# Developing Guidelines for Assessing the Effectiveness of Intelligent Compaction Technology

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**16. Abstract**

Many factors affect pavement compaction quality, which can vary. Such variability may result in an additional number of passes required, extended working hours, higher energy consumption, and negative environmental impacts. The use of Intelligent Compaction (IC) technology during construction can improve the quality and longevity of pavement structures while reducing risk for contractors and project owners alike. This study develops guidelines for the implementation of IC in the compaction of pavement layers as well as performing a preliminary life-cycle cost analysis (LCCA) of IC technology compared to the conventional compaction approach. The environmental impacts of the improved construction process were quantified based on limited data available from the case studies. The LCCA performed in this study consisted of different scenarios in which the number of operating hours was evaluated to estimate the cost efficiency of the intelligent compaction technique during construction. The analyses showed a reduction in energy consumption and the production of greenhouse gas (GHG) emissions with the use of intelligent compaction. The LCCA showed that the use of IC technology may reduce the construction and maintenance costs in addition to enhancing the quality control and quality assurance (QC/QA) process. However, a more comprehensive analysis is required to fully quantify the benefits and establish more accurate performance indicators. A draft version of the preliminary guidelines for implementation of IC technology and long-term monitoring of the performance of pavement layers compacted thereby is also included in this report.

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# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# Executive Summary

The performance of transportation infrastructure foundations and pavement structures is dependent on the compaction quality and uniformity during the construction process. The current state of practice for compaction quality control of pavement layers is to estimate in-situ density on randomly selected spots across the construction area. However, the inherent material variability and other sources of uncertainties during the production and construction phases introduce spatial variability that cannot be captured with random spot testing. A more comprehensive test method that can cover the entire compacted area is necessary to ensure the uniformity and durability of the compacted pavement layer. With the recent advancements of construction techniques such as Intelligent Compaction (IC), a comprehensive data set describing the construction process can be collected. IC systems usually include a vibration sensor (accelerometer) mounted inside the roller drum, a Global Positioning System (GPS) receiver mounted on the roller cabin, and a data acquisition system attached to a display that presents real-time construction data to the operator. IC systems provide a comprehensive set of information during and after the construction process that could be used to improve and enhance construction uniformity and quality.

One of the main objectives of this study was to provide the means to ensure that the foundation layers of transportation infrastructure are properly constructed and rehabilitated using IC, which can extend the life and enhance the resilience of the infrastructure. The outcomes of this research can help to improve current practices in the construction of infrastructure foundation layers using an intelligent construction technique that optimizes performance and ensures uniformity and quality.

This report summarizes the authors' efforts toward developing guidelines for the use of intelligent compaction in the construction quality management process pertaining to pavement layers. The report includes the following chapters.

Chapter I introduces Intelligent Compaction technology, describes its basic concepts, and discusses how it can improve compaction quality and uniformity.

Chapters II and III summarize background information related to IC implementation and the state of practice in the application of IC to the construction of pavement layers.

Chapter IV includes the details of field data collection during the construction of pavement layers in the case study.

Chapter V summarizes the process of conducting a cost-benefit analysis based on the limited data available from the field evaluations and a case study.

Chapter VI includes basic information about the life-cycle cost analysis (LCCA) for the implementation of IC.

Chapter VII focuses on a case study that was performed as a part of this project to apply the methods and processes developed here.

Chapter VIII summarizes the preliminary version of the authors' draft guidelines for the implementation and long-term monitoring of pavement sections compacted with IC rollers and compares the IC sections with those constructed with conventional compaction methods.

Chapter IX summarizes the conclusions and outcomes of this project.

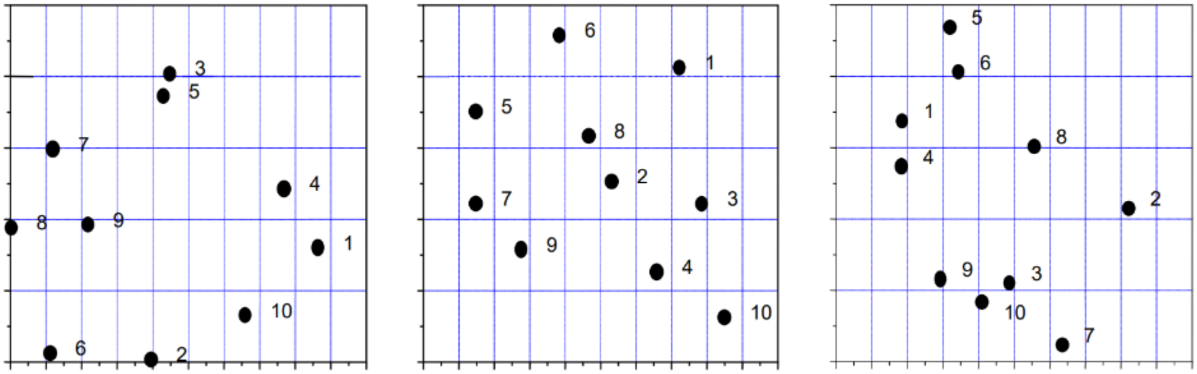
# I. Introduction

Improving construction quality and extending the life of transportation infrastructures and the state highway network in California is one of the major goals of Senate Bill 1 (SB1) and the funding it allocates. According to Caltrans, 17,000 miles of pavement will be repaired or replaced by 2027 through SB1 funds. California's state-maintained transportation infrastructure will receive half of the revenue, which is about $26 billion. About $1.5 billion will be spent on road replacements and repairs.

The performance of transportation infrastructure foundations and pavement structures depends, among other things, on the compaction quality and uniformity during the construction process. Compactions of earthwork and pavement layers are evaluated based on the in-situ dry density of the compacted layer (in comparison to the laboratory values) using a nuclear gauge. Even though the density criterion has been the main method of evaluating the compaction quality in the field, there is not a direct correlation between the density and stiffness of the compacted layer (Nazarian et al. 2015; Schwartz et al. 2017; Mazari et al. 2017, and Fathi et al. 2019). Moreover, the Mechanistic-Empirical Pavement Design Guide (MEPDG), also known as AASHTOW or PaveME, considers stiffness and modulus as the main criteria for the design of subgrade and unbound granular layers. There is a missing link between a density-based field compaction quality control and a modulus-based design approach. Moving toward a modulus-based field quality control and quality acceptance (QC/QA) process, even though it seems straightforward, will be associated with some difficulties at the agency level between contractors and owners (Nazarian et al. 2020).

The current state of practice for compaction quality control of pavement layers uses a density gauge to perform in-situ density tests on randomly selected locations across the construction area. Figure 1 shows a sample of suggested random test locations per California Test 231 (Caltrans 2013). Even though the random selection process reduces the chance of a defective compaction process, most areas across the construction section will not be tested. The under-compacted areas will eventually affect the performance of the top pavement layers under traffic loads and will cause localized deterioration problems. A uniform compaction quality control process that covers 100 percent of the compacted area (Figure 2) can ensure the uniformity of compaction and extend the service life of the pavement structure. The intelligent compaction (IC) technology can facilitate this process. It collects a comprehensive set of data, including vibration frequency and amplitude as well as number of passes and roller speed, during the compaction process that covers the entire construction section. The vibration sensor on the IC roller captures the vibration response of the compacted layer that can be translated to stiffness, which is a better indication of the compaction quality. The under-compacted areas are then identified on the color-coded maps by the IC system, which can be mounted on any regular vibratory roller compactor. Those less stiff locations can be selected by the quality engineer for additional in-situ spot tests (Fathi et al. 2018). A uniformly compacted layer can be ensured with the use of IC technology. Moreover, the application of IC during the compaction process optimizes compaction energy consumption by avoiding over-compaction (Saravanan et al. 2018). Once the required in-situ stiffness is achieved, the operator can optimize the rolling pattern and avoid any unnecessary operations. The real-time IC maps also prevent the team from overlooking missing spots that could not be identified by traditional compaction processes (Fathi et al. 2020 and Mazari et al. 2017).

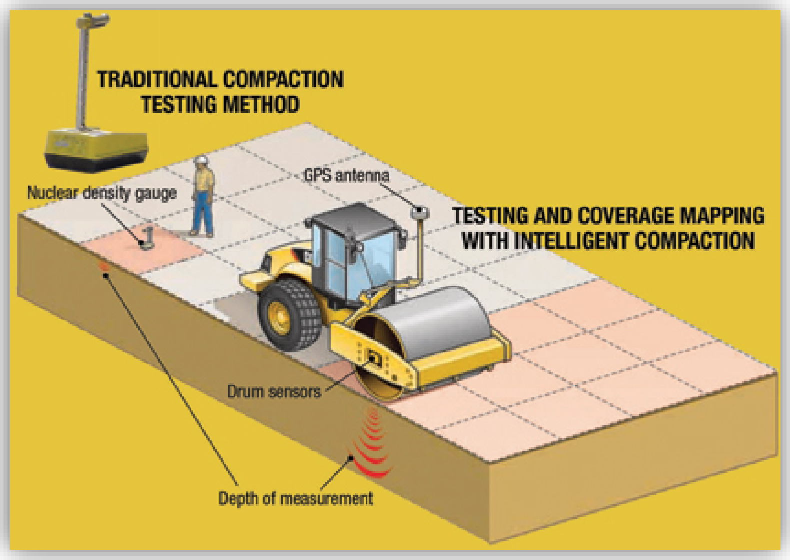
Figure 1. Current State of Practice for Random Selection of In-Situ Compaction Quality Control Spots



*Source*: California Test 231, Caltrans 201

The creation and improvement of the IC approach along with its applications, advantages, and limitations has been the focus of many studies during the past two decades. Anderegg and Kaufmann (2004) reviewed the compaction feedback control technology and the nonlinearity of the compaction process. Xu et al. (2012 and 2013) synthesized the Intelligent Compaction measurement values (ICMVs) along with a summary of field correlation studies between the ICMVs and different in-situ spot tests. White et al. (2008) characterized the ICMVs for different Intelligent Compaction (IC) systems for the compaction quality management of unbound materials. Mooney et al. (2010) performed a comprehensive review of IC technologies; they discussed the state of the current IC equipment along with the fundamentals of roller measurement values that were developed and used by different IC equipment vendors. Even though many studies have been performed to evaluate the use of IC in construction quality management of pavement layers (Nazarian et al. 2015, Mazari et al. 2016, Lemus et al. 2018, Fathi et al. 2019, and Tirado et al. 2019), the fundamental differences between the reported measurement values by different IC systems have been the source of uncertainty during the quality management processes.

Figure 2. Example of Complete IC Coverage versus Randomly Selected Quality Control Spots



*Source*: HAMM 2010

In 2014, Caltrans developed two non-standard specifications for the use of IC in the construction of Hot Mix Asphalt (HMA) and Cold In-Place Recycling (CIR) along with design guidance to assist Caltrans designers in adapting IC specifications according to project specifics. Since 2014, Caltrans has awarded over $10.5 million of IC contracts in over 35 pilot projects. It is anticipated that IC can be fully integrated in the construction of roadways.

One of the main objectives of this study was to provide the means to ensure that the pavement layers are properly constructed and rehabilitated such that IC can ensure the uniformity, extended life, and resilience of the infrastructure. Other project objectives include:

- Review the current IC technologies to evaluate their benefits, limitations, and challenges.
- Perform a life-cycle cost analysis (LCCA) for intelligent compaction processes and compare with traditional compaction for earthwork and base layers.
- Preliminary evaluation and implementation of the developed methods during limited filed case studies.

After consultation with Caltrans' Division of Construction regarding the applicability of this research study, the authors have adjusted and modified the research strategy and methodology to address the current challenges regarding the application and implementation of IC technology in construction of pavement layers. The following chapters consist of the details of project tasks in terms of reviewing the state of practice in using IC technology for quality management of pavement layers and summary of field evaluations. They also include the findings as well as the draft version of guidelines for implementation of IC and long-term monitoring of the performance of pavement layers constructed with the use of IC technology.

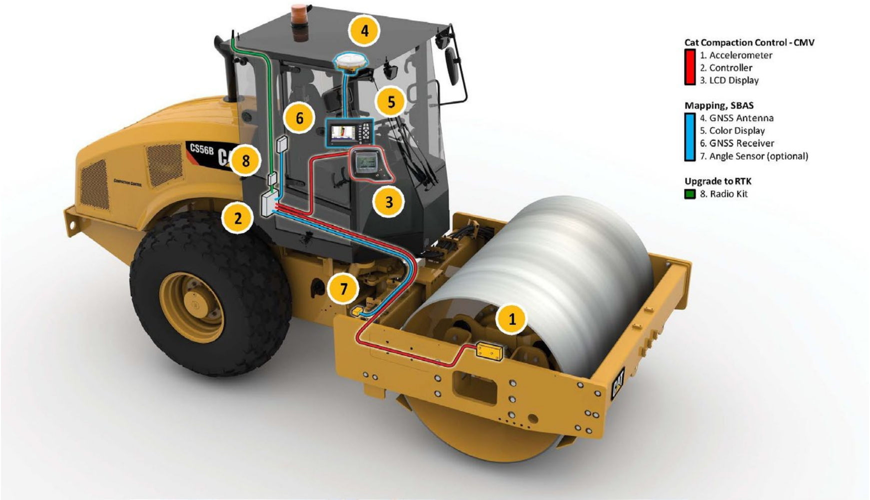
# II. Technical Background

The conventional quality management approach includes spot testing methods that are used to evaluate the quality of the compacted layer. The typical spot tests are nuclear density gauge (NDG), falling weight deflectometer (FWD), sand cone test, pavement quality indicator (PQI), and laboratory evaluation of drilled cores. Conducting spot tests is a time-consuming process, and in some cases (such as coring), test results may delay the quality control and assurance process. Moreover, performing spot tests may cause delays in the construction process. To overcome these challenges, the early stages of intelligent compaction systems were developed as Continuous Compaction Control (CCC) where the vibration parameters of the roller were correlated with the stiffness of the compacted pavement layer. IC systems have been evolving during the past two decades and have been successfully implemented in many construction projects.

## 2.1 Intelligent Compaction (IC) Systems

Intelligent compaction systems can be deployed in two forms: (i) original equipment manufacturer (OEM) IC rollers, which are instrumented with all the necessary IC-related equipment, and (ii) the IC retrofit kits that can be installed on most of the current vibratory roller compactors, turning the compactor into an IC system. In each case, the IC technology consists of an accelerometer (vibration sensor), data acquisition and processing system, temperature sensor (for asphalt compaction), Global Positioning System (GPS) with real-time kinematic (RTK) accuracy, and a data display screen. Figure 3 shows a typical IC roller and its components.

Figure 3. Components of an IC Roller



*Source*: Courtesy of CAT

***Global Positioning System (GPS)***. Collecting geospatial data is the most important component of the IC technology. As shown in Figure 4, the GPS antenna and receiver are mounted on the roller cabin. The GPS system records the precise location of the roller, which helps to produce the color-coded IC maps. These maps represent various information, such as layer stiffness, number of passes, vibration frequency and amplitude, and roller speed, which are collected during the IC implementation process. GPS calibration needs to be performed at the beginning of the compaction process to ensure the accurate location of collected data with respect to a local or virtual base station. A test strip is usually required to analyze the rolling patterns and calibrate the positioning of the roller (Nazarian et al. 2015, Kumar et al. 2016, Mazari et al. 2016, Lemus et al. 2017).

Figure 4. Global Positioning System Antenna

*Source*: Courtesy of HAMM

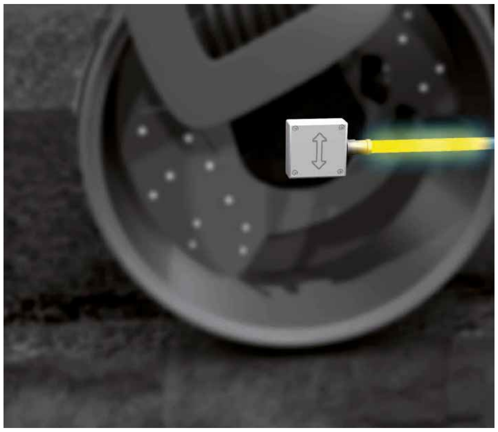
***Temperature Sensor***. This infrared sensor scans the pavement surface and records the real-time temperature of the compacted asphalt layer. Temperature data from the sensor can be automatically transferred to the IC system, which helps to generate the temperature map of the compacted area. Figure 5 shows an example of a temperature sensor mounted on the IC roller.

Figure 5. Infrared Sensor

*Source*: Courtesy of HAMM

***Accelerometer***. The vibration sensor estimates the vibration response of the compacted layer in terms of amplitude and frequency of the vibration imparted by the roller drum to the pavement surface. The vibration data are continuously transferred to the IC system to estimate the compaction meter value (CMV), which is a unitless estimation of the stiffness. Figure 6 shows an example of the vibration sensor mounted inside the roller drum.

Figure 6. Accelerometer Mounted on Roller Drum



*Source*: Courtesy of HAMM

***Onboard Display***. A portable high-resolution display is mounted onboard to keep track of compaction data (Figure 7). The display shows the color-coded map of roller passes, surface temperature, and current roller speed as well as other compaction parameters such as vibration frequency and amplitude, stiffness, and design alignment. Typically, the system is equipped with a USB port to transfer the IC data to other devices for further analyses.

Figure 7. Onboard Display

*Source*: Courtesy of HAMM

The IC rollers use vibration data, and in some cases machine operation parameters, to represent the layer stiffness as a measure of compaction quality (Figure 8). Intelligent compaction measurement value (ICMV) is a generic term used to describe a measure of the stiffness of the compacted layer. Since each roller manufacturer uses a unique stiffness measurement unit, the ICMV can be used as a general term to refer to the measured stiffness in the IC process. Some ICMVs, such as compaction meter value (CMV) and compaction control value (CCV), are calculated based on the vibration response of the compacted layer in terms of the amplitude of the forcing frequency and the harmonics. Figure 8 illustrates the vibration impulse from the drum and the response from the compacted pavement layer captured by the IC vibration sensor. Once the IC data collection process is complete, the generated georeferenced data can be downloaded from the onboard IC display or from the vendor's cloud storage. The process of reducing IC data, after the completion of compaction process, needs to be performed with geospatial analysis techniques to produce the additional color-coded maps for post construction analysis purposes. Figure 9 shows an example of IC data flow.

A review of the state of practice with a focus on the implementation of existing IC guidelines is provided in Chapter III.

Figure 8. Vibration Response from Soil Layers

*Source*: Courtesy of HAMM

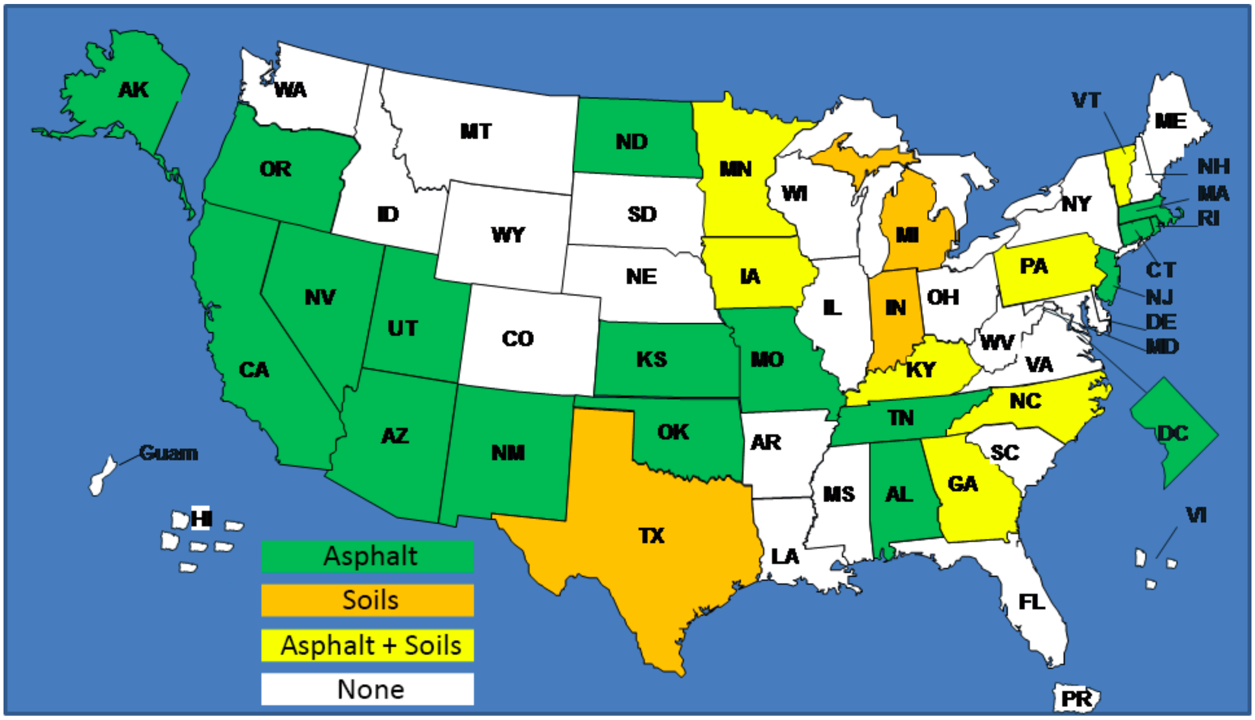
Figure 9. Process of Collecting IC Data and Generating the Compaction Quality Map

*Source*: Nazarian et al. 2020

# III. State of Practice: Implementation of Intelligent Compaction Technology

Several state Departments of Transportation (DOTs) have already adopted specifications and guidelines for the use of intelligent compaction in quality control and quality assurance for earthwork, unbound materials, and asphalt layers. Figure 10 shows the state DOTs with their respective IC specifications (FHWA 2017). Although many highway agencies have already moved to implement IC in their quality management processes, there are still challenges associated with the use of IC in terms of technological complexities, variability of measurement systems and units, implementation of quality assurance with IC, and the limited information regarding the long-term benefits of implementing IC in the construction process.

Figure 10. State DOTs with IC Specifications for Soils and Asphalt



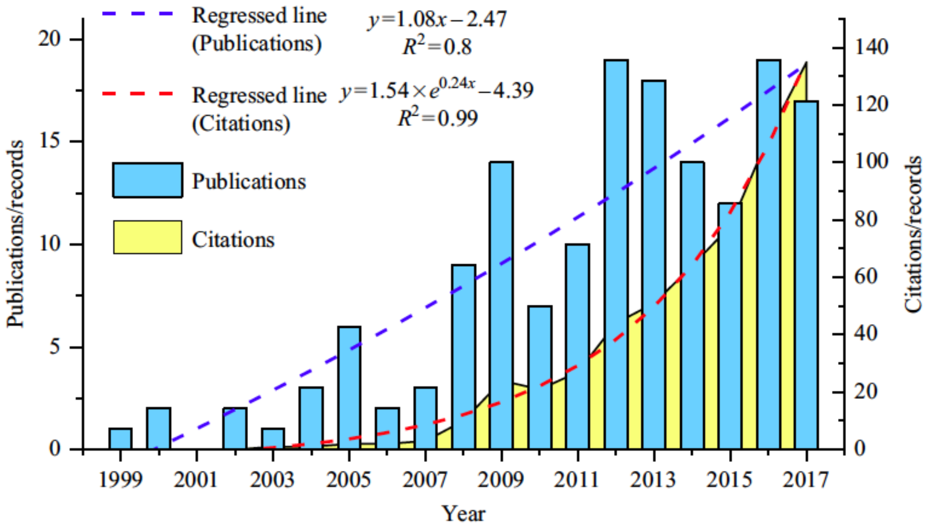
*Source*: FHWA 2017

The adoption and implementation of IC in pavement construction processes and state DOT specifications has evolved over the past several years. With the advancements in the IC components as well as the knowledge to understand the IC operations, the gradual advancement of IC applications has always been one the main implications of using IC in the construction of pavement layers. The International Society for Intelligent Construction (IS-IC) compiled a list of developmental stages for the use of Intelligent Compaction Measurement Value (ICMV) as a generic unit for measuring the response of compacted pavement layers among various IC-equipped roller compactors (Chang and Nazarian 2020). They have envisioned five levels of ICMV development as the following:

- Level I: Vibration frequency-based measurement based on empirical solutions
- Level II: Solutions based on machine drive power and rolling resistance
- Level III: Mechanistic solutions based on simplified static response
- Level IV: Hybrid approach with integrations of dynamic models
- Level V: Predictive models based on dynamic solutions combined with artificial intelligence techniques.

These developmental levels can help state DOTs to plan for implementation of IC in their construction specifications for both asphalt and soil pavement layers. Such advancements require extensive research and development both for developing new technologies and implementing the research findings. The number of studies focusing on investigating and implementing the IC technology has increased constantly over the past two decades. Liu et al. (2019) complied a bibliographical study of a list of publications relevant to IC technology beginning from 1999. They presented a temporal distribution of IC publications as shown in Figure 12. Their findings show that there is a globally consistent increase in the number of studies focusing on the applications and implementation of IC technology.

Figure 11. Advancement of IC-Related Studies from 1999 to 2018



*Source*: Liu et al. 2019

Based on the state of practice in implementing IC, the FHWA (2017) has recommended the following strategies for facilitating future IC applications.

- Development of national guidelines and a certificate program for personnel training
- Harmonization of IC specifications among state DOTs and highway agencies
- Standardizing the GPS calibration process to ensure consistent IC data collection
- Using a systematic approach to download the IC data from different vendor software platforms
- Incorporating the mechanistic approach for interpretation of IC data.

The following chapters of this report describe the process of field data collection as well as conducting a parallel assessment of IC and conventional compaction processes. A life-cycle cost analysis is also performed to partially evaluate the benefits of using an IC system. Finally, the last chapter provides the guidelines for implementation of intelligent compaction and long-term monitoring of the pavement section compacted with IC technology. The proposed guidelines in this study provides additional information to the existing state of practice with regards to the implementation of IC for compaction of pavement layers.

# IV. Field Data Collection

## 4.1 Project Details

The field data were collected as a part of the construction of a Rubberized Hot Mix Asphalt (RHMA) overlay in California. The thickness of the RHMA overlay was 0.2 in. and the width of the paved section was 12 ft. A double-drum vibratory roller was utilized to collect the IC data during the compaction process.

## 4.2 Data Collection

Three rollers were used to compact the pavement layer following the placement of materials by the paver machine. Two rollers were responsible for the breakdown and intermediate compaction, with no pause between the operations. Thereafter, the finisher roller was used to ensure a smooth surface.

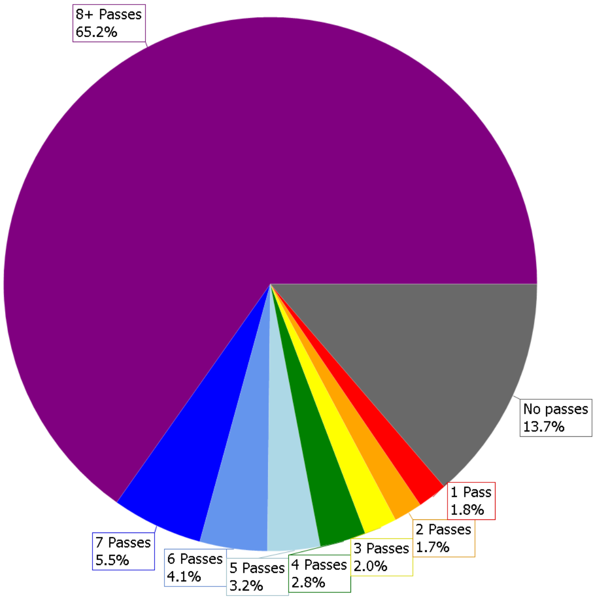
The goal of this field data collection was to record the operating time, the number of passes, average speed, frequency, vibration status, GPS locations, and nuclear gauge density data to compare the performance of IC with the conventional compaction process. However, the field measurements encountered some challenges. As an example, although the first two rollers were meant to work as a twin, their performance was not identical in practice. At some segments, the machines were operating behind each other, which indicates two passes, and then they switched to parallel performance, which would be counted as one pass. Due to the lack of a consistent compaction pattern, it was difficult to record the machine path. Another challenge arose because segments were not pre-identified, and there were several overlapping segments in both longitudinal and transverse directions. One reason for such variability could be the variable speed of the paver machine ahead of the rollers. To meet the DOT specification requirements for the limited temperature range of the compacted asphalt layer, the overlapping was inevitable in some areas, which contributes to the change in number of passes in some sections. Regarding all these challenges, the research team managed to record the data for 13 segments of the conventional compaction (CC) process. Table 1 summarizes the recorded field data.

The IC data collection was performed during three night paving shifts. The construction lengths for these three shifts were 0.54, 1.77, and 0.34 miles, respectively. The second night paving shift was selected for comparison with the conventional compaction data in this study due to the matching length and consistency of the collected data. Using the VETA® software, which is the common tool used to reduce IC data, the number of passes and the coverage percentage for each pass were determined (Figure 12). The total area of the section constructed during this shift was calculated as 131,104 $ft^2$. Multiplying the number of passes by the corresponding area and dividing by the width of the roller, the total traveled length can be estimated.

Table 1. Summary of Recorded Data for Conventional Compaction (Northbound)

| Section | Length (miles) | No. of Passes | Total Time (minutes) | Calculated Avg. Speed (mph) |
|---|---|---|---|---|
| 1 | 0.03 | 17 | 13 | 2.39 |
| 2 | 0.05 | 12 | 13 | 2.62 |
| 3 | 0.03 | 6 | 17 | 0.61 |
| 4 | 0.19 | - | 33 | - |
| 5 | 0.12 | 6 | 34 | 1.26 |
| 6 | 0.14 | 12 | 41 | 2.51 |
| 7 | 0.02 | 21 | 7 | 3.37 |
| 8 | 0.06 | 15 | 13 | 4.01 |
| 9 | 0.10 | 14 | 20 | 4.18 |
| 10 | 0.12 | 22 | 22 | 7.00 |
| 11 | 0.14 | 29 | 30 | 7.88 |
| 12 | 0.13 | 27 | 42 | 5.08 |
| 13 | 0.11 | 21 | 18 | 7.92 |
| **Total** | **1.22** | **202** | **302** | |

Figure 12. Number of Passes and Coverage Percentage for the IC Operation



According to the analysis results, the average speed of the roller is 4.7 mph. Table 2 shows a summary of results from IC data calculations.

Table 2. Summary of the Results from IC Data Calculations

| Segment Length | Traveled Length (miles) | Speed (mph) | Total Time (hr) | Time per Mile Completed (hr) |
|---|---|---|---|---|
| 1.8 | 32.1 | 4.7 | 6.77 | 3.83 |

## 4.3 Data Analysis

During the conventional compaction, a 1.22-mile stretch of the paved section was surveyed, and the corresponding time was estimated to be 5.0 hours. In other words, it takes up to 4.1 hours to compact one mile of asphalt overlay with the conventional compaction approach. Table 3 shows a summary of the performance of both construction techniques.

Table 3. Summary of Construction Performance

| Technique | Miles | Hours | % Difference |
|---|---|---|---|
| Intelligent compaction | 1 | 3.83 | 7 |
| Conventional compaction | 1 | 4.11 | - |

Table 4 shows a summary of laboratory density test results for the cores extracted from the compacted section. A single factor Analysis of Variance (ANOVA) was performed for the results and summarized in Table 5. It shows that at 0.05 significance level, there is a significant difference between the mean value of the core densities at different construction segments. It should be noted that the limited number of field density data from the extracted cores were not enough to make meaningful understanding of the impact of IC compaction process on the uniformity of the compacted layers. The other possible sources of variations was that the variability of pavement materials among the sections compacted with IC and CC were relatively high; the roller operator relied on his experience more than the IC feedback during the compaction process; and the roller operator performed very well during the CC construction period.

Table 4. Density Results from the Cores

| Construction Shift | 1 | 2 | 3 | 4 | 5 | **6** |
|---|---|---|---|---|---|---|
| Compaction Method | CC Density (pcf) | CC Density (pcf) | CC Density (pcf) | CC Density (pcf) | CC Density (pcf) | **IC Density (pcf)** |
| Core sample 1 | 136.4 | 135.7 | 137.5 | 139.1 | 137.7 | **136.4** |
| Core sample 2 | 135.8 | 135 | 135.7 | 139.3 | 138.1 | **136.8** |
| Core sample 3 | - | 134.2 | 134.9 | 138.8 | 138.3 | **136.5** |
| Core sample 4 | - | - | 136.6 | 138.7 | 138.0 | **136.6** |
| Average density | 136.1 | 135.0 | 136.2 | 139.0 | 138.0 | **136.6** |
| Standard deviation | 0.4243 | 0.7506 | 1.1236 | 0.2754 | 0.2500 | **0.1708** |
| Coefficient of Variation | 0.0031 | 0.0056 | 0.0083 | 0.0020 | 0.0018 | **0.0069** |

Table 5. Single Factor ANOVA for Density Results

SUMMARY

| Groups | Count | Sum | Average | Variance |
|---|---|---|---|---|
| Shift 1 (CC) | 2 | 272.2 | 136.1 | 0.18 |
| Shift 2 (CC) | 3 | 404.9 | 135.0 | 0.56 |
| Shift 3 (CC) | 4 | 544.7 | 136.2 | 1.26 |
| Shift 4 (CC) | 4 | 555.9 | 139.0 | 0.07 |
| Shift 5 (CC) | 4 | 552.1 | 138.0 | 0.06 |
| **Shift 6 (IC)** | **5** | **546.3** | **136.6** | **0.03** |

ANOVA

| Source of Variation | SS | df | MS | F | P-value | F critical |
|---|---|---|---|---|---|---|
| Between groups | 37.23 | 5 | 7.45 | 19.96 | 3.81E-06 | 2.90 |
| Within groups | 5.60 | 15 | 0.37 | | | |
| | | | | | | |
| Total | 42.83 | 20 | | | | |

Further analysis of these results along with side-by-side comparison of the performance of both IC and CC methods, based on the same dataset and an additional case study, is included in the following chapters. A benefit-cost analysis is also performed to quantify the benefits of using IC compared to the conventional approach.

# V. Benefit-Cost Analysis

As the implementation of IC technology is advancing, there is a need to consider the benefits of this technique compared to the conventional compaction process. The long-term benefits of using IC in the construction phase will also need to be monitored to evaluate its impact on the longevity and performance of the compacted layers. Although many studies in the literature have focused on the development and field implementation of IC, there has been very little work studying the benefits of IC and quantifying its long-term impact. In a study performed by Savan et al. (2017), the benefit-cost analysis of the application of IC technology was mainly determined based on two approaches: the construction cost and the roadway life-cycle cost. The construction costs were the initial costs of the project, which included the cost of equipment, operator labor, GPS, and the QC/QA process. These cost items were estimated using the number of operating hours or the equivalent length of the project. For the roadway life-cycle cost, average annual maintenance required for the length of the project during a 10-year design period was considered. The annual maintenance rate was assumed to be lower for the sections compacted by IC due to the potential improvement of compaction quality and optimization of quality control and assurance process based on the IC data. The rest of this chapter includes a preliminary cost-benefit analysis for application of IC compared to the conventional compaction approach based on a series of assumptions for various cost items and long-term maintenance scenarios.

## 5.1 Construction Cost Approach

Savan et al. (2017) showed that IC technology has the short-term advantage of saving about $349 per mile of asphalt pavement construction compared to conventional compaction. Table 6 summarizes the result of those authors' analysis and comparison of the two systems. The sources of the relevant cost items are listed in Table 7.

Table 6. Cost Breakdown of Conventional Compaction versus IC per One Mile of Asphalt Pavement (after Savan et al. 2016)

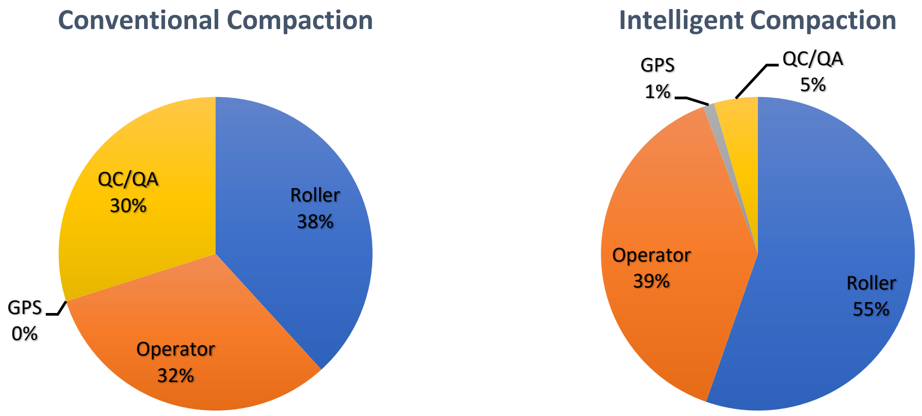
| Item | *Conventional Compaction* | | | | *Intelligent Compaction* | | | |
|---|---|---|---|---|---|---|---|---|
| | Unit Cost ($) | Unit | Number of Units | Total Cost ($) | Unit Cost ($) | Unit | Number of Units | Total Cost ($) |
| Roller | 36 | hour | 10 | 360 | 43 | hour | 7.7 | 328 |
| Operator | 30 | hour | 10 | 300 | 30 | hour | 7.7 | 231 |
| GPS | - | - | - | - | 0.90 | hour | 7.7 | 7 |
| QC/QA | 0.05 | $m^2$ | 5886 | 282 | 0.05 | $m^2$ | 558 | 27 |
| Total | - | - | - | 942 | - | - | | 593 |

Table 7. Cost Items for Benefit-Cost Analysis (after Savan et al. 2017)

| Item | Quantity | Source |
|---|---|---|
| ***Construction Costs*** | | |
| QC/QA per square meter | $0.05 | Simon Contractors, WY (Bastian 2014) |
| IC reduction in compaction cost | 30% | Briaud and Seo (2003) |
| Lane width | 3.7 m | Assumption |
| IC to conventional QC/QA cost | 10% | NCHRP 676 (Mooney et al. 2010) |
| Conventional roller cost per hour | $36 | High Country Construction, WY (Newman2014) |
| 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 per 1.6 lane-km | 10 | High Country Construction, WY (Newman 2014) |
| Compaction cost per square yard | $0.20 | Simon Contractors, WY (Newman 2014) |
| GPS rental per year | $1,800 | Trimble Navigation Limited (2014) |
| Test section length | 152 m | NCHRP 676 (Mooney et al. 2010), DOT IC Specs (The Transtec Group, Inc. 2014) |
| Work hours per week | 40 | Assumption |
| ***Life-Cycle Costs*** | | |
| Increased service life with IC, multiplier | 2.6 | Xu et al. (2012) |
| Average years of asphalt life | 10 | Average overlay service life |
| Cost per 1.6 lane-km | $250,000 | WYDOT (2011), Caltrans (2011), City of Woodland (2007) |

Further analyses showed that for the conventional compaction method, approximately 30% of the costs are associated with the QC/QA process, while those cost items can be reduced to about 5% when using IC technology (Figure 13). The comprehensive data set that is collected by the IC system can be used as the basis for quality management that eliminates the need for a conventional QC/QA process. In such optimization process, only less stiff areas, identified from the IC stiffness maps, may be evaluated using the spot tests for quality management. It was also observed that the higher hourly cost of IC equipment can be compensated for by the reduced QC/QA cost and improvement of compaction speed.

Figure 13. Cost of the Asphalt Pavement Construction using CC versus IC



*Data Source*: Savan et al. 2016

If the compaction factor (30% faster in IC) is ignored, and it is assumed that both conventional compaction and IC operators perform with a similar operating duration (i.e., 10 hours), the results of the cost analysis for this scenario show that IC technology reduces the cost by as much as $180 per mile per day (Table 8).

Table 8. Construction Cost Items with the Assumption that IC has No Improvement on the Compaction Speed

| Item | *Conventional Compaction* | | | | *Intelligent Compaction* | | | |
|---|---|---|---|---|---|---|---|---|
| | Unit Cost ($) | Unit | Number of Units | Total Cost ($) | Unit Cost ($) | Unit | Number of Units | Total Cost ($) |
| Roller | 36 | hour | 10 | 360 | 43 | hour | 10 | 426 |
| Operator | 30 | hour | 10 | 300 | 30 | hour | 10 | 300 |
| GPS | - | - | - | - | 0.90 | hour | 10 | 9 |
| QC/QA | 0.05 | $m^2$ | 5886.3 | 282 | 0.05 | $m^2$ | 558 | 27 |
| Total | - | - | - | 942 | - | - | | 762 |

## 5.2 Roadway Long-Term Cost Approach

Briaud and Seo (2003) found that uniformity of the compacted area provides consistent properties in the material and the performance life of the pavement will be closer to the estimated design value with a lower cost of maintenance. Xu et al. (2011) showed that a heterogeneously compacted pavement layer results in lower rutting and better fatigue performance. Based on that study, a uniform compaction can improve the fatigue life of the asphalt pavement by up to 2.6 times compared to conventional compaction. In other words, if an average life cycle of the pavement is 10 years, having a uniform compaction can extend the service life up to 26 years. However, this is only based on limited laboratory evaluations, and long-term performance monitoring of the compacted pavement layers with different compaction methods is needed to estimate the actual longevity factor.

Per Table 9, the cost of annual maintenance per mile is estimated to be $25,000 (Savan et al. 2016). If the lifetime of the pavement is extended to 26 years, the costs associated with the maintenance are distributed over 26 years by a factor of 1/2.6. Table 9 summarizes the cost reductions after 1, 10, and 26 years.

Table 9. Roadway Life-Cycle Cost per Mile for One Year and Twenty-Six Years (after Savan et al. 2016)

| Compaction Type | Service Life (years) | Life Factor | Cost per Year | Cost Over 10 Years | Cost Over 26 Years |
|---|---|---|---|---|---|
| Conventional | 10 | - | $25,000 | $250,000 | $650,000 |
| Intelligent | 26 | 2.6 | $9,600 | $96,000 | $250,000 |
| Difference | -16 | - | $15,400 | $154,000 | $400,000 |

Since there are other factors (e.g., traffic parameters, environmental factors, and long-term material properties) that influence the long-term performance of the pavement structure. Therefore, for sensitivity analysis in the present study, the 26 years has been adjusted to 15 years to be more realistic in terms of prolonging impact of a uniform compaction approach based on the recommendations by Savan et al. (2016) in their study. In this scenario (Table 10), the life cycle factor has been adjusted to 1.5 to reflect a more reasonable impact. The updated cost savings for this scenario, by using the IC system, are still considerable.

Table 10. Roadway Life-Cycle Cost per Mile for One Year and Fifteen Years (after Savan et al. 2016)

| Compaction Type | Service Life (years) | Life Factor | Cost per Year | Cost Over 10 Years | Cost Over 15 Years |
|---|---|---|---|---|---|
| Conventional | 10 | - | $25,000 | $250,000 | $375,000 |
| Intelligent | 15 | 1.5 | $16,700 | $167,000 | $250,000 |
| Difference | -5 | - | $8,300 | $83,000 | $125,000 |

It should be re-stated that the long-term performance monitoring requires a rigorous testing program for periodical evaluation of the in-service pavement structure. The assumptions made for this preliminary cost-benefit analysis were only based on the limited information from the literature. A comprehensive testing and monitoring program is needed to properly evaluate the long-terms impacts of the improved compaction process by using the IC rollers.

To further study the long-term impacts of using IC in the construction process, the next chapter summarizes the life-cycle cost analysis of a pavement section compacted with IC compared to the conventional method.

# VI. Life-Cycle Cost Analysis (LCCA)

This chapter summarizes the process for evaluating the feasibility of implementing a life cycle cost analysis for the pavement layers compacted with IC technology. The analysis was based on the limited field data collected in this project and additional information retrieved from the studies in the literature. As judged by the title of such analysis, the long-term performance monitoring of the compacted pavement layers are required to successfully perform the cost analysis over the life-cycle of the pavement structure.

Several studies in the literature have focused on the life cycle assessment and cost analysis of pavement structures (Tighe 2001, Ozbay et al. 2004, Huang et al. 2009, Santos et al. 2015, Babashamsi et al. 2016, Harvey et al. 2016, Xu et al. 2019 and Satani et al. 2020). Per the Federal Highway Administration (FHWA), the life-cycle cost analysis (LCCA) is defined as the analysis based on the principles of economics to evaluate the long-term efficiency for alternative investment options. The analysis incorporates initial and discounted future agency, user, and other relevant costs and attempts to identify the best value—the lowest long-term cost that satisfies the performance objective criteria—for the investment (Walls and Smith, 1998).

For roadway agencies, it is challenging to minimize the cost of expenses such as new construction costs, replacement of existing components, vehicle operation costs, work zone and user delay costs, maintenance and rehabilitation costs, and environmental costs. LCCA can keep track of all these activities related to the project over the life cycle.

## 6.1 LCCA Methodology

The following steps are required to perform a life-cycle cost analysis.

- Establishing an alternative design: In this first step, all possible alternatives are considered. Each strategy must include all design criteria and performance parameters, as well as an effective period. At least two significant alternative activities should be compared in this step to determine the more economical one. Each alternative should have a sufficient time frame for comparison: defining an analysis period is most important in this stage. Other parameters such as maintenance and rehabilitation costs must be defined in an initial stage.
- Determining the required timing for activities: The most important step after defining all major alternatives is to consider a schedule for short-term and long-term performance expenses for a project. For example, pavement construction needs periodic maintenance and rehabilitation after a few years. In LCCA, all costs within a life cycle should be forecasted.

- Calculating the costs: LCCA does not require an account of all costs occurring with an activity. Only agency costs and user costs are considered for the analysis. The costs that make a major impact on overall life cycle for each alternative should be taken as count variables only.

- Estimating the life-cycle costs: After determining all costs, the goal is to calculate the total life-cycle costs of each alternative that may be compared directly. The best method to assess life-cycle costs is the expenditure diagram. An expenditure diagram visualizes initial costs, maintenance and rehabilitation costs, and salvage value over the analysis period of a project. Typically, a constant dollar scale is used for best results. All cost items should be considered constant throughout the analysis period of a project.

- Evaluation of the result: After calculating life-cycle costs, alternatives are ready to be analyzed. Typically, a deterministic or probabilistic approach is used in LCCA to decide between alternatives. However, the result of LCCA is based on economic analysis and there are many other parameters that are related to a project; LCCA may not include political, scientific, or environmental factors.

## 6.2 LCCA Terminology

The following paragraphs provide brief explanations of general terminologies used in the LCCA.

***Agency Costs***. All costs that affect the agency over the life of the project are considered to be agency costs. They include costs for initial primary engineering, construction supervision, contract administration, future routine and preventive maintenance—and, in such cases, roller operation (Walls and Smith 1998).

***User Costs***. User costs are the differential costs incurred by users when considering alternatives maintenance and rehabilitation strategies over the life cycle of the structure. For instance, in roadway construction, cost items such as vehicle operating costs, delay costs, and crash costs are considered as user costs.

***Net Present Value (NPV)***. NPV is a discounted value of the total benefit which is calculated by subtracting present value costs from present value benefits using the appropriate discount rate. In the cash flow diagram, NPV represents each year's present worth. NPV can be positive or negative. Generally, a project with negative NPV should be ignored. As stated by Walls and Smith (1998), NPV can be calculated as follows:

$$NPV = Initial\ Cost + \sum_{K=1}^{N} Rehab\ Cost_K \left[\frac{1}{(1+i)^{n_K}}\right] \quad (1)$$

where i = discount rate and n = years of expenditure. $\left[\frac{1}{(1+i)^{n_K}}\right]$ is known as the present value factor for a given year.

***Salvage Value***. A project is always associated with depreciation, which means that a value of a newly constructed highway would not be the same as its value at the end of the service life. The value of an asset after considering depreciation is referred to as salvage value. In economic analyses, salvage value is typically considered as 25–30% of the initial investment value.

***Discount Rate***. Discount rate is the rate of return on investment stated as percentage. It is used to calculate how many percentages of discount should be applied to get such a return on investment at a specific period.

## 6.3 LCCA Approaches

The following is a summary of common approaches and analysis techniques used for LCCA. In this study, we have employed a preliminary deterministic approach.

***Deterministic Approach***. This approach is based on professional judgments or historical experiences. The analysis is based on fixed and discrete values for all the LCCA input variables. However, there are uncertainties that are not considered in this approach. By using a sensitivity analysis, the uncertainties associated with this approach can be eliminated (FHWA 2002).

***Sensitivity Analysis***. This method is used to define the variables that can have a major impact on the results for a deterministic approach (FHWA 2002). In the case of compaction, variables such as compaction efficiency, roller costs, and service life improvement can impact the results. In this approach, the uncertainty in dependent variables can be measured. It is also useful to choose the lowest present values for a project.

***Probabilistic Approach***. This approach analyzes the individual inputs by using a probability distribution. For each uncertain parameter, the sampling distribution of possible value is developed. To compute a forecasted present value for each input variable, a simulation is used to randomly draw values. The probabilistic approach allows uncertainty in the analysis. However, some levels of risk are involved in this approach (FHWA 2002).

***Risk Analysis***. When interpreting the probabilistic analysis results, one might estimate the risk involved with the results (FHWA 2002). The risk analysis is carried out to evaluate the variability associated with certain alternatives and the selected analysis method.

## 6.4 LCCA Case Study for Intelligent Compaction

This section describes the application of LCCA to compare the two compaction alternatives. The analysis is based on a limited field data collection for a 2.5” Hot Mix Asphalt (HMA) overlay on the existing pavement layer that was previously described in this report. All other pavement layers such as base course, subbase course, and compacted subgrade were considered constant to minimize the variables in the calculations. The roadway section selected was one mile long. The

Average Annual Daily Traffic (AADT) was 2,900 vehicles on the eastbound lane and 2,300 westbound with 1.49% average traffic growth.

The goal of this study was to compare intelligent compaction to conventional approach for the analysis periods of 10, 15, and 26 years. Construction costs, maintenance costs, and user costs were selected as the main parameters of the LCCA. A typical method of determining cost is to find out the number of quantities required and then multiply quantities by the unit cost; unit costs are easily accessible from previous records and bids. In this study, an analysis was performed using constant dollars, if the value of the dollar would not change throughout the life cycle of the project. For instance, if the operating cost of the roller is $100 as of the date of writing, it will also be $100 after 15 years. The LCCA was performed with the assumption of constant dollar value to maintain consistency of costs and minimize the errors in cost calculations.

The following discussion summarizes the agency costs related to the compaction project. To narrow down the list of activities related to pavement construction, the placement and compaction cost of a one-lane mile of HMA was assumed to be $250,000.

***Compaction Cycle Cost***. The compaction cycle cost for conventional and intelligent compaction was assumed to be $940 and $590, respectively (Savan et al. 2017). Total cost was converted to 2019 USD using the inflation rate. The cumulative rate of inflation from 2016 to 2019 was 7%; thus, the compaction cycle cost for conventional and intelligent compaction would be $1,006 and $631, respectively, in 2019 USD. Table 11 presents total agency cost associated with the construction of one lane-mile of pavement. Total agency costs were used in this study to perform the LCCA.

Table 11. Agency Cost Calculation per Lane-Mile

| | Conventional Compaction | Intelligent Compaction |
|---|---|---|
| Initial construction cost | $250,000 | $250,000 |
| Compaction cycle cost | $1,007 | $634 |
| Total agency cost | $251,007 | $250,634 |

***User Delay Cost***. The following discussion describes the process of estimating the incurred delay costs to the road users due to the traffic congestion caused by the construction process.

In this study, traffic congestion was assumed to be associated with user costs during the construction activities. The two-lane highway section had one lane in each direction. Figure 14 represents traffic routing near the work zone, which was always protected with channelizing devices during construction. The Annual Average Daily Traffic (AADT) on the eastbound lane was estimated to be 2,900 in 2019. The current traffic counts can be estimated by using a traffic growth rate factor as follows:

$$i = \left(\frac{F}{P}\right)^{\frac{1}{n}} - 1 \tag{2}$$

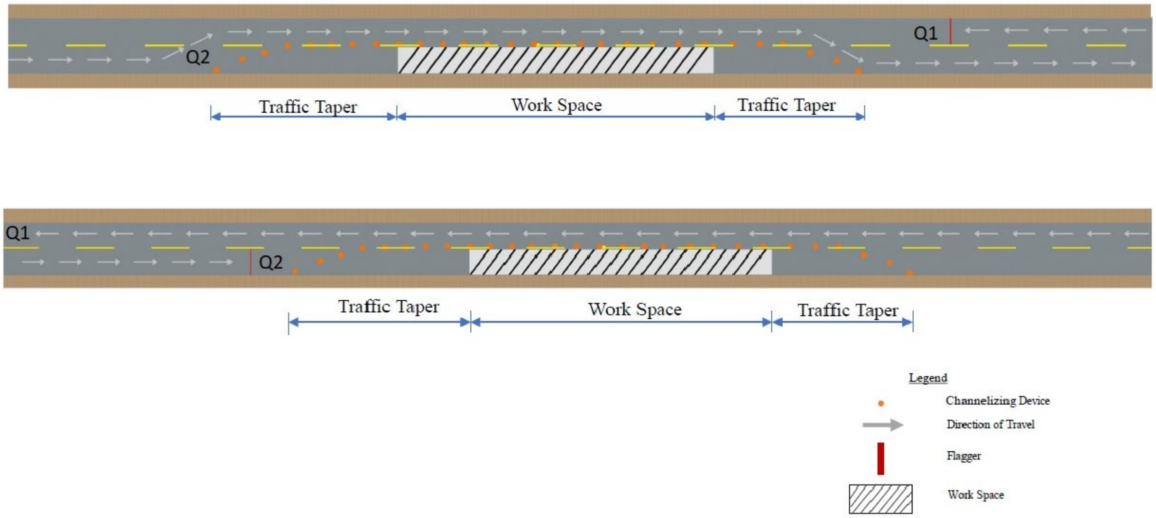
where F = future year AADT, P = present year AADT, i = traffic growth rate, n = number of years. By incorporating the values of $F_{2016}$ = 2,850, $F_{2013}$ = 2,800, and i = 3, the growth rate is estimated to be 0.60%. The growth rate formula is also useful to predict the future AADT. By using i = 0.60% and $F_{2016}$ = 2,850, $F_{2019}$ for the east- and westbound lanes was 2,900 and 2,300, respectively. Table 12 presents a conversion of the value of user time from the 2016 to 2019 USD.

Table 12. Value of User Time

| | $/hr (2016 USD) | Inflation Rate | $/hr. (2019 USD) |
|---|---|---|---|
| Automobile | 13.65 | 6% | 14.47 |
| Truck | 31.4 | 6% | 33.28 |

A cycle of 15 minutes of a temporary lane closure for each direction was assumed to accurately describe the status of queued vehicles during work. Arrival and departure rates were assumed constant in the work zone. Vehicle operational speed under normal conditions and in the work zone was 55 and 20 mph, respectively.

Figure 14. Work Zone Traffic Diversion Cycle



Schonfeld and Chien (2015) proposed an equation to calculate the total user delay cost per kilometer per lane for two-lane highways as follows:

$$C_u = D\frac{Q_1\left(\frac{3600}{H} - Q_1\right) + Q_2\left(\frac{3600}{H} - Q_2\right)}{V\left(\frac{3600}{H} - Q_1 - Q_2\right)} \times Value\ of\ User\ Time\ in\ \$/hr \qquad (3)$$

where $C_u$ = total user delay cost ($/lane-km), D = total maintenance/working hours (hr), $Q_{i\ (i=1,2)}$ = flow rate in each direction (veh/hr), H = average headway (s), and V = average speed of vehicles when passing the work zone (kph). Table 13 presents the input parameters used to calculate the total user delay costs.

Table 13. Inputs for Total User Cost Delay Formula

| Input | *Conventional Compaction* | | *Intelligent Compaction* | |
|---|---|---|---|---|
| | Automobile | Truck | Automobile | Truck |
| D (hr) | 10 | 10 | 7.7 | 7.7 |
| $Q_1$ (veh/hr) | 102 | 18 | 102 | 18 |
| $Q_2$ (veh/hr) | 81 | 14 | 81 | 14 |
| H (s) | 3 | 3 | 3 | 3 |
| V (km/hr) | 32.2 | 32.2 | 32.2 | 32.2 |
| Value of user time ($/hr) | 14.47 | 33.28 | 14.47 | 33.28 |

Table 14 presents the outputs from the total user delay cost formula. From this preliminary evaluation, it seems that intelligent compaction can save 23% of user delay cost for one lane-mile of highway pavement overlay construction compared to conventional compaction.

Table 14. Total User Cost Calculation

| | Conventional Compaction $/lane-mile | Intelligent Compaction $/lane-mile |
|---|---|---|
| Automobile | 1,375 | 1,060 |
| Truck | 540 | 415 |
| Total | 1,915 | 1,475 |

***Maintenance Costs***. This discussion focuses on comparing maintenance costs between IC and conventional compaction. Since the environmental effects and traffic loading can cause the pavement to deteriorate over time, frequent maintenance and rehabilitation will be required to avoid pavement deterioration and extend the service life. Pavement maintenance can be performed via various methods based on pavement condition, traffic loading, climate, cost of treatment, and service life. Pavement maintenance can be preventive, corrective, and emergency based. The authors of this study assumed that only a few types of maintenance treatments are commonly required to enhance pavement service life. The types of treatment methods considered in this study were fog seal, crack seal, chip seal, slurry seal, and thin HMA overlay. Table 15 summarizes the maintenance unit costs for different treatment options (Johnson 2000). The costs were converted to 2019 USD using the inflation rate as shown earlier in this study.

Table 15. Maintenance Treatment Cost Calculation per Lane-Mile

| Treatment Type | Unit Cost | No. of Units per Mile | Cost per Lane-Mile |
|---|---|---|---|
| Fog seal | $0.22/sy | 7,040 | $1,550 |
| Crack seal | $0.30/lf | 5,280 | $1,580 |
| Chip seal | $2.24/sy | 7,040 | $15,700 |
| Slurry seal | $2.24/sy | 7,040 | $15,700 |
| Thin HMA overlay | $37.28/ton | 380 | $14,170 |

sy = square yard, lf = linear foot

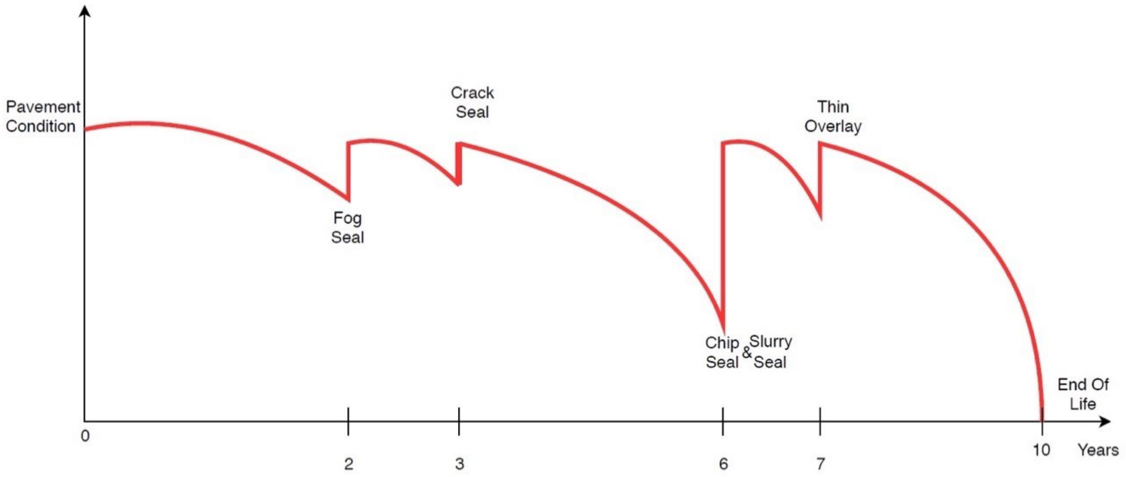
Two different scenarios were considered based on the life-cycle factor for the pavement structure (see Table 16). Scenario 1 represents average extended service life for each treatment option when using conventional compaction, whereas scenario 2 shows the extended service life calculated using intelligent compaction.

Table 16. Average Application Time for Pavement Treatments for Different Scenarios

| | | *Scenario 1* | *Scenario 2* | |
|---|---|---|---|---|
| Maintenance Option | Treatment Type | Average Treatment Years | Life-Cycle Factor | Average Treatment Years |
| Maintenance #1 | Fog seal | 2 | 1.5 | 3 |
| Maintenance #2 | Crack seal | 3 | 1.5 | 5 |
| Maintenance #3 | Chip seal | 6 | 1.5 | 9 |
| Maintenance #4 | Slurry seal | 7 | 1.5 | 11 |
| Maintenance #5 | Thin HMA overlay | 7 | 1.5 | 11 |
| | End of life | 10 | 1.5 | 15 |

Let us consider scenario 1, which presents the life cycle of pavement using conventional compaction. Figure 15 shows the pavement condition over the pavement period. The life cycle of pavement for conventional compaction was assumed to be 10 years. As shown in Figure 15, at certain points during the pavement service life, treatment options can be applied to maintain the pavement condition. After each treatment, the pavement condition is increased, and then it diminishes until the next treatment.

Figure 15. Lifespan of Pavement Constructed using CC



Let us now consider scenario 2, which presents the life cycle of pavement using intelligent compaction (with a life-cycle factor of 1.5). Figure 16 represents a typical life cycle of pavement constructed using intelligent compaction. Due to the potential improvements in rutting and fatigue performance, the life cycle of the compacted pavement structure can be extended by a factor of 1.5 (Savan et al. 2017). That assumption implies that same length of the roadway section compacted by intelligent compaction will last longer compared to the conventional compaction methods.

Figure 16. Lifespan of Pavement Constructed using IC

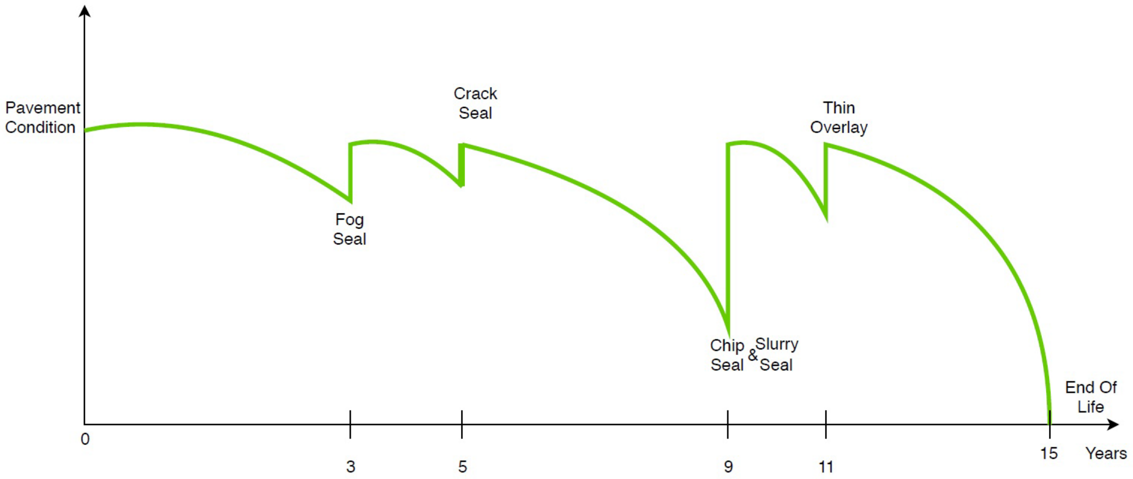
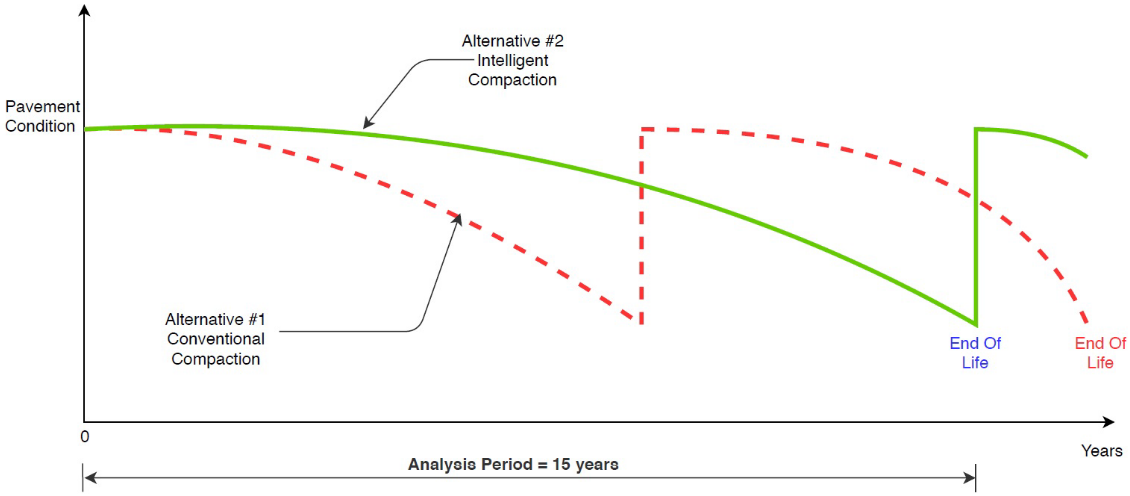


Figure 17 further illustrates the comparison between conventional and intelligent compaction methods in terms of life cycle and end of life. The analysis period was 15 years in this scenario. The pavement condition in alternative #1 (CC) is almost at the end of life at the 15-year mark.

Figure 17. Comparison of Analysis Period for CC versus IC



Even though the extension of service life by using intelligent compaction needs further investigations to study the long-term performance, the compaction uniformity and availability of comprehensive compaction data are among the main benefits of using IC technology.

The discussion now turns to the calculation of Net Present Value (NPV), which indicates the cost difference between two alternatives. After determining all agency costs and user costs, NPV can be estimated using the following equation:

$$NPV = Initial\ Cost + \sum_{K=1}^{N} Rehab\ Cost_K \left[\frac{1}{(1+i)^{n_K}}\right] \quad (4)$$

where i = discount rate and n = years of expenditure. In the above formula, $\left[\frac{1}{(1+i)^{n_K}}\right]$ is known as the Present Value Factor (PVF) for a given year.

Maintenance and rehabilitation costs are multiplied by the PVF and added to the initial cost to calculate NPV for a single year future amount. Table 17 summarizes the calculations of NPV over the entire life of the project for Scenario 1. In this scenario, the LCCA was performed for a period of 30 years. After each maintenance activity, user costs must be applied to calculate NPV as traffic needs to be stopped during the maintenance work. Table 17 includes different maintenance treatment options such as fog seal, crack seal, chip seal, slurry seal, and thin HMA overlay as discussed earlier in this chapter (see Table 15). Discount rate was 4% in this study. To calculate NPV, the cost of a single year is multiplied by the discount factor.

At the end of the analysis, all NPV values must be summed up for each option to compare the two alternatives. Table 18 presents NPV calculations for scenario 2, where the analysis was performed for a life span of 15 years. In this case, the timeline of applying maintenance activities was longer than scenario 1 due to the improved compaction quality achieved by using intelligent compaction.

Table 17. Net Present Value Calculation for Scenario 1 with Conventional Compaction

| Activity | Year | Discount Factor | Cost ($) | NPV ($) | Cumulative Cost ($) |
|---|---|---|---|---|---|
| Initial construction | 0 | 1.0000 | 251,007 | 251,007 | 251,007 |
| User cost | 0 | 1.0000 | 1,913 | 1,913 | 252,921 |
| Maintenance #1 | 2 | 0.9246 | 1,550 | 1,433 | 254,354 |
| User cost | 2 | 0.9246 | 1,913 | 1,769 | 256,123 |
| Maintenance #2 | 3 | 0.8890 | 1,580 | 1,404 | 257,528 |
| User cost | 3 | 0.8890 | 1,913 | 1,701 | 259,229 |
| Maintenance #3 | 6 | 0.7903 | 15,700 | 12,407 | 271,637 |
| User cost | 6 | 0.7903 | 1,913 | 1,512 | 273,150 |
| Maintenance #4 | 7 | 0.7599 | 15,700 | 11,930 | 285,080 |
| User cost | 7 | 0.7599 | 1,913 | 1,454 | 286,535 |
| Maintenance #5 | 7 | 0.7599 | 14,170 | 10,768 | 297,303 |
| User cost | 7 | 0.7599 | 1,913 | 1,454 | 298,757 |
| Salvage | 10 | 0.6756 | -75,302 | -50,871 | 247,885 |
| Initial construction | 10 | 0.6756 | 251,007 | 169,571 | 417,457 |
| User cost | 10 | 0.6756 | 1,913 | 1,292 | 418,750 |
| Maintenance #1 | 12 | 0.6246 | 1,550 | 968 | 419,718 |
| User cost | 12 | 0.6246 | 1,913 | 1,195 | 420,913 |
| Maintenance #2 | 13 | 0.6006 | 1,580 | 948 | 421,862 |
| User cost | 13 | 0.6006 | 1,913 | 1,149 | 423,011 |
| Maintenance #3 | 16 | 0.5339 | 15,700 | 8,382 | 431,394 |
| User cost | 16 | 0.5339 | 1,913 | 1,021 | 432,415 |
| Maintenance #4 | 17 | 0.5134 | 15,700 | 8,059 | 440,475 |
| User cost | 17 | 0.5134 | 1,913 | 982 | 441,458 |
| Maintenance #5 | 17 | 0.5134 | 14,170 | 7,274 | 448,732 |
| User cost | 17 | 0.5134 | 1,913 | 982 | 449,715 |
| Salvage | 20 | 0.4564 | -75,302 | -34,367 | 415,348 |
| Initial construction | 20 | 0.4564 | 251,007 | 114,556 | 529,904 |
| User cost | 20 | 0.4564 | 1,913 | 873 | 530,777 |
| Maintenance #1 | 22 | 0.4220 | 1,550 | 654 | 531,431 |
| User cost | 22 | 0.4220 | 1,913 | 807 | 532,239 |
| Maintenance #2 | 23 | 0.4057 | 1,580 | 641 | 532,880 |
| User cost | 23 | 0.4057 | 1,913 | 776 | 533,656 |
| Maintenance #3 | 26 | 0.3607 | 15,700 | 5,662 | 539,319 |
| User cost | 26 | 0.3607 | 1,913 | 690 | 540,009 |
| Maintenance #4 | 27 | 0.3468 | 15,700 | 5,445 | 545,454 |
| User cost | 27 | 0.3468 | 1,913 | 663 | 546,118 |
| Maintenance #5 | 27 | 0.3468 | 14,170 | 4,914 | 551,033 |
| User cost | 27 | 0.3468 | 1,913 | 663 | 551,696 |
| Salvage | 30 | 0.3083 | -75,302 | -23,217 | 528,479 |
| **Total NPV** | | | | | **528,479** |

Table 18. Net Present Value Calculation for Scenario 2 using Intelligent Compaction, Life-Cycle Improvement Factor = 1.5

| Activity | Year | Discount Factor | Cost ($) | NPV ($) | Cumulative Cost ($) |
|---|---|---|---|---|---|
| Initial construction | 0 | 1.0000 | 250,634 | 250,634 | 250,634 |
| User cost | 0 | 1.0000 | 1,473 | 1,473 | 252,107 |
| Maintenance #1 | 3 | 0.8890 | 1,550 | 1,377 | 253,485 |
| User cost | 3 | 0.8890 | 1,473 | 1,309 | 254,795 |
| Maintenance #2 | 5 | 0.8219 | 1,580 | 1,298 | 256,093 |
| User cost | 5 | 0.8219 | 1,473 | 1,210 | 257,304 |
| Maintenance #3 | 9 | 0.7026 | 15,700 | 11,030 | 268,335 |
| User cost | 9 | 0.7026 | 1,473 | 1035 | 269,370 |
| Maintenance #4 | 11 | 0.6496 | 15,700 | 10,198 | 279,568 |
| User cost | 11 | 0.6496 | 1,473 | 956 | 280,525 |
| Maintenance #5 | 11 | 0.6496 | 1,4170 | 9,204 | 289,730 |
| User cost | 11 | 0.6496 | 1,473 | 956 | 290,687 |
| Salvage | 15 | 0.5553 | -75,190 | -41,750 | 248,936 |
| **Total NPV** | | | | | **248,936** |

In LCCA, the analysis period should be the same to compare two alternatives over the same period and choose the more economical option. The following tables present the cost advantages over the same period for the two alternatives in this study. Table 19 represents the total cost advantage of choosing intelligent compaction over conventional compaction. Cost advantage was defined as the cost difference between two scenarios. Total NPV includes all costs such as initial construction cost, maintenance cost, and user cost. As shown earlier in Table 17, the analysis was performed for 30 years in scenario 1. However, the total NPV of scenario 1 after 15 years was derived by interpolating the NPV of the years 13 and 16 to compare with the NPV of scenario 2 after 15 years. By choosing the IC method, about $180,000 can be saved per lane-mile over 15 years of service life.

Table 19. Total Cost Comparison of Two Scenarios

| Alternative | Analysis Period | Total NPV ($) |
|---|---|---|
| Scenario 1 (CC) | 15 | 429,280 |
| Scenario 2 (IC) | 15 | 248,936 |
| Cost advantage | | 180,344 |

Table 20 presents the agency cost advantage between the IC and CC methods. The agency maintenance costs will be reduced by $172,822 per lane-mile by using intelligent compaction.

Table 20. Agency Cost Comparison of Two Scenarios

| Alternative | Analysis Period | Agency Cost ($) |
|---|---|---|
| Scenario 1 (CC) | 15 | 417,951 |
| Scenario 2 (IC) | 15 | 245,129 |
| Cost advantage | | 172,822 |

Table 21 presents the user cost advantage between the two scenarios in this study, whose context is a two-lane, two-way highway where traffic volume was already moderate. Therefore, the user cost savings does not seem as high compared to total NPV and agency cost.

Table 21. User Cost Comparison of Two Scenarios

| Alternative | Analysis Period | User Cost ($) |
|---|---|---|
| Scenario 1 (CC) | 15 | 14,464 |
| Scenario 2 (IC) | 15 | 6,942 |
| Cost savings | | 7,522 |

The life-cycle cost analysis performed in this study was based on limited field data available from a pavement rehabilitation project. To validate the preliminary results and provide a more comprehensive analysis, the long-term monitoring of the constructed pavement sections is required to quantify the cost items and estimate the user costs. however, based on this initial analysis, the use of intelligent compaction shows improvements in terms of life-cycle cost savings compared to the conventional compaction approach.

Chapter VII includes the summary of the field data collection for another pilot project to compare the performance of intelligent and conventional compaction methods in a side-by-side field evaluation. The data from the second field evaluation was collected with more details regarding the performance indicators during the construction of pavement section.

# VII. Case Study

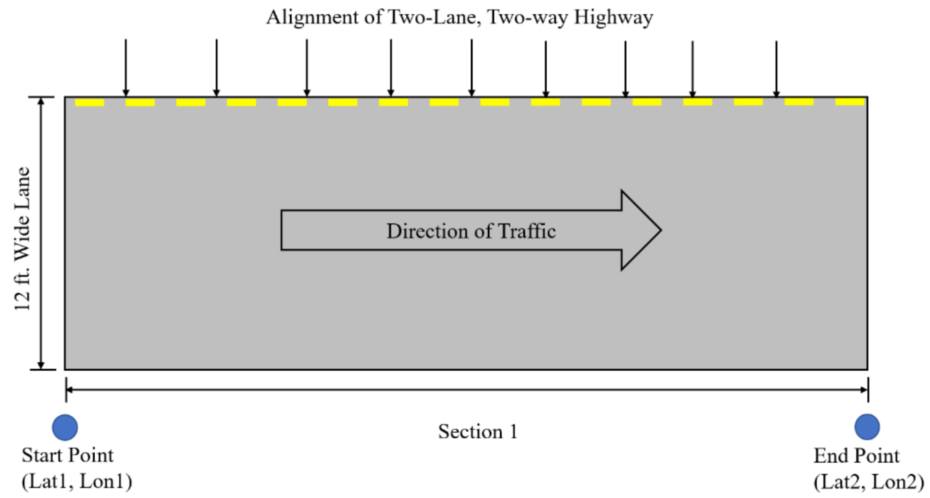
## 7.1 Project Details

Another pavement overlay project was selected to collect field data and implement the LCCA approach that was introduced in Chapter VI of this report. The project was a part of a two-lane highway with 12-ft lane width and a total length of 7.5 miles. A 0.2-ft-thick Rubberized Hot Mix Asphalt (RHMA) overlay was placed on the existing milled pavement surface. To collect the IC data, a tandem vibratory drum roller was used. GPS calibration was performed by the contractor at the beginning of the work. The compaction process was performed by three rollers. The breakdown roller began running immediately after the placement of the RHMA layer by the paver machine. The intermediate roller was operating behind the paver machine. The finisher roller followed the path of the intermediate roller to ensure a smooth finished layer. The main goal of the field data collection was to compare the performance of intelligent compaction and conventional rollers during compaction of a pavement layer.

## 7.2 Data Collection Approach

The roller performance data were monitored and collected by the research team at the construction site. Various data were recorded: for example, the number of passes, duration of each pass, total operation duration, and the GPS locations. The construction data were recorded on site for a total of three miles. Depending on the paver speed and the roller's compaction patterns, the entire construction section was divided into several segments with different lengths. The GPS location of the start and end point of each segment was recorded. A sample road segment from the field data collection site is illustrated in Figure 18.

Figure 18. A Sample Segment at the Field Data Collection Site



The additional field data were collected by the contractor and field engineers. Those data items included the IC data, density readings from the nuclear density gauge, and the laboratory test results of cores extracted from the construction site.

## 7.3 Data Analysis

Field data were collected for both intelligent and conventional compaction rollers during the construction of the asphalt overlay. A flowchart of the data analysis approach is presented in Figure 19. The data were collected according to the planned data collection approach. However, in some cases, due to the construction constraints, not all the field data were available. A summary of recorded data is presented in Table 22.

Figure 19. Field Data Collection Approach

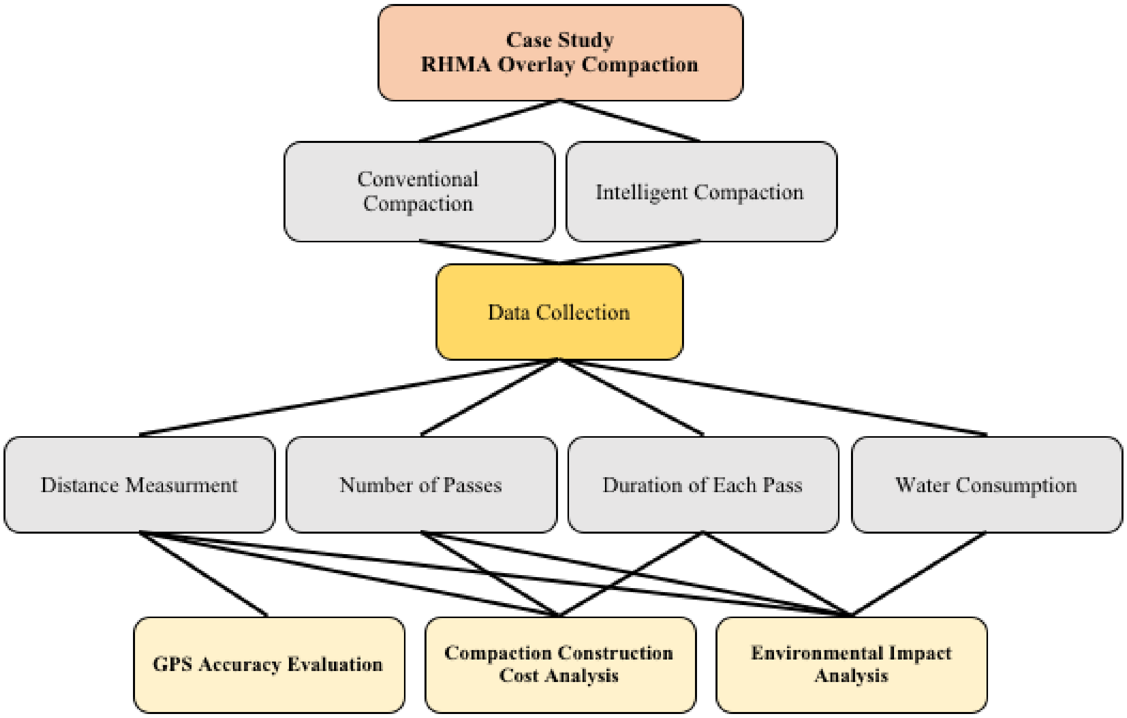


Figure 20 shows the average duration of compaction, in minutes, per lane-mile for the intermediate roller for both IC and CC rollers. It shows that the use of IC roller reduces the duration of intermediate compaction by 27%. Then, in Figure 21 the average construction duration per lane-mile of breakdown roller is presented: the IC roller can reduce the compaction duration by about 20%.

Table 22. Summary of the Recorded Field Data

| Compaction Technique | Roller Type | Total Length (miles) | No. of Passes | Total Duration (min) | Average Duration for Each Pass (min/pass) | Duration per Lane-Mile (min) |
|---|---|---|---|---|---|---|
| IC | Breakdown | 0.90 | 117 | 95 | 0.81 | 106 |
| IC | Intermediate | 0.76 | 96 | 89 | 0.93 | 118 |
| IC | Breakdown | 0.77 | 104 | 101 | 0.97 | 131 |
| CC | Breakdown | 1.33 | 152 | 171 | 1.13 | 129 |
| CC | Intermediate | 1.38 | 194 | 214 | 1.10 | 155 |

Figure 20. Average Compaction Duration per Lane-Mile for Intermediate Roller

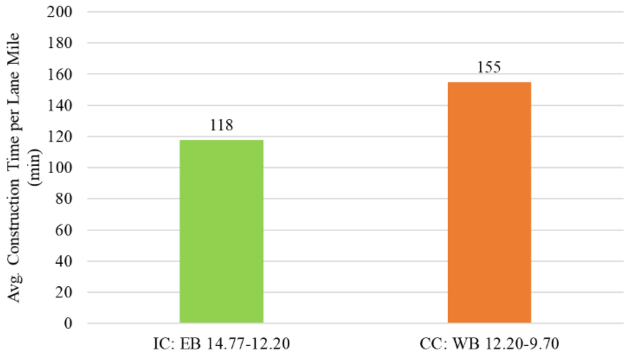


Figure 21. Average Compaction Duration per Lane-Mile for Breakdown Roller

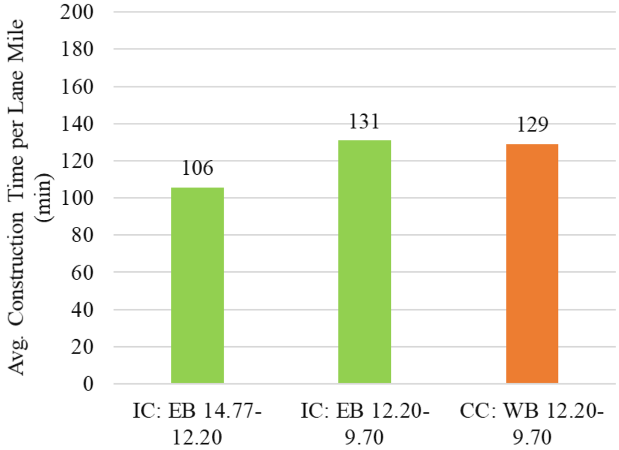


Table 23 indicates that the total duration of construction for one lane-mile of IC and CC is 3.72 and 4.73 hours, respectively. Using the benefit-cost analysis methodology introduced in the previous chapters, the construction cost for both methods can be estimated. Based on the data presented in Table 23, the IC approach can reduce the cost of compaction by $245 for one lane-mile. Note that these figures only consider the cost of compaction during the construction phase, and other benefits of using a roller equipped with IC are not quantified in this preliminary analysis.

Table 23. Estimated Cost of Construction for One Lane-Mile

| Item | *Conventional Compaction* | | | | *Intelligent Compaction* | | | |
|---|---|---|---|---|---|---|---|---|
| | Unit Cost ($) | Unit | Number of Units | Total Cost ($) | Unit Cost ($) | Unit | Number of Units | Total Cost ($) |
| Roller | 85 | hour | 4.73 | 402 | 100 | hour | 3.72 | 372 |
| Operator | 22 | hour | 4.73 | 104 | 22 | hour | 3.72 | 82 |
| QC/QA | | $m^2$ | | 217 | | $m^2$ | | 24 |
| Total | | | | 723 | | | | 478 |

For the roadway life-cycle cost analysis, several assumptions were made. The annual maintenance disbursements are about $84,000 per mile. The inflation rate in 2019 was 2.3%, which was adopted in this study. Moreover, the assumption of repairing or replacing 17,000 miles of pavement within the next 10 years by Senate Bill 1 (SB1) funds corresponds to about 1,700 miles per year at a constant pace. Consideration all the assumptions mentioned here, Table 24 summarizes the roadway life-cycle costs for both IC and conventional compaction scenarios.

Table 24. Roadway Life-Cycle Cost for IC and CC Scenarios

| Compaction Type | Service Life (years) | Life Factor | Cost per Year ($) | Cost over 10 Years ($) | Cost for 1,700 miles ($) |
|---|---|---|---|---|---|
| Conventional | 10 | - | 84,000 | 932,500 | 1,585,340,000 |
| Intelligent | 15 | 1.5 | 56,000 | 621,700 | 1,056,890,000 |

Based on the above assumptions for roadway life-cycle costs for the IC scenario, Figure 22 illustrates the cumulative maintenance cost savings accrued using IC during a period of 10 years for 1,700 lane-miles.

Figure 22. Cumulative Maintenance Cost Savings for 1,700 Lane-Miles after using IC

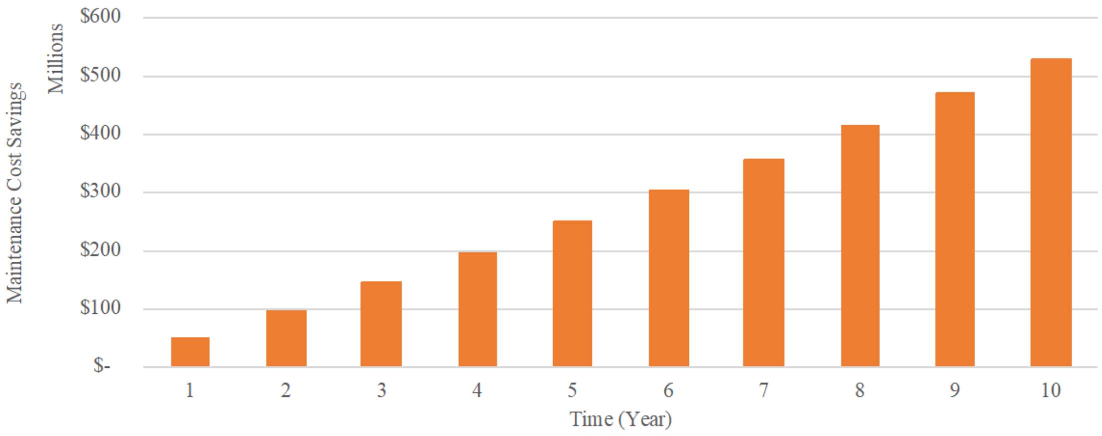


Table 25 summarizes the resource usage for the roller compactor that was used in this construction project. The main energy and emission resources are fuel consumption, carbon monoxide (CO), and nitrogen oxide (NOx) emissions as well as water consumption. Table 26 summarizes the environmental impact of using two compaction techniques per lane-mile. Then, Figure 23 through Figure 26 present the resource savings as well as the reductions in emissions based on 1,700 lane-miles of pavement surface construction and maintenance.

Table 25. Roller Energy and Emission Estimations for One Hour*

| Category | Unit | Number of Units | Engine Power (kw) | Total Usage |
|---|---|---|---|---|
| Fuel (diesel) | US gal/hr | 7.33 | N/A | 7.33 gph |
| CO | gram/kilowatt-hr | 5 | 97 | 485 g/kWh |
| NOx | gram/kilowatt-hr | 4 | 97 | 388 g/kWh |
| Water | US gal/hr | 105.5 | N/A | 105.5 gph |

*Based on EPA Tier 3 Non-Road Diesel Engine (engine power = 97 kW)

Table 26. Energy Usage and Emissions for One Lane-Mile of Compaction

| Category | Total Project Time | Total Fuel Usage | Total CO Emission | Total NOx Emission | Total Water Usage |
|---|---|---|---|---|---|
| Unit | (hr) | (US gal) | (g) | (g) | (US gal) |
| Convention compaction | 4.73 | 35 | 2294 | 1835 | 499 |
| Intelligent compaction | 3.72 | 27 | 1804 | 1443 | 392 |

Figure 23. Fuel Savings after One Year and Ten Years

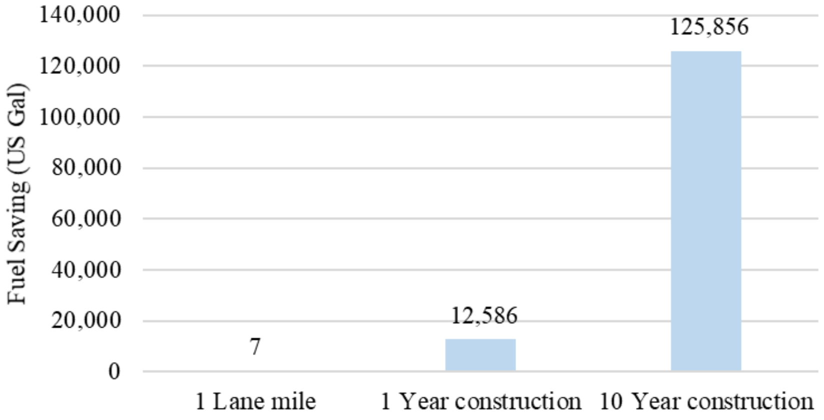


Figure 24. Water Usage Savings for One Year and Ten Years

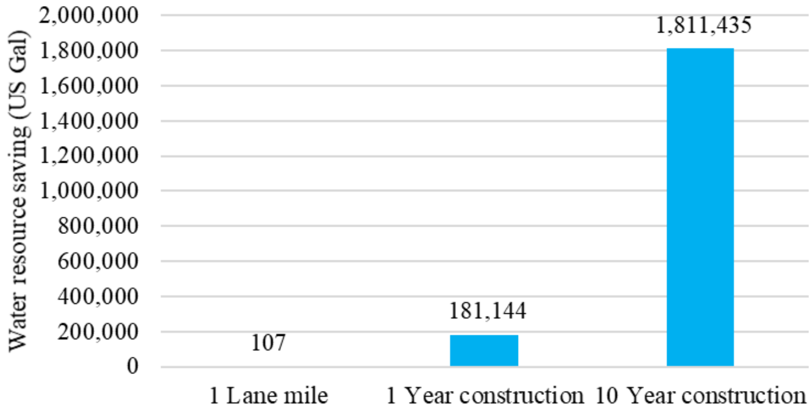


Figure 25. CO Emission Reductions for One Year and Ten Years

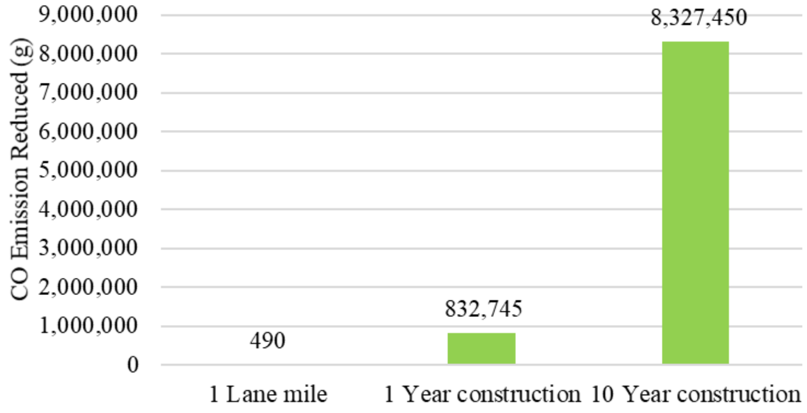
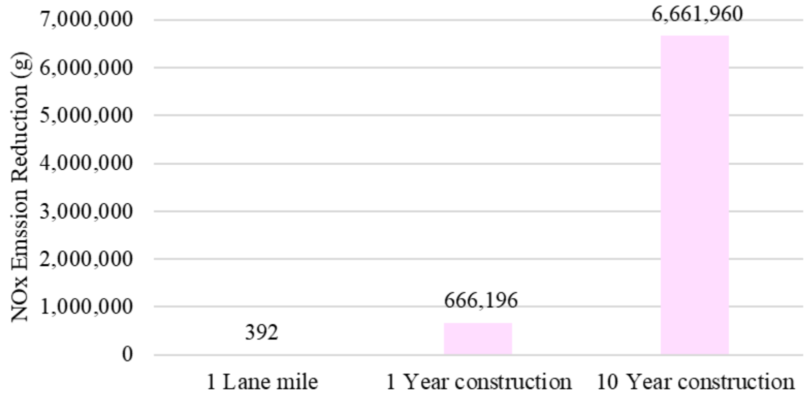


Figure 26. NOx Emission Reductions for One Year and Ten Years



A schematic view of the construction segments used in the field data collection phase of this study is shown in Figure 27. The special setup of the construction segments allowed for side-by-side comparison of the compaction quality and uniformity for conventional and intelligent compaction methods.

Analysis of the middle construction segments showed that the average relative compaction of core samples was 93.9% and 93.1% for CC and IC-3 segments, respectively. Even though the average relative compactions were close, the standard deviations between the density values showed 38 percent more uniformity in the samples taken from the segment compacted by IC. Figure 28 summarizes the variation of density values for the cores extracted from the section compacted with the CC method compared to the results from the section compacted with IC. Overall, the standard deviation of the density core data from the IC sections shows less variation compared to the sections compacted with conventional compaction. Although there are other factors that affect the uniformity of the compacted pavement layer, such as asphalt material variability, the preliminary comparison of density cores shows more uniformity achieved using IC.

The side-by-side comparison of both IC and CC methods for construction an asphalt overlay project showed that the use of IC improves the compaction uniformity and optimizes the construction efficiency. However, even this second field evaluation was limited to a small part of a construction project and not all the field data were available to collect due the construction constraints. As mentioned earlier in this report, the long-term performance monitoring of the constructed sections will provide more information about the impact of IC on improving the longevity of the constructed pavement layers. Moreover, the use of IC for compaction of all pavement layer is ideal to ensure the consistency and uniformity of compacted layers.

Figure 27. Location of Segments Compacted with Conventional and Intelligent Compaction

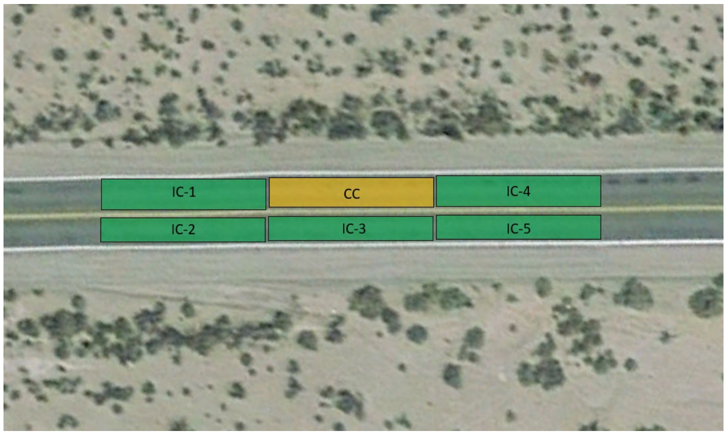
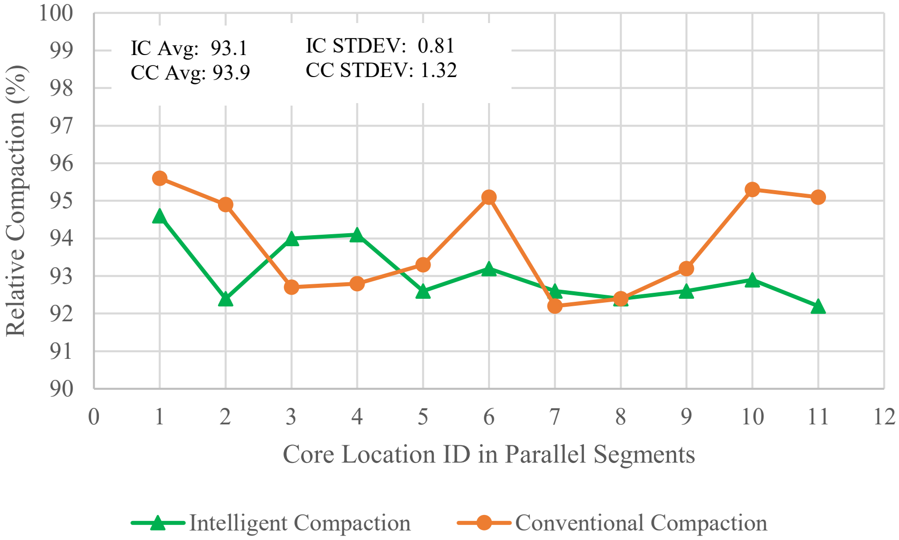


Figure 28. Comparison of Density Values for the Cores Extracted from the Segments Compacted with CC and IC



Chapter VIII includes a draft version of guidelines for the implementation and long-term performance monitoring of pavement sections compacted with IC technology.

# VIII. Draft Guidelines for Assessing the Effectiveness of IC Technology

Based on the limited field data collection and preliminary analyses performed in this project, this chapter summarizes the parameters required to implement the IC and monitor the long-term performance of the constructed pavement layer. The monitoring task starts before construction and continues until the end of the pavement life. The following sections summarize the necessary steps for each phase.

## 8.1 Phase I: Construction Monitoring

This section summarizes the parameters and performance measures that can be evaluated during and after the construction process for IC implementation. Tracking the path of the roller compactors is a challenging task since operators working with conventional rollers mostly rely on their experience and the in-situ density readings to evaluate the rolling patterns during compaction. The starting and ending locations of each segment are not consistent, as the rollers follows the paver machine. As a result, some compaction areas could be under- or over-compacted. During a side-by-side comparison of conventional and intelligent compaction, it is necessary to utilize a high-precision GPS recording system for the conventional roller compactor. Furthermore, the data items listed in Table 27 can be collected during the construction phase.

Table 27. Proposed Tasks during the Construction Phase for Implementation of IC

| Parameter | Timing |
|---|---|
| International Roughness Index (IRI) | Before & after construction |
| Nuclear gauge density and its GPS location | Before & after construction |
| Machine specifications | Before or during construction |
| Machine fuel | Before or during construction |
| Vibration status (on/off) | During construction |
| Frequency (vpm) | During construction |
| Amplitude | During construction |
| HMA Temperature | During construction |
| Intelligent compaction measurement values (ICMV) | During construction |
| Intelligent Compaction Target Value | During construction |
| Elevation Data | During construction |
| Training: Intelligent Compaction data analysis | Before construction |
| Training: Intelligent Compaction equipment operation | Before construction |
| Cost of training | Before construction |

## 8.2 Phase II: Long-Term Pavement Monitoring

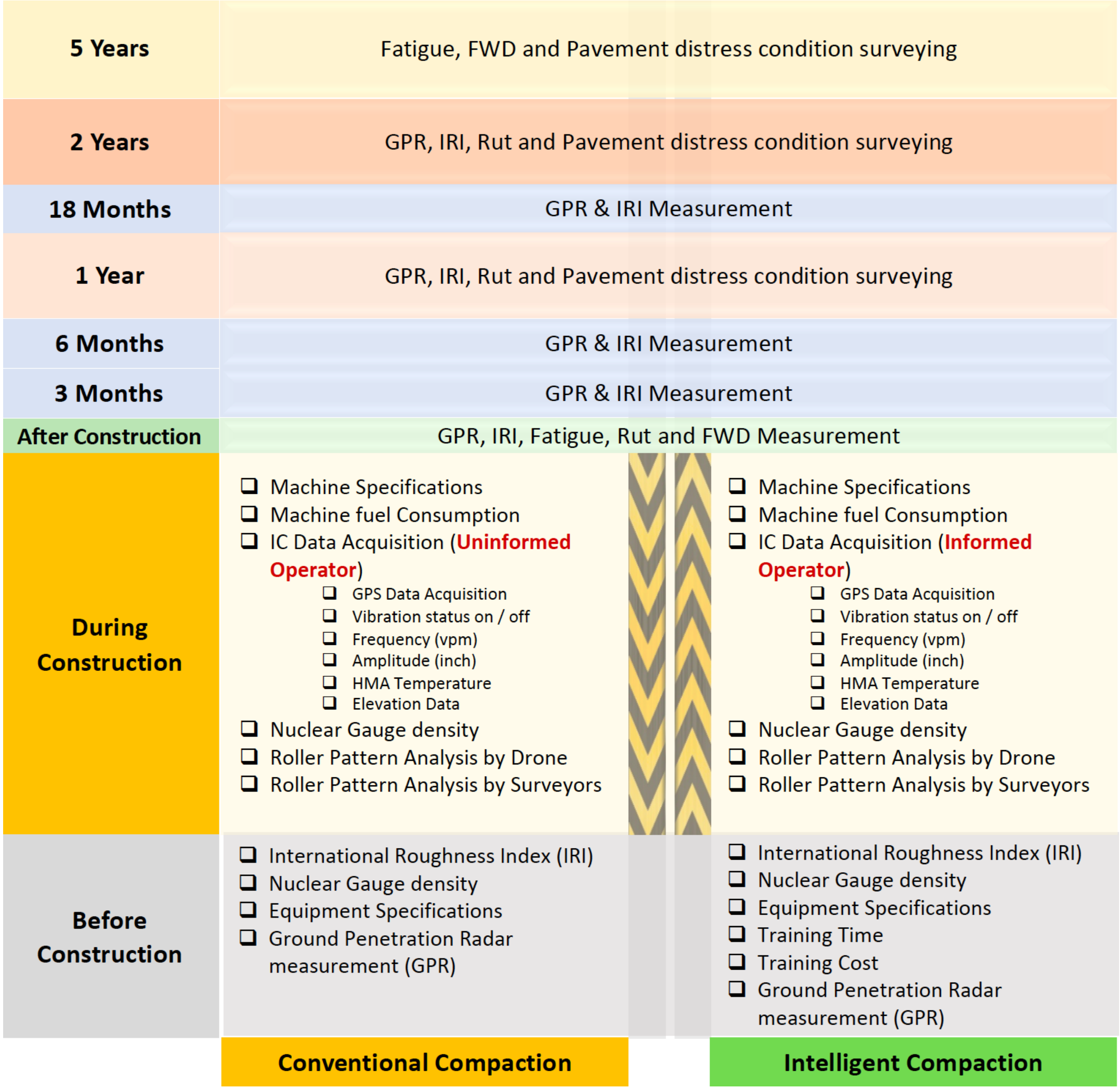
Although the parameters captured during the construction phase can predict the performance of the pavement, the actual performance can only be evaluated during long-term monitoring. Several items are considered to evaluate the performance of the pavement structure as listed in Table 28.

Table 28. Proposed Schedule for Pavement Monitoring

| Performance Measurement | Intervals |
|---|---|
| Ground penetration radar measurement (GPR), upon availability of the testing equipment | Before and after construction, as well as 3, 6, 12, 18, and 24 months after |
| International Roughness Index (IRI) | Before and after construction, as well as 3, 6, 12, 18, and 24 months after |
| Fatigue cracking core test | After construction and 5 years after construction |
| Rut survey | After construction, as well as 1 and 2 years after construction |
| Falling weight deflectometer (FWD) | After construction and 5 years after construction |
| Pavement distress condition surveying | 1, 2, and 5 years after construction |

The draft guidelines IC implementation and long-term performance monitoring of the compacted pavement sections are summarized in Figure 29. This plan also contains the list of necessary data to be collected for a side-by-side comparison of IC with conventional compaction methods.

Figure 29. Draft Guidelines for Implementation and Performance Monitoring of IC



| | | |
|---|---|---|
| **5 Years** | Fatigue, FWD and Pavement distress condition surveying | |
| **2 Years** | GPR, IRI, Rut and Pavement distress condition surveying | |
| **18 Months** | GPR & IRI Measurement | |
| **1 Year** | GPR, IRI, Rut and Pavement distress condition surveying | |
| **6 Months** | GPR & IRI Measurement | |
| **3 Months** | GPR & IRI Measurement | |
| **After Construction** | GPR, IRI, Fatigue, Rut and FWD Measurement | |
| **During Construction** | ☐ Machine Specifications<br>☐ Machine fuel Consumption<br>☐ IC Data Acquisition (**Uninformed Operator**)<br>☐ GPS Data Acquisition<br>☐ Vibration status on / off<br>☐ Frequency (vpm)<br>☐ Amplitude (inch)<br>☐ HMA Temperature<br>☐ Elevation Data<br>☐ Nuclear Gauge density<br>☐ Roller Pattern Analysis by Drone<br>☐ Roller Pattern Analysis by Surveyors | ☐ Machine Specifications<br>☐ Machine fuel Consumption<br>☐ IC Data Acquisition (**Informed Operator**)<br>☐ GPS Data Acquisition<br>☐ Vibration status on / off<br>☐ Frequency (vpm)<br>☐ Amplitude (inch)<br>☐ HMA Temperature<br>☐ Elevation Data<br>☐ Nuclear Gauge density<br>☐ Roller Pattern Analysis by Drone<br>☐ Roller Pattern Analysis by Surveyors |
| **Before Construction** | ☐ International Roughness Index (IRI)<br>☐ Nuclear Gauge density<br>☐ Equipment Specifications<br>☐ Ground Penetration Radar measurement (GPR) | ☐ International Roughness Index (IRI)<br>☐ Nuclear Gauge density<br>☐ Equipment Specifications<br>☐ Training Time<br>☐ Training Cost<br>☐ Ground Penetration Radar measurement (GPR) |
| | **Conventional Compaction** | **Intelligent Compaction** |

# IX. Conclusions

In this study, a dynamic vibratory roller, equipped with all instruments necessary for intelligent compaction (IC) data collection, was utilized for compaction of a Hot Mix Asphalt overlay along a section of a construction site. In collaboration with field engineers and the contractor, the research team recorded in-situ data such as the number of passes, duration of machine operations, and direction of machine movements, as well as in-situ density and other construction performance measures. The data set from the IC roller was also extracted to compare with the density readings taken during the conventional compaction process. A preliminary life-cycle cost analysis (LCCA) was performed to evaluate the impact of IC on cost savings during the life of the compacted pavement section. Data from field evaluations were collected to perform the cost-benefit analysis and compute the LCCA for both IC and conventional compaction processes. The following can be concluded from the outcomes of this study.

- IC can potentially reduce the time needed for construction. This reduction results in lower construction costs and lower environmental impacts.
- The improved compaction quality of the pavement layers by using IC, has the potential to minimize maintenance costs during the service life of the pavement.
- A draft guideline was developed to collect the necessary data during and after the construction of pavement layers using intelligent compaction.
- Long-term monitoring of the performance of pavement sections compacted using IC technology can help estimate the effectiveness and efficiency of this technology compared to the conventional compaction practice.
- The extended service life of the pavement layers compacted using the IC rollers needs to be further evaluated with in extensive laboratory and field settings.
- The successful implementation of IC requires attention to many aspects of the construction process and collection of the appropriate geo-referenced field data. The collection and interpretation of IC data requires trained project personnel to be able to extract meaningful information both during and after the construction process.

Within the various constraints experienced during the collection of field data in this study and the limited scope of this project, the draft version of guidelines for the implementation and monitoring of compacted pavement section is proposed to enable a comparison of the performance of the IC system in different project settings. However, to develop a comprehensive set of guidelines and draft specifications, more field data collected during different pavement construction projects will be required in future studies.

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