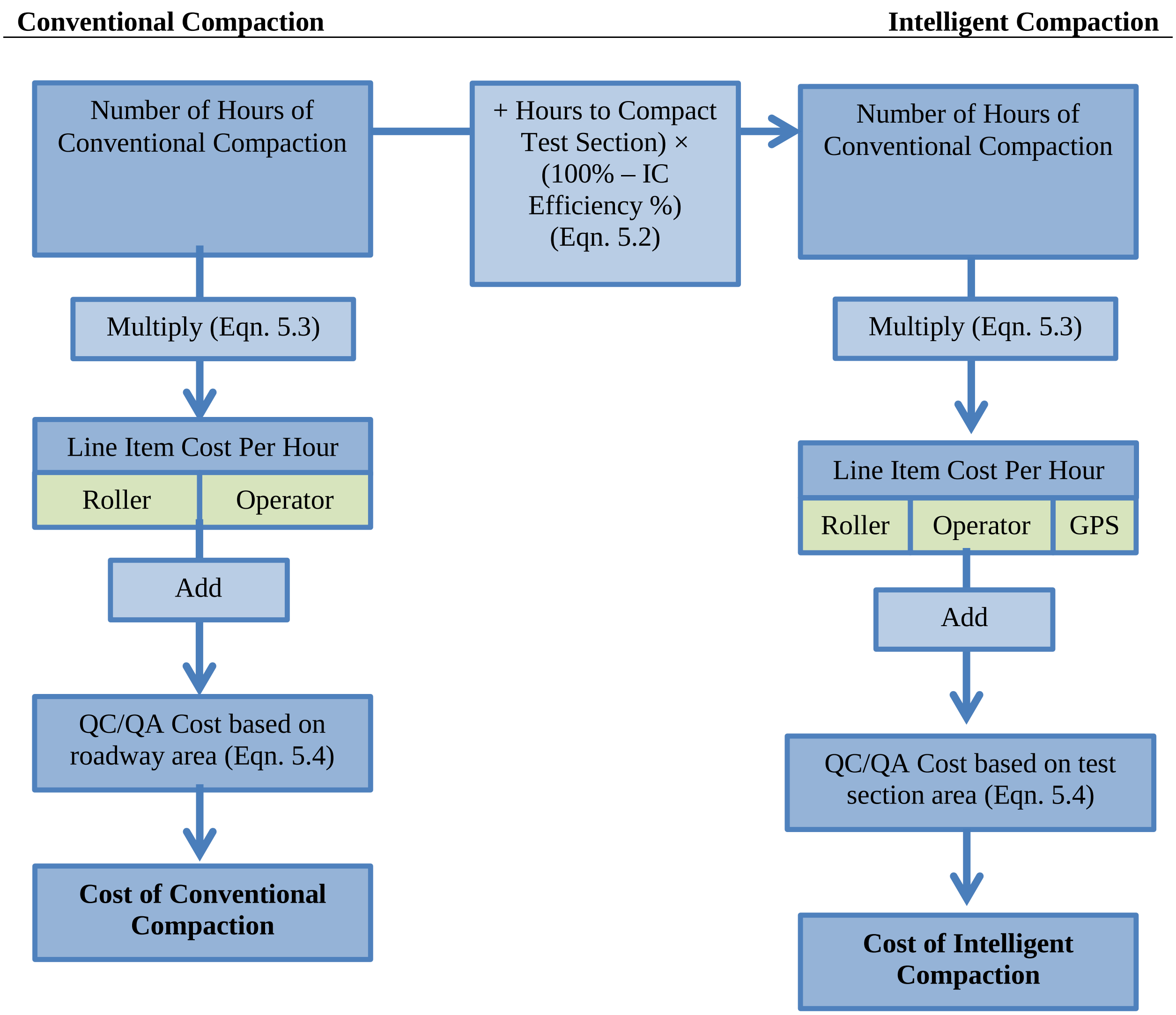

Figure 5.1 Flow Chart for Calculating Compaction Cost

The QC/QA program costs are also part of the total construction cost. The information for conventional compaction and testing can be obtained by surveying contractors on their costs related to QC/QA. Contractors may provide this information with equipment and labor costs separated or combined. The costs will be in either an hourly or unit area rate, such as square feet. In order to calculate the QC/QA program costs from hours, the rate of QC/QA performance must be converted using a time per unit volume or area as given by Equation 5.4. The calculated unit volume or unit area can then be converted into a total cost based on the size of the roadway being analyzed. The cost for the QC/QA program for intelligent compaction is then multiplied by the test section area divided by the total project area. QC/QA is provided on the test section area in order to correlate MVs with conventional testing methods, such as nuclear gauge or core sampling. The area used can vary depending on the project but is often between 300 to 600 feet (Mooney, et al., 2010) and several DOT IC specifications (The Transtec Group, Inc, 2014). Figure 5.1 is a flow chart for calculating the cost of each type of compaction based on the equations and description of calculations.

QC/QA Cost = (Hours to perform QC/QA) × (Area of QC/QA per hour) × (Cost of QC/QA per area) (5.4)

Roadway Lifecycle: One of the largest benefits provided by IC is that it provides a more uniform compaction. Uniformity translates into an extended pavement life. In order to calculate the benefit from using IC, the cost per lane mile for a thick asphalt overlay was divided by the remaining service life improvement to the roadway as noted in Equation 5.5. The average cost per lane mile and remaining service life improvement should be obtained from a state DOT or local municipality. The increase in remaining service life from IC is 2.6 times (260%) the conventional compaction method based on Chang, et al. (Chang, et al., 2012). This is due to an increase in fatigue life, where pavement fatigue from loading is assumed to be the cause of most roadway failures.

Cost per lane-mile per year = (Cost of Roadway per Lane-Mile) / (Service Life in Years) (5.5)

5.2 Case Study No. 1: Pavement Analysis

The cost comparison between the two compaction methods comprises a summation of the costs from the two cost cycles over similar construction lengths and roadway lifecycles. To illustrate the application of proposed benefit-cost analysis framework, a case study of a thick, one lane-mile overlay asphalt pavement was presented. Table 5.1 contains the data inputs used for the analysis, which are discussed in more details in the subsections.

5.2.1 Construction Cycle Data

The construction cycle costs for conventional compaction were gathered from a survey of contractors performing compaction services in Wyoming. The data used were the cost of a roller, roller operator, and GPS system per hour. These data were obtained from roller manufacturers, a phone survey of Wyoming contractors, and GPS system providers (Jones, 2014; Bastian, 2014; Newman, 2014; Trimble Navigation Limited, 2014). Also, QC/QA data were based on local contractor information (Bastian, 2014). The summation of these data was used to create a cost per lane mile for the construction of a 2- to 4-inch thick asphalt overlay as given in Equation 5.1.

Where data were given in ranges, a value within the range was assumed in order to create comparable data between the two compaction types. Also, the hourly rate for the roller operator was assumed to be the same for each type of roller. The cost of intelligent compaction was then calculated using a 30% reduction in the number of hours it would take a conventional roller. The reduction was based on the number of roller passes from IC rollers compared with conventional rollers as observed by Briaud and Seo (2003). The time to compact the 500-foot by 12-foot test section area for establishing MV correlational to conventional compaction testing was added.

QC/QA costs for IC were reduced to the area of the test section required to calibrate conventional testing methods with the IC's measurement values. The cost of QC/QA testing was then multiplied by lineal feet of the test section, 500 feet, divided by the lineal feet in a mile, 5,280 feet, which resulted in a multiplier of 0.095. Equation 5.6 is the cost of QC/QA for IC based on the conventional compaction QC/QA cost. This can also be described as the test section being 0.095 times the lineal length of one mile. Veda, a free software program developed by the Minnesota Department of Transportation, allows for instantaneous determination whether data comply with QC/QA standards. An initial expense to program QC/QA compliance into the software and train QC/QA engineers to use the software are required; however, it would not be a significant contributor to cost to a single project when averaged over several compaction projects.

QC/QA Cost for IC = (QC/QA Cost of Conventional Compaction) × (Test Section Lineal Length / Length of Roadway Section) (5.6)

Table 5.1 Input Data for Benefit-Cost Analysis

Item	Unit Cost ($)/ Quantity	Source
Construction Costs		
QC/QA per square yard	$ 0.04	Simon Contractors, WY (Bastian, 2014)
IC Reduction in compaction cost	30%	Briaud & Seo (Briaud & Seo, 2003)
Lane width, feet	12	Assumption
IC to conventional QC/QA cost	10%	NCHRP 676 (Mooney, et al., 2010)
Conventional roller cost per hour	$ 36	High Country Construction, WY (Newman, 2014)
IC pavement roller cost per month	$ 7,500	Sakai America (Jones, 2014)
Roller operator per hour	$ 30	High Country Construction, WY (Newman, 2014)
Conventional compaction hours/lane-mile	10	High Country Construction, WY (Newman, 2014)
Compaction cost per square yard	$ 0.20	Simon Contractors, WY (Newman, 2014)
GPS System rental per year	$ 1,800	Trimble (Trimble Navigation Limited, 2014)
Test Section Length, feet	500	NCHRP 676 (Mooney, et al., 2010), DOT IC Specs (The Transtec Group, Inc, 2014)
Work hours per week	40	Assumption
Lifecycle Costs		
Increased service life with IC, multiplier	2.6	(Chang, Gallivan, Horan, & Xu, 2012)
Average asphalt life, years	10	Average overlay service life
Cost per lane-mile	$ 250,000	WYDOT (Wyoming Department of Transportation, 2011), Caltrans (Caltrans, 2011), Woodland (City of Woodland, 2008)

5.2.2 Roadway Lifecycle Data

The benefit from increased uniformity was calculated for the thick asphalt overlay using the increased fatigue life multiplier. The average cost per lane mile for thick asphalt overlay is approximately $250,000 based on estimates from WYDOT and other jurisdictions (Wyoming Department of Transportation, 2011; Caltrans, 2011; City of Woodland, 2008). Also, the average remaining service life improvement of a thick asphalt overlay is assumed to be 10 years under conventional compaction methods. Under greater uniformity from IC, a thick asphalt overlay has been calculated to have a service life of 2.6 times greater, or 26 years, due to the increased fatigue life (Chang, Gallivan, Horan, & Xu, 2012).

5.2.3 Results of Pavement Case Study

The results for the construction cycle and the roadway lifecycle are presented separately in the following subsections. Calculations for the cost per unit and number of units are described in each subsection.

5.2.3.1 Construction Cycle

The unit costs for the roller, operator, and QC/QA for conventional compaction are listed in Table 5.1. The unit cost for the IC roller was based on the cost per month of the roller (i.e., $7,500) divided by 176 work hours in a month. This was calculated using the assumption of 40 hours per work week, or eight hours per work day, and 22 work days per month. This yielded an hourly rate of $42.61 for the IC roller. The same method was used to calculate the hourly cost of the GPS unit at $0.89 per hour, which had a yearly rate of $1,800. The conversion from monthly rates to hourly rates is given by Equation 5.7.

$$\text{Line Item Hourly Rate} = (\text{Line Item Cost / month}) \times (\text{One month / 176 working hours}) \qquad (5.7)$$

The number of units in hours or per square yard was calculated using a combination of the rate of construction and the areas of the road section and test section. The rate of construction is 10 hours per lane-mile for conventional compaction as noted in Table 5.1. The distance of the test section was added to the one-mile distance of the road section and then divided by the rate of construction. This result was then reduced by 30% to account for the reduction in time using an IC roller as given by Equation 5.2 (Briaud & Seo, 2003). The result of the reduction yielded an equivalent of 7.7 hours to perform IC.

The number of units for QC/QA was calculated as the unit cost of $0.04 per square yard to perform QC/QA from Table 5.1 multiplied by the number of square yards that QC/QA was performed on. For conventional compaction, the QC/QA was performed on the area of the road section, which is 5,280 feet multiplied by 12 feet and divided by 9 square feet per square yard. The area of the test section, which is 500 feet by 12 feet, was the square yards for QC/QA for IC. The remaining QC/QA is performed based on readings from the IC roller. The data can be downloaded from the roller and inputted into the VEDA software in a limited amount of time to check for compliance on the road section.

The costs were yielded by summing the cost of each line item as shown in Table 5.2. Conventional compaction yields a cost of $940.52 per lane-mile and IC yields a cost of $592.63 per lane-mile, which is a 37% reduction compared with conventional compaction. The 37% reduction was mainly a result of the 30% reduction in compaction time and also the reduction in QC/QA costs. The increase in cost from the GPS system was marginal. The GPS cost was calculated by using the annual rental cost and dividing it by the ratio of hours that it was used during compaction. The number of hours to complete compaction of a roadway was 23% less using IC. This was calculated using the 30%reduction in compaction time using IC and increased by the additional 500-feet long by 12-feet wide area for the test section. Line-itemed calculations are contained in Table 5.2.

Table 5.2 Cost of Construction Cycle per Lane-Mile

	Conventional Compaction				Intelligent Compaction			
Item	**Cost per Unit**	**Unit**	**Number of Units**	**Total Cost**	**Cost per Unit**	**Unit**	**Number of Units**	**Total Cost**
Roller	$ 36.00	hour	10	$ 360.00	$ 42.61	hour	7.7	$ 328.10
Operator	$ 30.00	hour	10	$ 300.00	$ 30.00	hour	7.7	$ 231.00
GPS	n/a	n/a	n/a	n/a	$ 0.89	hour	7.7	$ 6.85
QC/QA	$ 0.04	yd^2	7040	$ 281.60	$ 0.04	yd^2	667	$ 26.68
Total				$ 941.60				$ 592.63

n/a - Data is not applicable

5.2.3.2 Roadway Lifecycle

The total cost of performing a thick, one lane-mile asphalt overlay was divided by the service life increase from the improvement. The service life improvement using conventional compaction was noted as 10 years in Table 5.1. The total cost per lane-mile of $250,000 was divided by 10 years to yield the annual cost for conventional compaction. The total cost was then divided by 26 years for IC, reflecting the 2.6 times of improved service life (Chang, Gallivan, Horan, & Xu, 2012). The annual costs were then multiplied by 26 years for each conventional compaction and IC to demonstrate comparable costs during the lifecycle of a one lane-mile road section using IC.

Table 5.3 contains the data used for each of the compaction types. Conventional compaction yielded 16 years less service life compared with IC. The cost savings for IC compared with conventional compaction is $15,385 per year, or $400,000, when spread over the lifetime of an IC road section. The cost savings using IC resulted from increased material uniformity.

Table 5.3 Roadway Lifecycle Costs per Lane-Mile for One Year and 26 Years

Compaction Type	Service Life (years)	Cost Per Year	Cost Over 26 Years
Conventional	10	$ 25,000	$ 375,000
Intelligent	26	$ 9,615	$ 250,000
Difference	-16	$ 15,385	$ 400,000

5.2.4 Sensitivity Analysis for Pavement Case Study

The results from the prior section demonstrate a cost savings by using IC in both the construction cycle and the roadway lifecycle. These results were based on the inputs from Table 5.1. A sensitivity analysis was performed on the pavement section analyzed in the prior sections in order to understand the effect of variations in input values on the outcome of the economic analysis. Variations may be anticipated because of the limited data that have been provided for inputs as well as different agencies in different regions. The inputs included in this sensitivity analysis include a range of values for compaction efficiency, roller cost, and the IC service life multiplier.

5.2.4.1 Compaction Efficiency

The compaction efficiency improvement for IC was provided at a rate of 30% based on work by Briaud and Seo (2003). Beyond these authors' work, very little has been done to summarize the efficiency savings of IC. The sensitivity analysis for this section includes compaction efficiency for IC ranging from negative 15% to 45%. The IC efficiency is plotted against the percent cost difference of conventional compaction to IC in Figure 5.2. The remaining inputs were held constant at the values provided in Table 5.1. The results of the sensitivity analysis apply only to the construction cycle. For example, at the previously selected IC efficiency of 30%, the percent cost difference is 37.1%, which is the difference in total costs of $941.60 for conventional and $592.63 for IC as indicated in Table 5.2 and expressed in percentage.

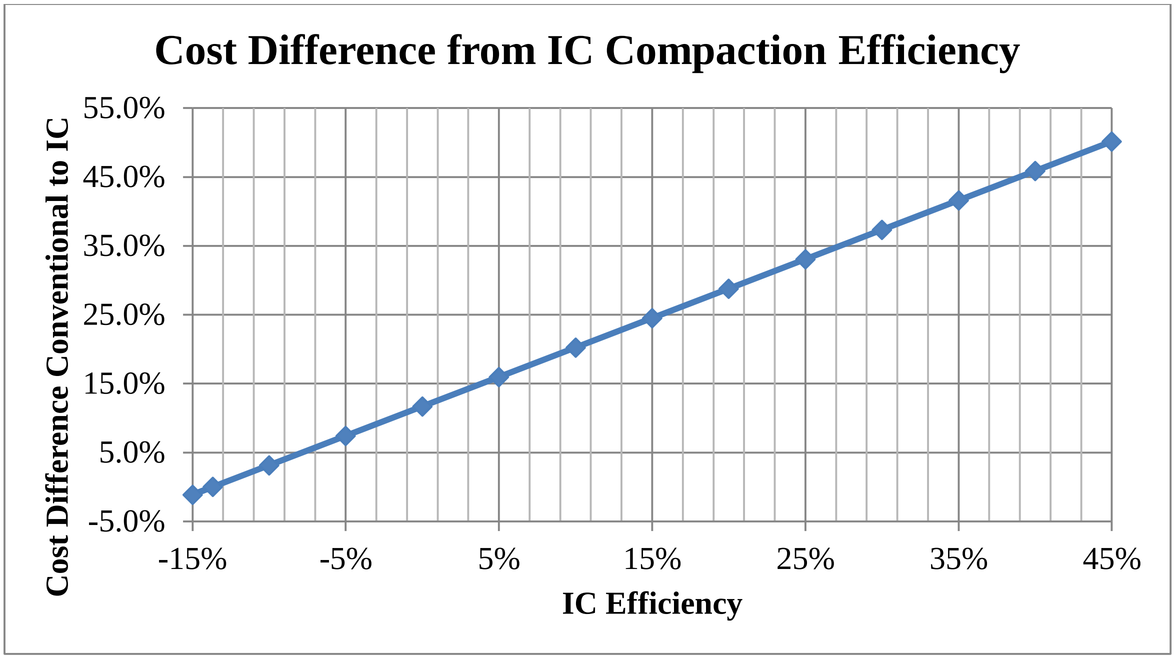

Figure 5.2 Cost Difference with Varying IC Efficiency

The relationship between the IC efficiency to the cost difference between conventional compaction and IC is linear. As discovered in the previous section, 30% efficiency results in a 37.1% decrease in costs for IC relative to conventional compaction. The break-even point (i.e., cost for conventional equals IC) is when the IC efficiency is negative 13.7%. The IC efficiency can be negative but still yield a cost savings due to the decrease in QC/QA costs associated with using IC. Comparatively, an IC efficiency of 45% yields a 50.2% cost savings. More research is needed to understand the range of IC efficiencies for different type of compaction projects; however, the savings from on QC/QA when using IC demonstrates that IC would still be viable even if the relative IC efficiency is below zero percent.

5.2.4.2 Roller Cost

A range of conventional roller costs was used to demonstrate the differing costs that exist in the roller compactor market. While the value used for the analysis in the previous section was based on data provided by High Country Construction, pricing for a conventional roller can depend on the age, type, and region of use. Also, companies or government agencies may own conventional rollers that have outperformed their anticipated service life and have a substantially lower cost relative to a newer roller model. A range of hourly costs of a conventional roller between $0 and $42.61 is provided. The upper value is the hourly cost of the IC roller. Figure 5.3 contains the hourly cost of a conventional roller plotted against the cost per lane-mile for compaction of a thick overlay. The cost per lane-mile of IC is plotted based on the hourly rate of a conventional compactor. The IC cost is the cost to perform IC at the prevailing hourly rate of IC equipment given in Table 5.2. Figure 5.4 shows the cost difference in terms of a percentage.

The resulting break-even point is when the hourly cost of a conventional roller is $1.10. This would require the roller to be greatly discounted from a typical price of $36 per hour (Table 5.1), the value used for the analysis in the previous section. A conventional roller costing the same amount as the IC roller would have a cost $415.07 greater per lane mile, which is 41.2% more than IC. This sensitivity analysis reveals that IC provides cost savings for a wide range of conventional roller costs, and savings for conventional compaction is only available at greatly depreciated conventional roller values.

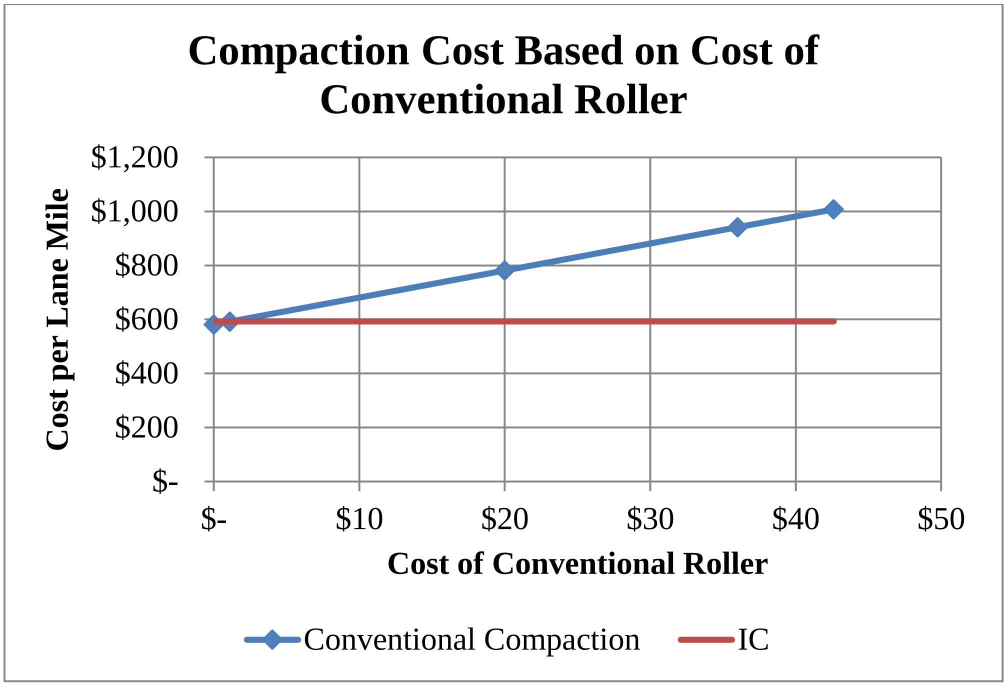

Figure 5.3 Cost Difference Based on Hourly Cost of Conventional Roller

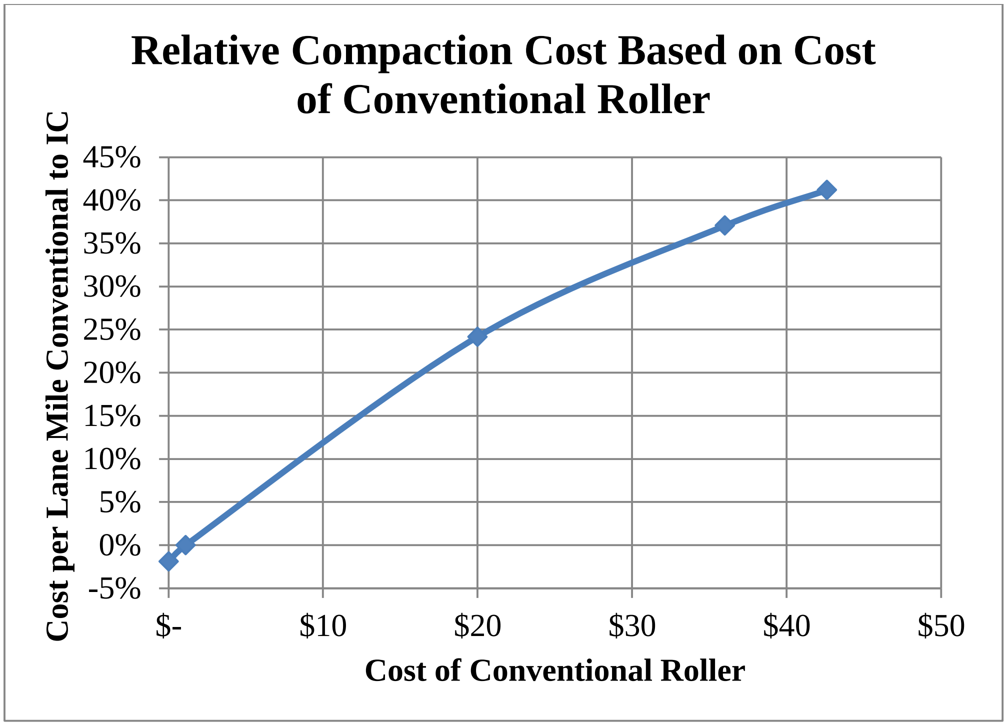

Figure 5.4 Percent Cost Difference Based on Hourly Cost of Conventional Roller

5.2.4.3 Service Life Improvement from Using IC

Improved pavement quality from compaction uniformity using IC was assumed to result in 2.6 times the service life of a conventionally compacted pavement section based on Chang, et al. (2012). Figure 5.5 shows the lifecycle cost savings based on a variety of service life multipliers from using IC. This sensitivity analysis was performed due to the limited amount of research on increased service life from using IC.

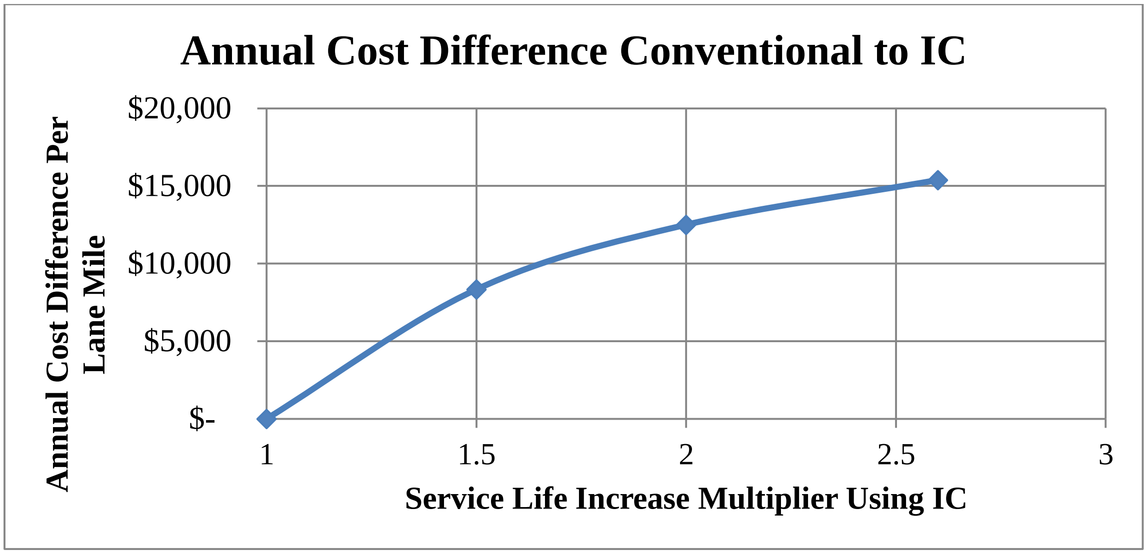

Figure 5.5 Lifecycle Cost Saving Based on Service Life Improvement from IC

The multiplier of 2.6 times the service life of a conventionally compacted pavement results in an annual cost savings of $15,385 per lane mile as demonstrated earlier in this section. A multiplier of 3 results in an annual cost savings of $16,667. A more conservative estimate for improved service life would be an improvement of 1.5 times the service life of a conventionally compacted section. A 1.5-times improvement results in an annual savings of $8,333, and annual cost savings decreases more rapidly as the multiplier approaches one. Table 5.4 contains the data for a roadway section that has a service life improvement of 1.5 times using IC.

Table 5.4 Roadway Lifecycle Costs per Lane-Mile for One Year and 15 Years

Compaction Type	Service Life (years)	Cost Per Year	Cost Over 15 Years
Conventional	10	$ 25,000	$ 375,000
Intelligent	15	$ 16,667	$ 250,000
Difference	-5	$ 8,333	$ 125,000

5.3 Case Study No. 2: New Roadway Construction

This case study examines the cost difference between compaction of a roadway section for both soil and pavement layers for a lane mile using conventional compaction and IC. The methodology used is similar to the methodology outlined in Section 5.1; however, there are two differences. The cost of rollers for soil materials were used for corresponding soil layers and the calculation of hours to complete the compaction was based on the speed of rollers. Speeds of three and eight miles per hour were used to demonstrate the difference in cost based on varying speeds, which were used in case studies (Mooney, et al., 2010). Table 5.5 lists the inputs used to calculate costs.

Table 5.6 contains the cost calculation per lane-mile of roadway based on the inputs and using the more conservative speed of three miles per hour. In order to calculate the amount of time to compact the soil and the pavement, the lane width divided by the roller width of 7 feet was rounded up to the nearest whole number and multiplied by the number of passes and the length and finally divided by the speed as given in Equation 5.8. The number of hours to perform compaction was then multiplied to the corresponding hourly rate for the soil and pavement compactors. The operator, GPS, and QC/QA costs were calculated similarly to the pavement case study.

Table 5.5 Inputs for Soil/Pavement Case Study

Construction Cycle		
Item	**Cost / Quantity**	**Source**
QC / QA per square yard per layer	$ 0.04	Simon Contractors, WY
IC Reduction in Compaction Cost	30%	Briaud & Seo, 2003
Lane Width, feet	12	Assumption
IC to Conventional QC/QA cost	10%	NCHRP 676 based on test section size
Conventional Soil Roller Cost per hour	$ 34.03	Wagner Rents, Fort Collins, CO
Conventional Pavement Roller Cost per hour	$ 36.00	High Country Construction, WY
IC Soil Roller Cost per month	$ 7,000	Sakai America
IC Pavement Roller Cost per month	$ 7,500	Sakai America
Operator Cost per hour	$ 30.00	High Country Construction, WY
Number of passes per layer	6	Assumption
Average Roller Speed (mph)	3 and 8	Assumption
Layer Thickness, inches (Subgrade/ subbase/ base/ binder/ surface)	8 / 8 / 8 / 4 / 2	Assumption
GPS System, per year	$ 1,800.00	Trimble

$$\text{Compaction Hours} = [\text{ROUNDUP TO INTEGER (Lane width / Roller Width)}] \times (\text{Number of passes}) \times (\text{Roadway length}) / (\text{Roller speed}) \quad (5.8)$$

Table 5.6 Cost of Construction Cycle per Lane-Mile

	Conventional Compaction				Intelligent Compaction			
Item	**Cost per Unit**	**Unit**	**Number of Units**	**Total Cost**	**Cost per Unit**	**Unit**	**Number of Units**	**Total Cost**
Soil Roller	$ 34.03	hour	12.0	$ 408.41	$ 39.77	hour	9.2	$ 365.83
Pav. Roller	$ 36.00	hour	8.0	$ 288.00	$ 42.61	hour	6.1	$ 261.31
Operator	$ 30.00	hour	20.0	$ 600.00	$ 30.00	hour	15.3	$ 459.90
GPS	-	-	-	$ -	$ 0.89	hour	15.3	$ 13.64
QC/QA	$ 0.20	sq yd	7040	$ 1,408.00	$ 0.20	sq yd	667	$ 133.40
Total				$ 2,704.41				$ 1,234.08

Compaction of the soil and pavement lanes for a lane mile at an average roller speed of three miles per hour results in a $1,470.33 savings using IC, which is a 54.4% decrease compared with conventional compaction. A sensitivity analysis was performed to demonstrate the cost savings at average roller speeds of three and eight miles per hour. These values were plotted with the percent of in-situ QC/QA performed on the roadway section versus the percentage of cost savings. Figure 5.6 depicts the results from the sensitivity analysis. The analysis reveals that using IC is more cost effective for each speed and percent of in-situ QC/QA performed except when 100% in-situ QC/QA is performed with a roller speed of eight miles per hour.

Figure 5.6 also serves as a way to calculate cost differences using QC/QA Option 1 for IC. QC/QA Option 1 requires testing the least compact areas, which are indicated by lower MVs, with conventional testing methods. Acceptance is met when an established percentage of conventional tests are above the required test result value. While there is not an established percentage of testing that must occur for Option 1, Figure 5.6 can be used to understand the reduction in cost that occurs from a decrease in the amount of conventional testing that is performed. For example, a reduction of conventional testing by 50% while using IC QC/QA Option 1 results in a cost savings of 28% assuming the roller speed is three miles per hour.

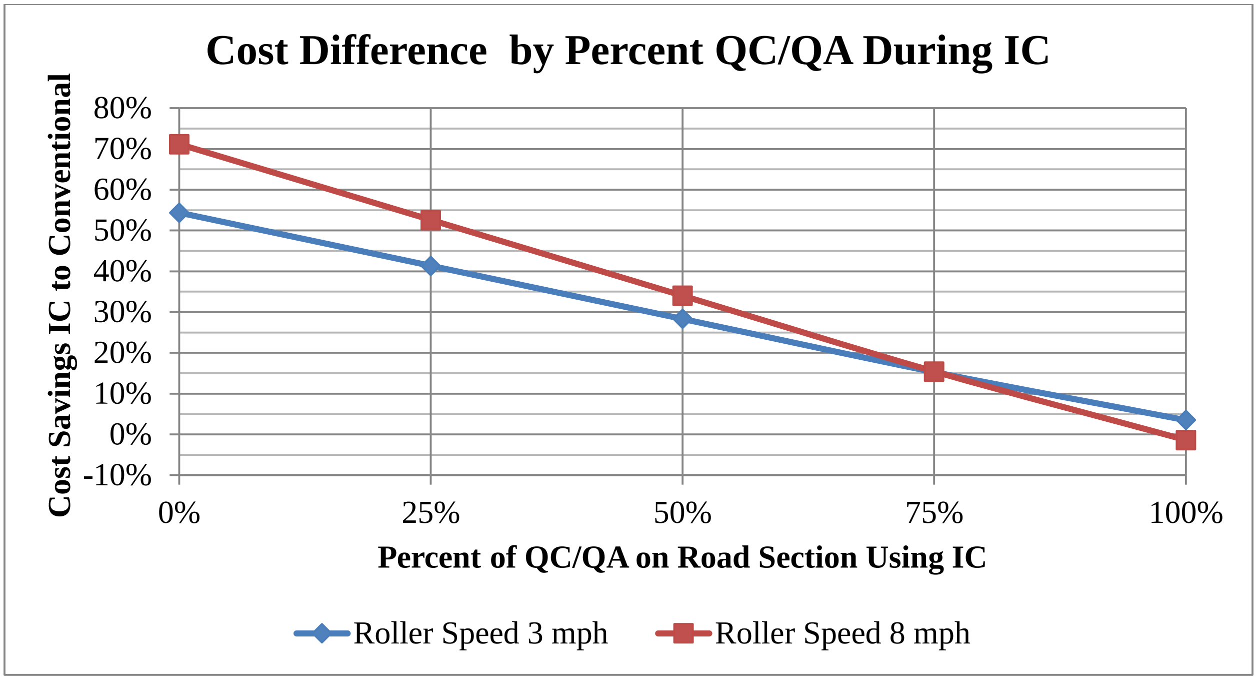

Figure 5.6 Cost Saving by Amount of QC/QA performed

5.4 Summary

The following summarizes the benefit-cost analysis from this section:

1. A thick asphalt overlay on one lane-mile yields a 37% savings on compaction costs when using IC versus conventional compaction;
2. Annual savings on a lane-mile's value for a pavement compacted with IC is approximately $15,000;
3. Sensitivity analysis for the thick overlay example demonstrated that a conventional roller would have to have nearly no cost in order to be more cost effective than an IC roller; and
4. Compaction of a new roadway section using IC results in a 54% savings compared with conventional compaction.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions highlighting key points from the literature review, surveys, and economic analysis are noted. Based on the information provided in the prior sections, conclusions and recommendations for implementation of IC in Wyoming and future research needs are included in this section.

6.1 Conclusions

This paper examined IC technology, IC QC/QA methods, application of IC QC/QA methods by various state DOTs, knowledge and perceptions of IC among practicing professionals, and the benefits and costs of IC as related to construction and lifecycle time periods. Conclusions about these topics are summarized as follows:

1. The FHWA is actively promoting IC as a tool to improve roadway quality and decrease roadway related costs;
2. IC can provide 100% coverage of compaction where conventional methods currently provide less than 1% coverage;
3. Roller manufacturers have formulas for calculating compaction values (MVs) that are unique to their system, but they are generally mechanistic-based or harmonic-based calculations;
4. Correlations between in-situ tests and MVs are more reliable for soils and less reliable for asphalt, but these values can be improved by multiple regression analysis and BE/FE analysis;
5. Most Wyoming professionals are supportive of implementation of IC, but there are concerns about cost and the reliability of data;
6. Twelve of 21 respondents on the national survey indicated that they are drafting, have drafted, or have adopted IC QC/QA specifications, and a majority of those respondents rely on correlations between MVs and in-situ tests to perform QC/QA;
7. National survey respondents indicated that construction costs with IC currently involve an increase in cost relative to conventional compaction;
8. IC, when used effectively, can produce a 37% decrease in construction costs based on a hypothetical thick asphalt overlay on one lane-mile long roadway and a 54% decrease in costs on a new roadway section; and
9. Improved pavement performance based on compaction uniformity using IC can yield approximately $15,000 per lane-mile per year in cost savings.

6.2 Recommendations

6.2.1 Implementation of IC in Wyoming

Implementation of IC at the state level has already begun due to the efforts of the FHWA to promote IC through its Every Day Counts initiative mentioned in Section 1.2. These efforts are bolstered by a body of research and practice in Europe that have laid the foundation for IC throughout the world. Specifically, implementation of IC in Wyoming unofficially began with the Intelligent Compaction Data Management workshop held in March 2014. This FHWA-sponsored workshop allowed private and public sector engineers, contractors, and other interested parties to learn about IC and understand QC/QA tools that can be used to analyze field data from IC rollers. The next steps for implementation of IC in Wyoming include:

1. Working with the FHWA and WYDOT to secure funding and a site for an IC demonstration project;

2. Adapting IC QC/QA specifications to be used during the demonstration project as a special provision;
3. Holding the demonstration project and inviting members from WYDOT, local governments, and the private sector to observe the demonstration;
4. Analyzing QC/QA data from the demonstration project to evaluate the performance of the IC roller with regard to its ability to ensure quality compaction;
5. Analyzing construction cost data and accounting for both training expenses and regularly anticipated IC costs after training;
6. Beginning a monitoring program of the pavement section where the demonstration project took place to obtain changes in pavement performance relative to conventionally compacted sections;
7. Preparing subsequent demonstration projects to confer with results from the first demonstration project and to test for other applications of IC;
8. Drafting QC/QA standards for adoption by public agencies to promote the use of IC by contractors if the demonstration projects prove that IC generates a net benefit;
9. Providing an incentive for contractors to adopt IC by establishing a monetary bonus structure for a temporary time period to offset initial costs associated with training and creating economies of scale with IC; and
10. Beginning IC QC/QA with Option 1, described in Section 2.4.2, in order to gain immediate roadway compaction quality benefits from IC while using it as method to establish correlation values in preparation for adoption of IC QC/QA Option 3a in the future.

6.2.2 Future Research Needs

Research has proven that IC can be used effectively given proper conditions. IC has demonstrated sufficient correlations with soil measurements taking into account discretion necessary for certain job sites. IC still requires further examination before it can be declared as a reliable tool for asphalt compaction. Also, economic analysis data can be improved by incorporating analysis of real-world IC projects and providing those data to academic and trade publications.

Reliability of IC data for compaction of soil and asphalt can be improved by incorporating various methods. Several IC project reports have used multiple regression analysis to improve correlation values between in-situ tests and MVs, but factors affecting the analysis may vary from project to project. An analysis of the types of factors that affect correlation values would provide better guidance for QC/QA engineers to improve the effectiveness of IC. Also, boundary element (BE) and finite element (FE) methods can help improve MV accuracy by accounting for different underlying layer properties. Literature on these approaches was published in 2013 and should be adapted for use in a demonstration projects to evaluate their practical application (Mooney & Facas, 2013). These methods may also improve the low correlation values that have been observed during asphalt case studies with the ability to make IC more viable as a tool for asphalt compaction.

From an economic standpoint, more data about construction-related costs must be analyzed to understand if real-world IC projects support the theoretical cost savings demonstrated in this paper. This requires that training costs be identified and accounted for in order to obtain the true construction costs of IC relative to conventional compaction. Also, pavement performance of existing roadway sections compacted with IC should be compiled to understand how IC affects long-term pavement performance. The first IC projects began approximately 10 years ago and any data regarding the pavement performance on those sections can provide valuable insight into the long-term benefits of IC. Also, literature on the economics of IC can be bolstered by starting a monitoring program of recent and new roadway sections constructed with IC. Specifically, the roadway sections should be monitored for various pavement condition metrics and compared to similar roadway sections that were compacted with conventional methods.

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APPENDIX A. ABBREVATIONS AND ACRONYMS

BE	Boundary element method
CBR	California Bearing Ratio
CCC	Continuous compaction control
CMV_D	Compaction meter value (Dynapac)
DOT	Department of Transportation
E_{vib}	Vibration modulus (Bomag)
FE	Finite element method
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GPS	Global positioning system
IC	Intelligent compaction
ISSMGE	International Society for Soil Mechanics and Geotechnical Engineering
LWD	Lightweight deflectometer
M_r	Resilient modulus
MV	Measurement value
NCHRP	National Cooperative Highway Research Program
NG	Nuclear Gauge
NNG	Non-nuclear Gauge
PCI	Pavement Condition Index
PI	Plastic index
PLT	Static plate load test
PSPA	Portable seismic pavement analyzer
TV	Target value
WYDOT	Wyoming Department of Transportation
γ_d	Soil dry unit weight
w	Soil moisture content

APPENDIX B. WYOMING SURVEY RESULTS

A list of the raw data from the survey responses are listed in the tables below. The question number is indicated by "Q#." Requests for a complete set of data may be sent to the authors or the Department of Civil and Architectural Engineering at the University of Wyoming.

Q1. What is your name and contact info?

Answer Options	Response Percent	Response Count
Name	100.0%	79
Title	86.1%	68
Business/Agency	93.7%	74
Address	84.8%	67
Email	91.1%	72
Phone	82.3%	65
answered question		**79**
skipped question		**0**

Q2. What field(s) do you primarily work in? [Select all that apply]

Answer Options	Response Percent	Response Count
Geotechnical Engineering	10.4%	8
Transportation Engineering	31.2%	24
Construction	49.4%	38
Department of Transportation	89.6%	69
County Government	2.6%	2
City Government	1.3%	1
Other (please specify)		4
answered question		**77**
skipped question		**2**

Q3. Does your agency/company perform or contract roadway compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
Performs Compaction Services	19.2%	14
Contracts Compaction Services	93.2%	68
Not sure	2.7%	2
Other (please specify)		3
answered question		**73**
skipped question		**6**

Q4. Have you heard of intelligent compaction before this workshop? [Select One]

Answer Options	Response Percent	Response Count
Yes	51.3%	40
No	48.7%	38
answered question		**78**
skipped question		**1**

Q5. What is your primary source of information for learning about intelligent compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
FHWA representatives or publications	50.8%	31
Academic journals	13.1%	8
Professional society newsletters	9.8%	6
Contractors	23.0%	14
Internet research	27.9%	17
None of the above	13.1%	8
Other (please specify)		19
answered question		**61**
skipped question		**18**

Q6. Which aspects of intelligent compaction are you familiar with? [Select all that apply]

Answer Options	Response Percent	Response Count
Operation of intelligent compaction rollers	30.7%	23
Technology used during intelligent compaction	41.3%	31
Cost and benefits	14.7%	11
Quality Control/Quality Assurance Standards	21.3%	16
None of the above	40.0%	30
Other (please specify)		3
answered question		**75**
skipped question		**4**

Q7. Has your agency/company ever used a compactor outfitted with intelligent compaction technology? [Select One]

Answer Options	Response Percent	Response Count
Yes, we own one	1.3%	1
Yes, we rent one	0.0%	0
Yes, but we no longer use it	0.0%	0
No, but we are considering using it	16.7%	13
No, and we have not considered using it	41.0%	32
Not sure	41.0%	32
answered question		**78**
skipped question		**1**

Q8. Which intelligent compaction rollers has your agency/company used? [Select all that apply]

Answer Options	**Response Percent**	**Response Count**
Ammann	0.0%	0
Bomag	10.0%	1
Case	0.0%	0
Caterpillar	0.0%	0
Dynapac	10.0%	1
Hamm – Wirtgen	0.0%	0
Sakai	10.0%	1
Volvo	0.0%	0
Not sure	80.0%	8
Other (please specify)		4
answered question		**10**
skipped question		**69**

Q9. Does your agency/company have operators that can operate compactors outfitted with intelligent compaction technology? [Select One]

Answer Options	**Response Percent**	**Response Count**
Yes	4.2%	1
No	54.2%	13
Not Sure	41.7%	10
answered question		**24**
skipped question		**55**

Q10. What effect does use of intelligent compaction have on the overall cost of compaction jobs? Consider total job costs including quality control/assurance savings and costs. [Select one]

Answer Options	**Response Percent**	**Response Count**
An increase in cost	0.0%	0
About the same cost	0.0%	0
A decrease in cost	16.0%	4
Not sure	56.0%	14
Not applicable	28.0%	7
answered question		**25**
skipped question		**54**

Q11. Which materials/layers have reliable intelligent compaction values? [Select all that apply]

Answer Options	Response Percent	Response Count
Not applicable	8.3%	2
Granular subgrade	29.2%	7
Non-granular subgrade	20.8%	5
Subbase/base layers	37.5%	9
Pavement layers	41.7%	10
Not sure	45.8%	11
Intelligent compaction values are not reliable	0.0%	0
Other (please specify)		1
answered question		**24**
skipped question		**55**

Q12. Which in-situ test values have the best correlation with intelligent compaction measurement values? [Select all that apply]

Answer Options	Response Percent	Response Count
Not Applicable	11.5%	3
Nuclear Gauge, Non-nuclear gauge/Electronic Density Gauge	23.1%	6
Dynamic cone penetrometer data	3.8%	1
Falling weight deflectometer data	11.5%	3
Lightweight deflectometer data	11.5%	3
California bearing ratio	0.0%	0
Dry unit weight	3.8%	1
Moisture content	7.7%	2
Core density (for pavements)	19.2%	5
Not sure	42.3%	11
Other (please specify)		0
answered question		**26**
skipped question		**53**

Q13. Would your agency/company be more likely to use intelligent compaction technology if allowed in a DOT/governmental quality control/assurance specification? [Select all that apply]

Answer Options	Response Percent	Response Count
Yes, because:	37.8%	28
No, because	0.0%	0
Other	17.6%	13
Not Sure	44.6%	33
answered question		**74**
skipped question		**5**

Q14. Do you have any concerns with intelligent compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
Cost	33.3%	24
Reliability of data	26.4%	19
Reliability and durability of technology	19.4%	14
Not a specified quality control/assurance method	22.2%	16
Lack of operator ability and/or time and cost to train operators	22.2%	16
Unfamiliar with technology	20.8%	15
There are no concerns	19.4%	14
Other (please specify)		9
answered question		**72**
skipped question		**7**

Q15. If you would like to learn more about intelligent compaction, which method of delivery of information do you prefer? [Select all that apply]

Answer Options	Response Percent	Response Count
Workshop	32.4%	24
Field demonstration	58.1%	43
Newsletter	5.4%	4
Website	25.7%	19
Emails	18.9%	14
Web-based seminars (webinar)	18.9%	14
Other (please specify)		2
answered question		**74**
skipped question		**5**

Q16. Do you think that intelligent compaction should be adopted in Wyoming? [Select one]

Answer Options	Response Percent	Response Count
Yes	72.4%	55
No	0.0%	0
Not sure	27.6%	21
Other (please specify)		4
answered question		**76**
skipped question		**3**

Q17. What additional information would help facilitate implementation of intelligent compaction in Wyoming? [Select all that apply]

Answer Options	**Response Percent**	**Response Count**
Field demonstration	78.9%	56
Additional workshops	26.8%	19
Learning about other states' experience	52.1%	37
Learning about costs	52.1%	37
Other (please specify)		9
answered question		**71**
skipped question		**8**

Q18. Are you aware of any upcoming construction projects that would be suitable for an intelligent compaction demonstration project? [Select one and comment if applicable]

Answer Options	**Response Percent**	**Response Count**
Yes	48.6%	35
No	51.4%	37
answered question		**72**
skipped question		**7**

Q19. Was the training provided at this workshop beneficial in understanding intelligent compaction? [Select one and comment if applicable]

Answer Options	**Response Percent**	**Response Count**
Yes	100.0%	79
No	0.0%	0
answered question		**79**
skipped question		**0**

Q20. Would you like to receive a summary of the results from this survey? [Select one]

Answer Options	**Response Percent**	**Response Count**
Yes	26.0%	19
No	74.0%	54
answered question		**73**
skipped question		**6**

APPENDIX C. NATIONAL SURVEY RESULTS

A list of the raw data from the survey responses are listed in the table below. The question number is indicated by "Q#." Requests for a complete set of data may be sent to the authors or the Department of Civil and Architectural Engineering at the University of Wyoming. Note that response counts include responses included in comments from respondents selecting "Other."

Q1. What is your contact info (contact name, agency name, address, email, phone number)?

Answer Options	Response Percent	Response Count
Name	100.0%	32
Title	100.0%	32
Agency	100.0%	32
Address	96.9%	31
Email	100.0%	32
Phone	96.9%	31
answered question		**32**
skipped question		**0**

Q2. What is your primary source of information for learning about intelligent compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
FHWA representatives or publications	90.3%	28
Academic journals	19.4%	6
Professional society newsletters	3.2%	1
Contractors	19.4%	6
Internet research	35.5%	11
None of the above	6.5%	2
Other (please specify)		11
answered question		**31**
skipped question		**1**

Q3. Which aspects of intelligent compaction is your agency familiar with? [Select all that apply]

Answer Options	Response Percent	Response Count
Operation of intelligent compaction rollers	76.7%	23
Technology used during intelligent compaction	90.0%	27
Cost and benefits	50.0%	15
Quality Control and Assurance Standards	56.7%	17
None of the above	6.7%	2
Other (please specify)		5
answered question		**30**
skipped question		**2**

Q4. Does your agency have any concerns with the use of intelligent compaction for soil or pavement materials? [Select all that apply]

Answer Options	Response Percent	Response Count
There are no concerns	10.3%	3
Cost	31.0%	9
Reliability of data	34.5%	10
Ability to have it approved as a quality assurance technique by policymakers	41.4%	12
Less strict than current quality assurance methods	17.2%	5
Lack of staff knowledge to confirm data	41.4%	12
Unfamiliar with technology	20.7%	6
Other (please specify)		11
answered question		**29**
skipped question		**3**

Q5. What method does your agency require for quality control and quality assurance of roadway compaction of subgrade, subbase, and base layers? [Select all that apply]

Answer Options	Response Percent	Response Count
Nuclear Gauge	96.9%	31
Non-nuclear Gauge / Electric Density Gauge	9.4%	3
LWD (Light weight deflectometer)	3.1%	1
DCP (Dynamic cone penetrometer)	6.3%	2
CBR (California bearing ratio)	6.3%	2
Proctor tests	59.4%	19
Sand Cone test	18.8%	6
Intelligent Compaction	9.4%	3
Other (please specify)		8
answered question		**32**
skipped question		**0**

Q6. What method does your agency require for quality control and quality assurance of roadway compaction of pavement materials? [Select all that apply]

Answer Options	Response Percent	Response Count
Nuclear Gauge	75.0%	24
Non-Nuclear Gauge / Electric Density Gauge	28.1%	9
Core Sampling	81.3%	26
Intelligent Compaction	6.3%	2
Other (please specify)		2
answered question		**32**
skipped question		**0**

Q7. Has your agency conducted an intelligent compaction demonstration project? [Select one]

Answer Options	**Response Percent**	**Response Count**
Yes, multiple demonstrations	34.4%	11
Yes, one demonstration	37.5%	12
No, but we are scheduled to perform a demonstration	15.6%	5
No	9.4%	3
Not Sure	3.1%	1
answered question		**32**
skipped question		**0**

Q8. If your agency has published a report(s) of the demonstration projects, please write in the report titles, and, if applicable, attach a web link.

Answer Options	**Response Count**
	12
answered question	**12**
skipped question	**20**

Q9. Has your agency ever drafted quality control or quality assurance standards for intelligent compaction? [Select one]

Answer Options	**Response Percent**	**Response Count**
Yes, quality assurance standards for intelligent compaction have been adopted	14.3%	3
Yes, draft standards have been completed and are awaiting adoption	19.0%	4
Yes, we are in the process of drafting standards	23.8%	5
No, but we plan on drafting standards	4.8%	1
No, and we do not plan on drafting standards at the current time	38.1%	8
Other (please specify)		11
answered question		**21**
skipped question		**11**

Q10. If your agency has or is drafting quality control or quality assurance standards for intelligent compaction, what quality control or quality assurance methods does you agency utilize for intelligent compaction? [Select all that apply]

Answer Options	Response Percent	Response Count
Number of passes with intelligent compaction roller	41.2%	7
Testing weak soil / pavement areas indicated by intelligent compaction roller	41.2%	7
Percent difference of compaction values from intelligent compaction roller within a given area / uniformity testing	11.8%	2
Correlation of in-situ testing with intelligent compaction values	58.8%	10
Not sure	17.6%	3
Other (please specify)	29.4%	5

Q11. If your agency has or is drafting quality assurance standards for intelligent compaction, does your agency allow for automatic feedback to adjust compaction parameters during compaction? [Select one]

Answer Options	Response Percent	Response Count
Yes, but it is not required	11.8%	2
Yes, and it is required	17.6%	3
No	35.3%	6
Not Sure	35.3%	6

Q12. If your agency has or is drafting quality control or quality assurance standards for intelligent compaction, does you agency require operating parameters for measurement passes? [Select one]

Answer Options	Response Percent	Response Count
Yes, measurement passes should be conducted at constant drum amplitude and frequency	14.3%	3
Yes, measurement passes are determined on a project-by-project basis	14.3%	3
No, but the contractor is required to report the operating parameters for the measurement pass	19.0%	4
No, the contractor determines the parameters and does not have to report the operating parameters	9.5%	2
Not Sure	23.8%	5

Q13. If your agency uses correlations, which in-situ test values are required to be correlated to intelligent compaction values? [Select all that apply]

Answer Options	Response Count
Nuclear Gauge	10
Non-nuclear Gauge / Electric Density Gauge	1
Dynamic cone penetrometer data	3
Falling weight deflectometer data	2
Lightweight deflectometer data	2
California bearing ratio	0
Dry unit weight	3
Moisture content	4
Core density (for pavements)	5
Not applicable	7
Not Sure	1
Other (please specify)	4

Q14. If your agency uses correlations, what types of correlation values (e.g. coefficient of determination / R2) has your agency encountered and with each type of in-situ test? [Select one]

Answer Options	Response Percent	Response Count
Not sure	65.0%	13
Not applicable	35.0%	7
Other (please specify)		3
answered question		**20**
skipped question		**12**

Q15. What changes in bid costs or in-house costs does your agency incur with compaction services utilizing intelligent compaction? [Select one]

Answer Options	Response Percent	Response Count
An increase in cost	31.3%	10
About the same cost	0.0%	0
A decrease in cost	0.0%	0
Not sure	34.4%	11
Not applicable	34.4%	11
answered question		**32**
skipped question		**0**

Q16. Does your agency collect any data about the long-term benefits and costs of intelligent compaction? [Select all that apply]

Answer Options	**Response Percent**	**Response Count**
Yes, we have information specific to past projects that we have performed	7.1%	2
Yes, we have compiled information from other agencies	3.6%	1
No, but we plan on conducting a long-term assessment of the benefits and costs of intelligent compaction	17.9%	5
No, and we are awaiting benefit-cost information from independent agencies	14.3%	4
No, and we have no plans to collect benefit-cost information	7.1%	2
Not sure	21.4%	6
Not applicable	32.1%	9
Other (please specify)		7
answered question		**28**
skipped question		**4**

Q17. If your agency collects long-term benefit and cost information about intelligent compaction, what outcome has your agency encountered with projects using intelligent compaction compared to conventional compaction methods? [Select all that apply]

Answer Options	**Response Percent**	**Response Count**
Higher benefits than costs	7.1%	2
Higher costs than benefits	0.0%	0
No Change	0.0%	0
Not sure	28.6%	8
Not applicable	64.3%	18
Other (please specify)		1
answered question		**28**
skipped question		**4**

Q18. Would you like to receive a summary of the results from this survey? [Select one]

Answer Options	**Response Percent**	**Response Count**
Yes	90.6%	29
No	9.4%	3
answered question		**32**
skipped question		**0**