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Cost-Effectiveness of Conventional Compaction (CC) and Intelligent Compaction (IC) Methods of Asphalt Pavement Overlay

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Abstract: The use of intelligent compaction (IC) in asphalt overlay includes the use of double-drum IC rollers, a roller measurement system, global position system (GPS) radio/receiver/base station, infrared temperature sensors, and an onboard computer reporting system. GPS based mapping and optional feedback control help to overcome the drawbacks associated with conventional compaction such as identifying soft spots, achieving consistent roller patterns, and monitoring asphalt surface temperature and levels of compaction with adequate quality control or quality assurance (QC/QA). Cost-effectiveness of both compaction types was measured in terms of initial and roadway lifecycle cost based on the cost inputs received from South Korea and other published literatures. Roadway lifecycle cost was reported based on the improvement in in-place density, smoothness, and fatigue life. The results of this study showed that: (1) with IC an approximate 4.1% initial cost reduction can be achieved compared to conventional compaction; (2) QC/QA cost is found to have the most significant effect on the higher initial cost of conventional compaction compared to other associated costs whereas intelligent roller cost is the vital cost category for IC; (3) improvement of in-place air voids and density due to the IC has shown that at 97% field density (or at 3% air void content) the State Highway Agency can save approximately 44% over a 20-year service period; and (4) agency cost is observed to be reduced by approximately 62% with the IC method based on the 25-year analysis period due to the increase in fatigue life.

Keywords: intelligent compaction; conventional; initial cost; lifecycle cost

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1. Introduction

Conventional compaction is one of the vital methods to achieve a longer service period, especially for hot-mix asphalt (HMA) layers. However, there are some shortcomings with the conventional compaction process. Typically, in a conventional compaction method, a certain number of passes were used by a static or vibratory load to compact the material. As these rollers are controlled manually, it is difficult to achieve a uniform roller pattern which can cover an entire lane. A fixed number of passes cannot guarantee a uniform compaction level due to several critical issues such as non-uniform temperatures in HMA, degree of compaction, and changes in the underlying support. It is challenging to do any timely adjustments to overcome over-compaction or under-compaction problems because these problems are invisible to the roller operator sitting on a conventional roller. Ref. [1] mentioned that overcoming these long existing shortcomings is inevitable through the use of conventional compaction.

Intelligent compaction (IC) was invented in Europe for road construction in the late seventies and is still evolving today. IC involves a smooth drum vibratory roller installed with measurement/control system used as the concept of intelligent compaction. The measurement system includes the integration of an accelerometer, global positioning system

(GPS), and an on-board computer to an IC roller which allows for one-hundred percent compaction measurement of a highway versus less than one percent using conventional compaction measurement devices [2]. The information collected by the measurement system used to adapt the equipment performance continuously meets the required conditions and optimizes the compaction quality. The IC method controls different compaction parameters such as drum vibration, frequency, working roller distance, or impact distance through a reliable quality and interactive assurance system from the beginning of the construction project which helps to implement higher quality road construction. In the United States, over the past decade the IC method has been gaining momentum for measuring the soil and pavement compaction for road construction. Asphalt compaction is temperature and time dependent. IC is an obvious solution to ensuring that the entire asphalt overlay gets the correct amount of compaction effort. Using traditional rolling efforts, there are always some areas of the asphalt mat that do not receive total coverage. Additionally, the amount of these missed areas varies depending on roller operators' experience. However, even the most talented roller operators will leave some areas of the mat with an inadequate coverage. This creates places that will have less than optimum densities.

According to the Federal Highway Administration (FHWA), IC is defined as an improved compaction process using rollers equipped with an integrated measurement system including a highly accurate GPS, accelerometers, onboard computer reporting system, and infrared thermometers. The benefits of the IC technique are that with this advanced technique the critical factors such as roller passes and temperature are visible to roller operators with color-coded displays. As a result, a timely adjustment to the compaction pattern can be implemented which can ensure the potential to improve the quality and uniformity of asphalt layers [3–5]. In addition, IC has the potential to overcome the drawbacks of conventional QC/QA methods by covering 100% of the compacted area compared to the limited test spots in conventional compaction.

IC measurement value, which is known as intelligent compaction value (ICMV), can be used as an index to assess the stiffness and strength of the compaction of pavement at a certain depth. The ICMV mechanism is used to measure the vertical acceleration at the center of the vibrating drum and compute ICMV using various models and methods. This concept is simple and ingenious; measuring the properties of compacted materials during compaction enables real time compaction monitoring and control. In this method the roller drum exerts compaction force on the compacted materials and the compacted materials react the force back to the roller drum. The harder the compacted materials, the bigger the reactive force. The reactive force is captured by the accelerometer in terms of acceleration. Then, the control system processes the acceleration signals and computes ICMV (FHWA). As a result, this method can provide an instantaneous and complete evaluation of the compacted zone, remediate the weak spots, avoid the over-compaction, reduce the number of roller passes and conventional proof tests, and ensure a more uniformly compacted layer through providing a soil modulus at all locations where the roller passed. However, there are still challenges, such as the complex interaction between rollers and compacted materials, variances of field measurement due to major factors (roller vibration types, eccentric force, vibration amplitude and frequency, roller speed, asphalt mixture proportioning, asphalt mix temperatures and underlying support condition), and differences between ICMV and conventional spot tests.

To evaluate IC technology in the United States, 12 state DOTs and 15 demonstration projects were implemented. Based on the released specifications for IC technology applications for both HMA and soil by several state DOTs and agencies, it was reported that IC technology showed to provide compaction uniformity and therefore would improve QC in HMA compaction practices [6,7]. In order to find out the short-term and long-term cost-effectiveness, [8,9] performed a survey in which IC professionals participated. According to their survey, they reported that several DOTs were in the process of implementing or considering IC; however, the amount of data on costs is very limited. Ten respondents of the survey mentioned that an increase in initial construction cost was found in construction related costs when using IC, and this increase can be associated with the training for roller operators. However, long-term benefit and cost data were less available for this survey and only three DOTs have cost information. Texas mentioned that IC had higher benefits than costs, and other agencies are eager to assess the long-term cost benefit by other independent agencies. In another study, [10] concluded that an increased service life from using IC due to increased compaction uniformity resulted in USD 15,385 savings per year per 1.6 lane-kilometer. [1] also reported based on the four IC projects that an approximate 50% decrease in construction costs can be achieved due to the increased compaction uniformity and analysis for the projects; this should be investigated in future.

One of the main drawbacks is that the equipment is more expensive than ordinary rollers. According to FHWA, even though the IC roller can reduce the construction and maintenance cost, the insufficient benefit-cost data limit this claim. Other state DOTs and professionals also indicated the same concern in terms of initial and long-term cost-effectiveness. In order to collect substantial knowledge and address this concern of initial and long-term cost-effectiveness of IC and conventional compaction, a framework for a cost-effective analysis was adopted based on the cost inputs received from South Korea, agencies and other literatures. The consideration of the framework is based on one lane-mile with 3.6 m width and 5 cm (2-inch) thick asphalt overlay on an asphalt roadway section. Two specific cost cycles are considered: initial cost and roadway lifecycle cost. The difference between conventional and intelligent compaction types was analyzed and compared for each cost cycle.

2. Methodology

The methodology used for analysis considers initial construction costs and roadway lifecycle costs as two separate time periods and consideration. The framework used the following four terms to find out the objectives: (i) initial cost, (ii) roadway lifecycle cost, (iii) conventional compaction and testing, and (iv) IC compaction and testing.

Initial cost: The initial construction cost includes the construction cycle time period that begins with preparations for conducting roadway compaction. This consists of the costs of 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 of each 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.

Conventional compaction and testing: The QC/QA data of conventional compaction are obtained by using the roller which does not consist of on-board stiffness or density measuring devices. It is recorded through in situ field tests.

IC compaction: IC compaction includes the use of a device, such as an accelerometer, GPS unit, and on-board computer to aid roller operators in compaction efforts. QC/QA data are obtained from the roller and evaluated by a QC/QA technician or engineer [6].

The comparison between the two compaction methods comprises a summation of the costs from the two cost cycle periods which are initial construction cost and roadway lifecycle cost. The summed costs for each time period were compared to each other independently. A project type, size and costs were chosen from South Korea. The roadway project has implemented 5 cm (2-inch) thick overlay, one lane-mile asphalt overlay with a width of 3.6 m.

As mentioned earlier, QC/QA data for conventional compaction was obtained by in situ field tests whereas the use of accelerometer, GPS unit, and on-board computer were used to record the QC/QA data of IC.

The QC/QA costs are included to calculate the initial construction cost. The information for conventional compaction and testing were obtained by surveying contractors from their equipment and labor cost database. The calculation of QC/QA of conventional compaction cost is a function of hourly and unit area rate. The rate of QC/QA performance must be converted using a time per unit volume or area as given by Equation (1). Equation

(1) illustrates the equation to calculate the QC/QA cost. The length and width of the road by area calculated and unit cost per area for QC/QA was adopted from the literature. Then, the total time to perform the QC/QA, area of the road evaluated for QC/QA and cost per area to do the QC/QA are multiplied to get the total QC/QA cost. On the other hand, the cost of QC/QA of intelligent compaction is a function of the test section area. The test section area is used to calibrate the conventional testing methods/value such as nuclear gauge or core sampling with the IC measurement values (ICMV). The test section area often considered between 92 m to 183 m (300 to 600 feet) [2] and several DOT IC specifications [11]. The test section configuration of 152 m (500 feet) by 3.6 m (12 feet) was considered.

$$\text{QC/QA Cost} = (\text{Hours to perform QC/QA}) \times (\text{Area of QC/QA per hour}) \times (\text{Cost of QC/QA per area}) \tag{1}$$

2.1. Initial Construction Cost

Construction costs regarding roller equipment and roller operator for conventional compaction were gathered using pricing data from contractors in South Korea. The costs were set as an hourly rate by using the macadam (1st roller), pneumatic (2nd roller), and tandem roller (3rd roller). Additionally, the rate of compaction for construction crews and roller operator cost was also obtained from the contractors. This data input helps to calculate the total amount of time needed for the construction crew to complete the compaction work and 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. As Equation (2) illustrates, this total amount of compaction time is multiplied by the roller equipment and labor costs for conventional compaction and then added to the QC/QA cost.

$$\text{Initial construction Cost of CC} = (\text{Compaction Time in Hours}) \times [(\text{Roller Cost per Hour}) + (\text{Roller Operator Cost per Hour})] + [(\text{QC/QA Cost per Area}) \times (\text{Area})] \tag{2}$$

Initial construction costs for IC were calculated based on an amount of time to conduct roller operations and the cost of an IC roller. The IC roller cost was obtained from IC roller manufacturers. The test section area was determined, GPS cost was considered and used QC/QA cost also added into the amount of time needed for compaction using the IC roller. As it is shown in Equation (3), to calculate the initial construction cost of intelligent compaction the consideration of GPS cost per hours was included as the new variable compared to the initial construction cost of conventional compaction. The initial construction cost for IC compaction of the test area and the roadway section can be obtained as illustrated in Equation (3).

$$\text{Initial construction Cost of IC} = (\text{Compaction Time in Hours}) \times [(\text{Roller Cost per Hour}) + (\text{Roller Operator Cost per Hour}) + (\text{GPS Cost per Hour})] + [(\text{QC/QA Cost per Area}) \times (\text{Area})] \tag{3}$$

2.2. Roadway Lifecycle Cost

As mentioned in the literature, IC provides a more uniform compaction. Uniformity ensures the extended service life of asphalt pavement. In order to calculate the roadway lifecycle cost of IC and conventional compaction for a thick asphalt overlay, the cost per lane-mile per year was calculated by dividing the cost of roadway per lane-mile by the remaining service life of pavement in years as shown in Equation (4). Based on the earlier study it was reported that the service life of pavement by IC is increased by 2.6 times compared to the conventional compaction method due to the increase in fatigue life [12].

$$\text{Cost per lane-mile per year} = (\text{Cost of Roadway per Lane-Mile})/(\text{Service Life of pavement in Years}) \tag{4}$$

The calculation of two compaction methods comprises a summation of the costs from the two cost cycles over similar pavement lengths and roadway lifecycles cost.

The benefit from increased uniformity for the thick asphalt overlay contributed to increased fatigue life. Based on the data of WYDOT and other jurisdictions the average cost per lane-mile for thick asphalt overlay is approximately USD 250,000 [13]. In addition, the average service life of a thick asphalt overlay is assumed to be 10 years under conventional compaction methods. As a result, based on the study by [12], the service life of asphalt pavement overlay compacted by IC would be 2.6 times greater (or 26 years) than the pavement with conventional compaction method.

3. Results

3.1. Initial Construction Cost

3.1.1. Conventional Compaction (CC)

Estimated cost input data

Conventional roller cost per hour = USD 55;
Roller operator per hour = USD 36;
QC/QA per square meter = USD 0.04784;
Consider the cost per 1.6 lane-kilometer (1600 m/one lane-mile) and asphalt overlay is 2 inch (5 cm). Additionally, the width of the road is 3.6 m.
Conventional compaction hours/1.6 lane kilometer = 10 h;
Total conventional roller cost = USD 55 × 10 = USD 550;
Total roller operator cost = USD 36 × 10 = USD 360;
Total QC/QA cost = 1600 × 3.7 × 0.04784 = USD 283.21;
Total conventional compaction cost of 1.6 km lane = USD 550 + USD 360 + USD 283.21 = USD 1193.21.

3.1.2. Intelligent Compaction (IC)

Estimated cost input data

IC roller cost per month = USD 11,475;
Working hours per day = 8 h;
Total working hours in a month = 22 × 8 h = 176 h;
IC roller cost per hour = USD 11,475/176 = USD 65.20.
The unit cost for the IC roller was based on the cost per month of the roller (i.e., USD 11,475) divided by 176 work hours in a month. This was calculated using the assumption of 40 h per work week, or 8 hours per work day, and 22 work days per month. This yielded an hourly rate of USD 65.20 for the IC roller. The same method was used to calculate the hourly cost of the GPS unit at USD 0.85 per hour.

$$\text{Line Item Hourly Rate} = (\text{Line Item Cost/month}) \times (\text{One month/176 working hours}) \quad (5)$$

Roller operator per hour = USD 36;
GPS system rental per year = USD 1800;
GPS system rental per month = USD 1800/12 = USD 150;
GPS system rental per hour = USD 150/176 = USD 0.85;
QC/QA per square meter = USD 0.04784.
Consider the cost per 1.6 lane-kilometer (1600 m/one lane-mile) and asphalt overlay is 5 cm (2 inch). Additionally, the width of the road is 3.6 m.
IC needs to include the test section and lane (test section 152 × 3.6) and (lane 1600 × 3.6).
The area of the test section is 500 feet (152 m) by 12 feet (3.6 m) for QC/QA for IC. The remaining QC/QA is performed based on readings from the IC roller. Therefore, the total length of road section is 1752 m (1600 m + 152 m = 1752 m).
IC compaction hours = (10/1600) × 1752 = 10.95 h;
0% reduction in time = 10.95 h;
Total IC roller cost = USD 65.20 × 10.95 = USD 713.94;
Total roller operator cost = USD 36 × 10.95 = USD 394.20;
Total GPS cost = USD 0.85 × 10.95 = USD 9.31;
Total QC/QA cost = 152 × 3.7 × 0.04784 = USD 26.91;
Total IC compaction cost of 1.6 km lane = USD 713.94 + USD 394.20 + USD 9.31 + USD 26.91 = USD 1144.36.

From the above calculation, it can be observed that the initial cost of conventional compaction and intelligent compaction for overlay of an asphalt pavement were USD 1193.21 and USD 1144.36 per lane-mile, respectively. With IC compaction, a 4.1% reduction in cost can be achieved compared to conventional compaction. The reduction is mainly due to the lower cost in QC/QA for the IC compaction. Once the calibration is completed at the test section, there is no need to do in situ tests at the jobsite.

3.2. Roadway Lifecycle Cost

3.2.1. Case 1 (Fatigue Life Consideration)

As mentioned earlier, the service life of one lane-mile asphalt overlay was assumed as 10 years. The total cost per lane-mile of asphalt overlay was considered as USD 250,000. Therefore, the total asphalt overlay cost was divided by service life of 10 years to yield the annual cost for conventional compaction.

On the other hand, to calculate the annual cost of IC compaction, the total cost was then divided by 26 years as it was reported that IC compaction can increase the fatigue life of pavement by 2.6 times compared to the conventional compaction. For this study, the roadway lifecycle cost analysis was considered for a 25-year cycle period. After finding out the annual cost of both compaction methods, the annual cost was then multiplied by 25 years to find out the roadway lifecycle cost of a one lane-mile asphalt overlay road section.

Calculation:

Assuming the average overlay service life with conventional compaction is 10 years;

According to WYDOT, cost per 1.6 lane-kilometer thick asphalt overlay estimated to be = USD 250,000;

For conventional compaction pavement the cost per year = USD 250,000/10 = USD 25,000;

For IC compaction the cost per year = USD 250,000/26 = USD 9615;

For lifecycle cost analysis if we see the cost over a 25 year analysis period then;

Cost of asphalt overlay with conventional compaction = USD 25,000 $\times$ 25 = USD 625,000;

Cost of asphalt overlay with intelligent compaction = USD 9615 $\times$ 25 = USD 240,375.

From the above calculation, it can be observed that the roadway lifecycle cost of conventional compaction and intelligent compaction for overlay of an asphalt pavement over a 25-year analysis period were USD 625,000 and USD 240,375 per lane-mile, respectively. With IC compaction, a 62% reduction in cost can be achieved compared to conventional compaction. The reduction is mainly due to the increase of fatigue life with the IC compaction compared to the conventional compaction. Figure 1 presents the roadway lifecycle cost of conventional and intelligent compaction of asphalt overlay over its 25-year analysis period.

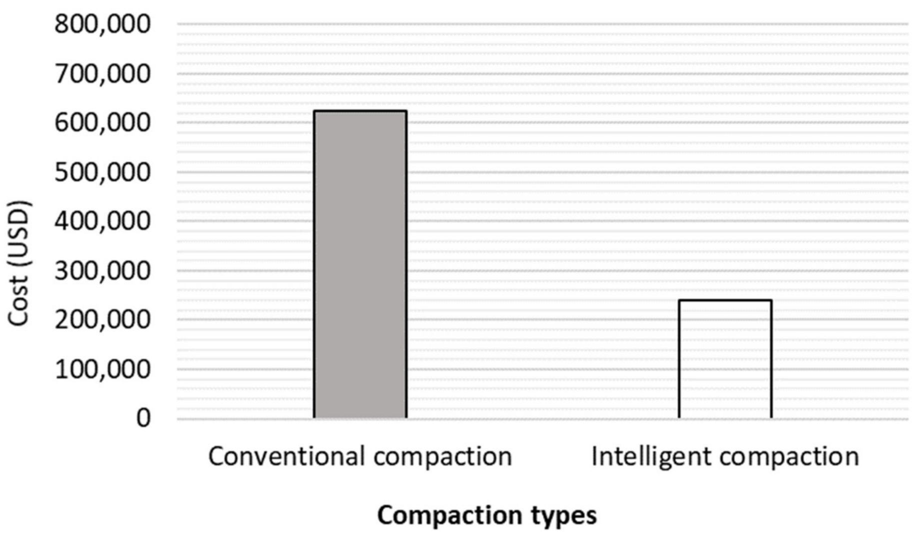

Figure 1. Roadway lifecycle cost of conventional and intelligent compaction.

3.2.2. Case 2 (Air Void Content Considering Unit Savings)

R. Bruce Noel stated at the 1977 annual meeting of the Association of Asphalt Paving Technologists (AAPT), "The single most important construction control that will provide for long-term serviceability is compaction." As the compaction is enhanced, in-place density can be optimized, and it helps to improve durability and extend the pavement service life.

Several past published studies clearly showed the effect of reduced air voids on improved fatigue and rutting performance of asphalt mixtures, both in the laboratory and field [14,15]. Fatigue performance improved between 8.2 and 43.8% with a 1% decrease in air voids. In addition, based on rutting results from WesTrack and laboratory flow number testing, rutting resistance is improved by 7.3 to 66.3% with a 1% decrease in air voids depending on mix type and analysis.

The results of a recent study conducted for the New Jersey Department of Transportation (NJDOT), which included data from 55 pavement sections, also suggest that a 1% decrease in in-place air voids increases asphalt mixture service life by (conservatively) 10%. In-place density is one of the most important factors that can significantly influence the long-term performance of an asphalt pavement [16]. A small increase in in-place density can potentially lead to a significant increase in the pavement service life. [17] found a correlation between in-place air voids and the service lives of asphalt overlays with in-place densities between 91 percent and 96 percent of the theoretical maximum density (G_{mm}), suggesting that a 1 percent increase in in-place density would extend the service life by 10 percent, or accordingly a 1 percent decrease in in-place density would reduce the service life by 10 percent.

They performed a lifecycle cost analysis (LCCA) over two asphalt overlays where one was constructed at 93% density and another at 92% density. They implemented the concept (1% increase in density extend the service period by 10%) and found that the State Highway Agency (SHA) would get a cost savings of USD 88,000 on a USD 1,000,000 paving project in term of net present value (NPV). That means 8.8% cost savings can be achieved by simply increasing the minimum required density by 1%. It is worth noting that this saving does not consider potential savings from other costs such as operation, maintenance, and road user costs.

According to [18], there is considerable evidence that dense graded mixes should not exceed 8 percent nor fall below 3 percent air voids during their service life. The reason is that if air voids fall below 3%, there will be inadequate room for expansion of the asphalt binder in hot weather. When the void content drops to 2% or less, the mix becomes plastic and unstable [16].

From the literature and aforementioned discussions, it is evident that the incorporation of IC increases the density of the asphalt pavement overlay which can significantly extend the service life of pavement, and at the same time has the potential to increase the savings of the agency.

In order to find out the potential cost savings by implementing IC over conventional compaction the study considered the following assumptions:

(i) The pavement compacted with conventional compaction has a density of 92%.
(ii) The traditional service life of asphalt pavement overlay compacted with conventional compaction is 20 years.
(iii) The cost for asphalt overlay for both compactions at the end at 92% air void are considered the same, at USD 500,000.
(iv) To understand the cost savings due to in-place density with IC the study considered five density scenarios: 93%, 94%, 95%, 96%, and 97% based on the previously mentioned reasoning, as air void should not drop below 3%.

For conventional compaction at 92% compaction the cost after 20 years is assumed to be USD 500,000.

IC compaction cost saving at 93% density:

The annual cost = USD 500,000/20 = USD 25,000;

Being as the 1% increase in air void can decrease the construction cost by 8.8%;

Therefore, the annual cost reduction = USD 2200;

Annual cost of asphalt overlay at 93% density = USD 25,000 – USD 2200 = USD 22,800;

The total cost of asphalt overlay at 93% density = USD 456,000.

Table 1 presents the cost reduction that can be achieved with IC as a function of air void.

Table 1. Cost savings with IC over CC as a function of air void.

Air Void Rate/Density	Conventional Compaction	Intelligent Compaction	Cost Savings
92%	USD 500,000	USD 500,000	USD 0
93%	USD 500,000	USD 456,000	USD 44,000
94%	USD 500,000	USD 412,000	USD 88,000
95%	USD 500,000	USD 368,000	USD 132,000
96%	USD 500,000	USD 324,000	USD 176,000
97%	USD 500,000	USD 280,000	USD 220,000

Figure 2 shows the cost savings with IC as a function of improved density.

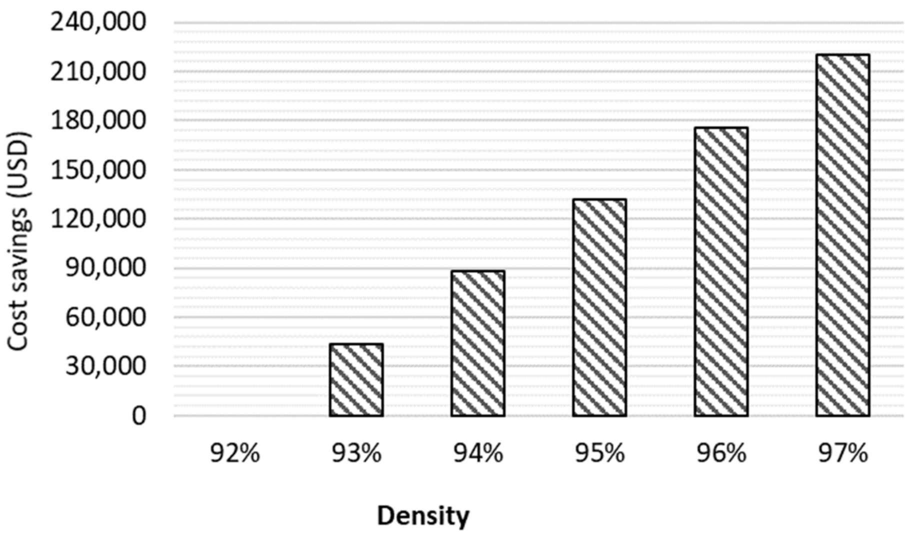

Figure 2. Cost savings with IC due to improved density.

3.2.3. Case 3 (Air Void Content Considering Rutting and Fatigue Performance)

As mentioned earlier, a review of several past studies clearly showed the effect of reduced air voids on improved fatigue and rutting performance of asphalt mixtures, both in the laboratory and field. Depending on mix type and experiment (rutting and fatigue results from WesTrack and laboratory flow number testing), they showed that on an average 37% and 26% of pavement life extension can be achieved due to rutting and fatigue resistance, respectively, with the reduction of 1% of air void content.

In order to find out the potential cost savings by IC due to the reduction of air void content and improvement on rutting and fatigue performance of the pavement life the study considered the following assumptions:

(i) The pavement compacted with conventional compaction has a minimum air void content of 8%.

(ii) The traditional service life of asphalt pavement overlay compacted with conventional compaction is 20 years.

(iii) The cost for asphalt overlay for both compactions at the end at 8% air void content is considered the same, at USD 500,000, so the annual cost for compaction is USD 25,000.

(iv) To understand the cost savings due to rutting and fatigue improvement with IC compared to conventional compaction the study conducted a simple calculation and varied the air void content from 8% to 3%.

Tables 2 and 3 present the cost reduction that can be achieved with IC as a function of rutting and fatigue resistance improvement due to percentage decrease of air void content.

Table 2. Cost reduction that can be achieved with IC as a function of rutting improvement.

Air Void	Pavement Life Extension (by Percentage)	Conventional Compaction (Constant Pavement Life)	Intelligent Compaction (Savings of Pavement Life)	Conventional Compaction Cost (Annually)	IC Cost Saving Due to Rutting
8%	0%	20 years	0 years	USD 25,000	USD 0
7%	37%	20 years	7.4 years	USD 25,000	USD 185,000
6%	74%	20 years	14.8 years	USD 25,000	USD 370,000
5%	110%	20 years	22 years	USD 25,000	USD 550,000
4%	147%	20 years	29.4 years	USD 25,000	USD 735,000
3%	184%	20 years	36.8 years	USD 25,000	USD 920,000

Table 3. Cost reduction that can be achieved with IC as a function of fatigue improvement.

Air Void	Pavement Life Extension (by Percentage)	Conventional Compaction (Constant Pavement Life)	Intelligent Compaction (Savings of Pavement Life)	Conventional Compaction Cost (Annually)	IC Cost Saving Due to Fatigue Cracking
8%	0%	20 years	0 years	USD 25,000	USD 0
7%	26%	20 years	5.2 years	USD 25,000	USD 130,000
6%	52%	20 years	10.4 years	USD 25,000	USD 260,000
5%	78%	20 years	15.6 years	USD 25,000	USD 390,000
4%	104%	20 years	20.8 years	USD 25,000	USD 520,000
3%	130%	20 years	26 years	USD 25,000	USD 650,000

Figure 3 illustrates the cost saving with IC due to rutting and fatigue improvement.

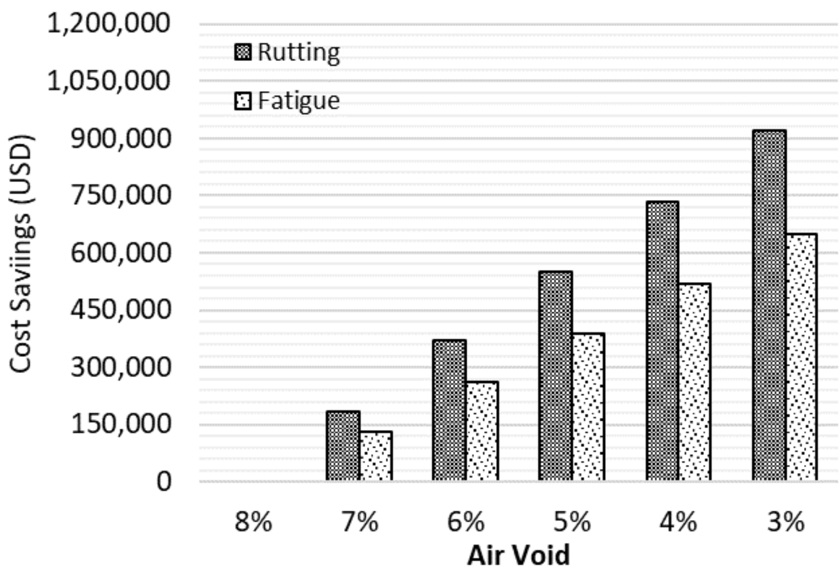

Figure 3. Cost savings with IC due to rutting and fatigue improvement.

3.2.4. Case 4 (Smoothness Consideration)

Smoother pavement provides user comfort and ensures efficient movement of vehicles. Initial smoothness is directly related to long-term roughness and average annual road maintenance costs. Roughness is an important pavement characteristic because it affects not only ride quality but also has a direct relationship with vehicle operating costs, fuel consumption and maintenance costs. It creates safety hazards, generates complaints from highway users, and causes vehicle damage. The Kansas Department of Transportation reported that smoother pavement requires less maintenance due to less dynamic loading from truck traffic, which can save maintenance costs up to USD 10,000 per mile the first year and at the same time IS an increase in savings for the life of pavement. Several studies conducted by FHWA, the National Cooperative Highway Research Program (NCHRP) and the National Asphalt Pavement Association (NAPA) found that pavement lasts longer when built smoother. This can be understood, as rougher pavement results in more dynamic loading and subjects the pavement to endure much heavier loads than it was designed for, resulting in wearing it out faster. According to NCHRP 1-31 research, 50% increase in pavement smoothness can result 15% increase in pavement life [19]. Compaction is one of the main factors that affect smoothness, and IC ensures consistent roller pattern, working speed, coverage, and temperatures compared to the conventional compaction.

From the literature and aforementioned discussions, it is evident that implementation of IC can increase the smoothness of the pavement significantly compared to the pavement compacted with conventional compaction.

In order to find out the potential cost savings by IC from the smoothness point of view the study considered the following assumptions:

(i) NCHRP estimated that a 15% increase in pavement life can be assured by having a 50% increase in smoothness. As a result, it can be deduced that for every 10% increase in smoothness, the pavement life can be increased by 3%.
(ii) The traditional service life of asphalt pavement overlay compacted with conventional compaction is 20 years.
(iii) The cost for asphalt overlay for both compactions at the end at 0% smoothness is considered the same, at USD 500,000, so the annual cost for compaction is USD 25,000.
(iv) To understand the cost savings due to smoothness with IC compared to conventional compaction the study conducted a simple calculation and varied the smoothness achievement of IC ranging from 0% to 100% with an interval of 10%.

Table 4 presents the cost reduction that can be achieved with IC as a function of smoothness.

Table 4. Cost reduction that can be achieved with IC as a function of smoothness.

Smoothness Increase	Pavement Iife Extension (by Percentage)	Conventional Compaction (Constant Pavement Life)	Intelligent Compaction (Savings of Pavement Life)	Conventional Compaction Cost (Annually)	IC Cost Saving Due to Smoother Pavement
0%	0%	20 years	0 years	USD 25,000	USD 0
10%	3%	20 years	0.6 years	USD 25,000	USD 15,000
20%	6%	20 years	1.2 years	USD 25,000	USD 30,000
30%	9%	20 years	1.8 years	USD 25,000	USD 45,000
40%	12%	20 years	2.4 years	USD 25,000	USD 60,000
50%	15%	20 years	3 years	USD 25,000	USD 75,000
60%	18%	20 years	3.6 years	USD 25,000	USD 90,000
70%	21%	20 years	4.2 years	USD 25,000	USD 105,000
80%	24%	20 years	4.8 years	USD 25,000	USD 120,000
90%	27%	20 years	5.4 years	USD 25,000	USD 135,000
100%	30%	20 years	6 years	USD 25,000	USD 150,000

Figure 4 shows the cost savings with IC due to smoothness improvement.

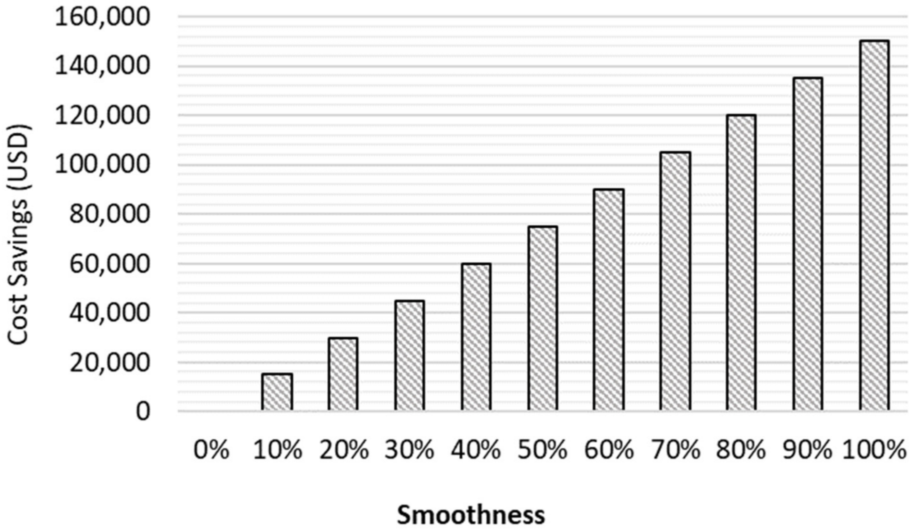

Figure 4. Cost savings with IC due to smoothness improvement.

4. Conclusions

This study was conducted to evaluate the cost-effectiveness between conventional compaction and intelligent compaction to construct asphalt pavement overlay. Potential cost factors were identified, recorded and analyzed for both compaction types to find out the initial and roadway lifecycle cost upon the data obtained from South Korea and other published literatures. Based on the results of the study, the following conclusions can be drawn:

(1) According to the published literature review and industry professionals the overall study on the cost-effectiveness between conventional and intelligent compaction methods is limited.
(2) The initial construction cost of conventional compaction is higher compared to intelligent compaction. Based on the results of the cost input, conventional compaction is approximately 4.1% higher than the intelligent compaction.
(3) With conventional compaction the cost factor that increases the initial construction cost is the QC/QA of the asphalt pavement overlay, whereas intelligent compaction has the lowest cost on QC/QA due to its initial calibration done on the test section.
(4) With IC compaction the cost of the intelligent roller plays a vital role on the initial construction cost, as the cost of the intelligent roller is higher than the conventional roller.
(5) Roadway lifecycle cost is measured based on the consideration of fatigue life and air void content. In both cases, it was found that IC can significantly reduce the agency cost compared to conventional compaction.
(6) Based on the 25-year analysis period, the agency cost can be reduced by approximately 62% per lane-mile compared to conventional compaction due to the increase of fatigue life with IC method.
(7) Based on the 20-year analysis period, significant cost saving for the agency was found on both cases considering the pavement life extension due to an increase in density and smoothness. Asphalt pavement overlay constructed at 97% field density (or at 3% air void content) using IC construction can help the agency to reduce the cost by approximately 44% compared to conventional compaction.

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