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Life Cycle Cost Evaluation of Alternatives to the Nuclear Density Gauge for Compaction Testing on Design-Build Projects

Kevin W. McLain, PhD, PE, MASCE [1] and Douglas D. Gransberg, PhD, PE, MASCE [2]

ABSTRACT

When Missouri Department of Transportation (MoDOT) implemented design-build (DB) contracting, it revised its quality assurance program and shifted most of the compaction testing to the design-builder. As a result, fewer compaction tests were performed by state personnel and the need for speedy quality control testing by the agency to facilitate construction production disappeared. This paper reports the results of a study conducted by the Department to evaluate three alternatives to the Nuclear Density Gauge (NDG) using life cycle cost analysis and cost index number theory. The study’s objective was to investigate alternative soil compaction test devices and provide input to a decision regarding whether or not MoDOT should retain or replace the NDG. Despite the NDG successful track record, the ease of employment and speed with which the compaction results are delivered comes with a price in terms of life cycle costs. The NDG is regulated by the Nuclear Regulatory Commission and entails an onerous, on-going administrative workload to permit its continued use. The NDG also incurs additional certification, storage and disposal costs, not found in non-nuclear compaction testing alternatives. This paper reports the results of a life cycle cost (LCC) analysis of NDG and three alternatives: dynamic cone penetrometer (DCP), electrical density gauge (EDG) and the sand cone (SC). The study finds that the SC and DCP are the most cost effective but are the least cost effective when measured on a basis of timely results. Thus, the NDG replacement/retention decision becomes one of how fast are compaction tests required by the agency.

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[1] Geotechnical Director, Missouri Department of Transportation, Construction and Materials Division, Jefferson City, MO, 65109, E-mail: kevin.mclain@modot.mo.gov

[2] Donald and Sharon Greenwood Chair of Construction Engineering, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, 494 Town Engineering Building, Ames, Iowa, 50011. E-mail: dgran@iastate.edu

Since MoDOT has adopted contractor acceptance testing in its DB program, it now only conducts verification testing of contractor test results. Thus, the paper recommends that the NDG be replaced.

KEYWORDS

Life Cycle Costs; Soil Compaction Testing; Nuclear Density Gauge; Quality Assurance; Quality Control

INTRODUCTION

Design-build (DB) project quality assurance (QA) programs require that an owner revise its traditional design-bid-build (DBB) QA process to account for the fact that the design-builder is providing the project's final design (Gad et al. 2015). Project delivery is often modeled as a three-legged stool where the legs are cost, schedule, and quality (Chan 2013; Goetsch and Davis 2014; Karlen et al. 1997). DBB quality is defined by the construction documents upon which construction contractors can bid (Ellis et al, 1991), the time is specified by the contract completion date, leaving cost as the only variable leg of the stool to ensure a level platform (Ellicott, 1994). Thus, DBB project delivery is a "system where the constructor tells the owner how much it will cost to deliver the quality defined in the design within the specified period of performance" (Gransberg et al 2006). DB procurement normally demands that lump sum price be offered by the design-builder with scope being established within a collection of performance criteria and a specified performance period (Ernzen and Feeney 2002). This leaves quality as defined during the design process as the variable leg in the DB stool.

As shown above, the design-builder is now in a position where the resultant level of quality is now a function of both the fixed price and the contract schedule. Therefore, a successful design-builder must produce a final design that can be built inside the cost and time constraints, and the owner must not allow its QA program to impede progress without a solid, defendable reason. The issue is exacerbated by the increased pace that usually accompanies a DB project (Stefani 2004), creating an environment where delay claims can become extremely expensive (Kandell 2014). This issue led MoDOT and other state DOTs to adopt the use of contractor acceptance testing (Smith 2001; Turochy et al. 2007) as described in a Federal Highway Administration (FHWA) Technical Advisory

6120.3 (2004). The overall impact is that the owner has transferred some of its traditional QA field testing responsibilities to the design-builder and no longer needs as large a component of in-house inspectors and testing equipment on DB projects (Ernzen and Feeney 2002).

The results of the shift to verification testing on DB projects for were so promising that in 2013 MoDOT adapted its DB QA program for use in its traditional DBB projects. In doing so, it made the construction contractor responsible for the bulk of the QA/QC field testing on MoDOT construction projects (Ahlvers et al. 2013). On projects involving large structural fills, achieving the specified compaction is the key quality function that must be properly deployed for the project to perform as intended over its service life (Arditi and Lee 2004). The nuclear density gauge (NDG) has been the tool of choice for both MoDOT and its contractors because it is easy to employ and gives immediate feedback on site.

The QA policy change shifted the compaction performance risk to the contractor, reducing the number of field compaction tests conducted by MoDOT inspectors. The upshot was that MoDOT inspectors no longer needed compaction test results as quickly as it did in the 1980s when the NDGs were originally fielded. The impact of the switch from using MoDOT NDGs for front-line QC tests where timeliness of compaction test results could drive contractor production to a QA verification role removed timeliness as a critical characteristic for in-house compaction testing. While this paper is not arguing that timely verification of the accuracy of contractor test results is no longer important, the shift in roles removed failing MoDOT test results as a potential barrier to progress and reduced the need for speed in compaction test results. Put another way, if the MoDOT QA verification test results do not correlate with the contractor’s QC results, the discrepancy has become a contractual problem where before timely test results were a production problem.

Research has established that when given a choice testing techniques, engineers generally choose the option that involves the highest level of technology (Schein 1996). However, enhanced technology comes with a cost, and the additional life cycle cost increment must be justified by a corresponding increase in value. Therefore, the primary research questions investigated in this study are as follows:

- Do the benefits of easy employment and speedy test results provided by the nuclear density gauge (NDG) justify its life cycle cost for MoDOT projects?
- Are there alternatives to the NDG that provide a better value?

Background

The Missouri Department of Transportation (MoDOT) has been using the NDG as its primary technology for compaction testing for nearly 35 years, and currently has nearly 56 units distributed across its 7 districts. The NDG has been found to have the following primary benefits:

- Speed for obtaining the results.
- Requisite level of precision.
- Portable and compact.
- Measure both moisture and density.

Given the role change and the need to conduct considerably fewer tests, MoDOT decided to re-evaluate its use of the NDG in light of the large number of administrative requirements for training, certification, calibration, storage, and hazardous waste disposal that form the NDG's administration and logistics tail. While its benefits are well documented, the department began to question whether they provided adequate value for money. The Virginia DOT defines value for money (VfM) as: "A project is said to have positive VfM when, relative to other procurement options, it is forecast to deliver and/or is demonstrated to have delivered the optimum combination of life cycle costs and service quality that will meet the objectives of the project" (VDOT 2011). It is important to note the dual metrics of "life cycle costs and service quality."

Life cycle cost analysis (LCCA) and cost indices are tools used to quantitatively evaluate a product or process (Riggs and West 1986). Pittenger et al. (2011) maintain that "…LCCA [can be used] to determine cost effectiveness and return on investment … [for] transportation decision-making … in transportation." LCCA relates the initial capital costs of investment along with the long-term usage costs of the product or process. Cost indices were first proposed by Riggs and West

(1986) and provide a means to permit the engineer to measure the “bang for the buck.” One study says that cost index number theory “seeks to combine cost and engineering measurements into a single index that can permit the direct comparison of two or more alternatives simultaneously and thus provide a measure of cost effectiveness on an engineering property basis… [and] compare a more expensive technology with a less expensive technology to determine if the incremental cost difference between the two alternatives is offset by enhanced engineering performance” (Gransberg and Zaman 2005). Thus, using both metrics to evaluate potential alternatives provides the analyst with two independent measures with which to compare the costs and the benefits of several alternatives over their services lives while including a measure of return on investment in engineering terms. Hence the use of LCCA and cost indices provides a similar set of evaluation criteria for the NDG and its technical alternatives.

In the past, MoDOT has used both LCCA and cost indices sparingly when evaluating technical alternatives for QA and QC testing for embankment and roadway construction. Each past investigation was limited to a single option and often the decision to not replace the NDG was a function of finding a more pressing requirement for the available funds. In a nutshell, the justification to expend the funds to replace a technology that is performing satisfactorily and is already available must be compelling if there are other unfulfilled requirements competing for the same block of funds. Therefore, MoDOT commissioned this study to make a comprehensive analysis on virtually all alternatives is using LCCA and cost indices as the evaluation tool in the investigation effort. The methodology described in the next section is designed to focus on VfM rather than merely capital costs. Therefore this paper reports the results reached in determining viable alternative testing methods for soil compaction in roadway and embankment construction.

Compaction Testing Alternatives

There are three classes of compaction measuring devices or tests. The three classes and the possible alternatives in each class are as follows:

- Density and Moisture Gauges

    - Nuclear Density Gauge (NDG)
    - Electrical Density Gauge (EDG)
    - Soil Density Gauge (SDG)
- Volume Replacement/Volume Measurement
    - Sand Cone (SC)
    - Density Drive Sampler (DDS)
- Stiffness/Modulus Measurement
    - Light Weight Deflectometer (LWD)
    - Dynamic Cone Penetrometer (DCP)
    - Electronic DCP (DCP-E)

This paper evaluates one alternative from the three different classes. It should be noted that the paper reports the results of the pilot test for a larger study that will eventually evaluate all the alternatives shown above. Table 1 describes three alternatives under investigation along with each option's advantages and disadvantages.

Table 1. Summary of Comparisons of Commonly Used Alternatives and the NDG

	NDG	**EDG**	**SC**	**DCP**
Measurement Method	A retractable probe is lowered into the soil through a pre-drilled hole. The probe emits gamma radiation though the tested soil and then to detectors in the gauge to measure density. Moisture measurement is done through a neutron source and detector located inside the gauge.	Measures the electrical dielectric properties and moisture levels of compacted soil using high, radio frequency traveling between darts driven into the soil being tested.	Uses premeasured container of sand to fill excavated hole in soil. The volume of used sand is determined. The moisture content of the removed soil is determined by other methods.	Operates by dropping an 8 kg mass a height of 575 mm (22.6 in). Impact causes the probe to be driven in the ground. A dynamic Penetration Index (DPI) is giving in units of mm/blow and is recorded versus depth
Advantages	1. Quick measurements for both density and moisture. 2. Portable.	Portable and lightweight.	Apparatus, accessories and consumables are inexpensive.	1. Simple to use with minimal required training 2. Standard unit relatively inexpensive. 3. Electronic DCP can be operated by one person

Disadvantages	1. Must be licensed by the NRC. 2. Operators must go through initial training and annual recertification. 3. Special storage requirements. 4. Hazardous material disposal requirements.	Must be calibrated against other compaction testing device with a minimum of five testing points but for better correlation need 8 points or more.	1. Destructive test. 2. Can be time consuming. Moisture determination done in separate second step. 3. Hard to use in base material, rocky soil, and very soft plastic soils. 4. Operator technique may impact the test results.	1. Hard to use in gravelly soils. 2. DCP needs to be operated by two person team. One to stand up the device and apply loads the other to read the side scale. 3. Moisture determination done in separate second step.

The most obvious difference is the requirement for specialized training and recertification necessary when using the NDG. It was this issue that provides the motivation for the study. While all other options to perform compaction testing require initial training, NDG is the only one that is regulated by the US Nuclear Regulatory Commission (NRC). Additionally in the words of one author:

> “The nuclear density gauge is the main device used for measuring the field density of compacted layers of unbound materials. However, the use of this device entails extensive regulations and prohibitive costs associated with its handling, storage, calibration, and maintenance and the transportation of radioactive materials.” (Nazzal 2014).

The same study reported that a survey of US DOTs and Canadian Ministries of Transportation found that “the majority were interested” in finding non-nuclear methods to measure compaction, largely because of the administrative and logistics issues associated with the NDG. MoDOT was one of those DOTs, and the remainder of this paper will detail the analysis of the NDG against the EDG, SC, and DCP on a LCC basis to determine the relative cost effectiveness of each alternative.

Life Cycle Cost Analysis Fundamentals

Barringer and Weber (Barringer and Weberl 1996) state that LCCA is not an exact science and researchers and statisticians will get different answers using similar sets of data. The differing answers are neither wrong or right only reasonable or unreasonable. LCCA estimates are never as accurate as their inputs, but with reasonable inputs and good judgment, LCC allows for examining costs and comparing competing methodologies. The FHWA encourages the use of LCCA for the comparison of alternatives in the design, construction and maintenance of all types of transportation assets (*9*,*10*) In essence LCCA is a mechanism whereby a public agency can justify purchasing an alternative that is not the lowest initial cost. In other words, LCCA allows the agency to quantitatively demonstrate to the taxpayer that the agency is making purchasing decision that provides good VfM. Thus, it is logical to look compare alternatives for measuring compaction using LCCA.

The underlying foundation of LCCA involves discounting all the costs and benefits during an alternative's service life to a single point in time where they can be compared (Beatty 2002). FHWA encourages the use of present value analysis (Walls and Smith 1998), which in the opinion of one author is an analog for the lowest bid, a decision criterion that permeates the public construction sector (Gransberg and Scheepbouwer 2010). However, there is an emerging opinion that since most public agencies receive funding on a fiscal year by fiscal year basis that Equivalent Uniform Annual Cost (EUAC) is a more appropriate approach since it reflects the annual impact on the agency budget (Pittenger et al. 2011). To apply LCCA to the comparison of compaction measurement alternatives, the following input parameters had to be determined:

1. The annual costs incurred by the system and/or mandated by regulations or testing standards.
2. The life of a method or system under average testing conditions.
3. The appropriate interest rate.

Water Environment Research Foundation's (WERF) Life Cycle Cost Tool specifies that the following typical costs be included in the analysis (WERF 2011):

- Acquisition Costs
- Operating Costs – cost for repairs, and spares
- Maintenance Costs – corrective, preventative, and predictive
- Disposal Costs

Inputs can be either deterministic or probabilistic, especially for costs related to operation and maintenance cost for a system. The authors placed initial and annual costs of each of the four compaction testing alternative into the following eight categories:

- Purchase Price (P)
- Annual Training Cost (T)
- Consumables (C)
- Disposal Costs (D)
- User Cost (U)
- Annual Calibration and Verification Costs (V)
- Storage Costs (S)
- Licensure Costs (L)

Fundamentals of Cost Index Number Theory

Cost index number theory is essentially a variation of classic utility theory (Riggs and West 1986). This theory permits the analyst to calculate a unit cost of quality for use in financial decision-making. In a nutshell, to be viable an alternative must furnish an increase in quality that is greater than its increase in cost. In layman's terms, to be adopted for use the alternative must give "more bang for the buck." This is particularly useful if the new technology turns out to be marginally more expensive than the traditional technologies. Thus, the analyst furnishes a justification for spending a bit more money up front to receive a commensurately better final product. This type of analysis is founded on life cycle cost fundamentals and is particularly applicable to public transportation projects (Aktaş et al. 2011).

An important aspect of cost index number theory that must be understood is its ability to establish relative relationships between alternatives. If one relies only on bottom-line dollar values to make management decisions, the decision-maker is disregarding the relative qualitative merits of each alternative (Pittenger et al. 2012). Therefore, the end-user of a construction project will always be given the minimum level of quality. This attitude is deeply ingrained in organizations like MoDOT who are required by law to award construction projects to the lowest bidder. In the low-bid paradigm, the engineer specifies the minimum level of quality in the plans and specifications. The construction contractor bids the cost of delivering the minimum level of quality and the inspector checks to make sure the minimum level of quality is received in the final product. The "minimize initial cost" without regard to quality mentality can permeate an organization's business practices. Cost index numbers provide a means to take a longer term approach to technical decision-making while retaining an objective decision-making criterion based on quantifiable parameters. Therefore, the challenge to the engineering analyst is to accurately portray the qualities of each alternative in a quantitative fashion that allows costs to be associated with those qualities that best describe the differences in alternatives.

A cost index number portrays the cost required for acquiring, maintaining or constructing a product, as measured in money, resources or time. A cost index is usually given as a ratio of cost per unit of measure and is a useful parameter that can assist in comparing alternatives for compaction test devices with regard to the long-term cost effectiveness of each option.

Replacing the NDG promises to reduce the administrative workload to manage the NRC training and certification requirements. MoDOT spends many precious dollars each year to meet NRC requirements regarding the use, storage and disposal of NDGs, and replacing it permits those resources to be applied elsewhere. As a result, it is important to prove that a non-nuclear compaction testing alternative does indeed deliver a product whose quality is commensurate with its LCC. The product of a compaction test can be measured in terms of how long it takes to complete a test and the time between test completion and the availability of results. Thus, times associated with each alternative’s procedure create a means to quantify its value. Additionally, the cost to the state for each test is another measure. In this case, Equations 1 and 2 below were used to develop cost indexes to measure the cost effectiveness of each compaction test device.

Time/Cost = Average time to perform test in minutes /EUAC cost for each device Eq. 1.

Cost/Test = EUAC cost for each device/ average annual number of tests Eq. 2.

Previous Study Analysis

A similar study was conducted by Cho et al. (Cho et al. 2011) used a LCC cost comparison over the assumed fifteen year useful life of an NDG and compared the annual ownership cost for the NDG with the cost of the Pavement Quality Indicator (PQI) for measuring asphalt pavement densities. The NDG measures density for both asphalt pavement and soil. Therefore, Cho et al. used the average cost of the LWD and EDG for the soil density measurements to create a comparable utility. In essence, they evaluated the possibility of replacing the NDG with two other devices. The pricing assumptions (Cho et al., 2011) made for the NDG and for the PQI, LWD and EDG are shown in Table 2. The results of this study are shown in Figure 1.

Table 2. LCC Singular Device Comparison From Cho et al., (Cho et al. 2011).

Ownership Cost	**NDG**	**LWD**	**EDG**	**PQI**
Initial Cost	$6950	$8675	$9000	$8200
Radiation and Cert. Class	$750	0	0	0
Safety Training	$179	0	0	0
Hazmat Cert.	$99	0	0	0
RSO Training	$399	0	0	0
TLD Badge Monitoring	$140/yr	0	0	0
Maintenance and Calibration	$500/yr	0	0	$500/yr
Leak test	$15	0	0	0
Shipping	$120	0	0	0
Radioactive Materials License	$1600	0	0	0
License Renewal	$1500/yr	0	0	0
Reciprocity	$750	0	0	0

In Figure 1, one can see the initial costs for the NDG is lower than those of the PQI plus average density device. However, after the fourth year, the NDG’s LCC surpasses the PQI + average of non-nuclear gauges. Thus, the decision to replace the NDG appears to be warranted. The remainder of the paper will detail a similar analytical approach for the same decision in Missouri.

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Figure 1. Break Even LCC Comparison From Cho et al. (Cho et al. 2011)

METHODOLOGY

The study used two primary research instruments to collect the necessary data to provide input to the analysis. It also entailed a pilot test to validate the approach to the LCCA and the cost index number analysis. The first research instrument was a survey of all MoDOT project offices where NDGs are stationed. The second instrument was a structured interview of MoDOT resident engineers, construction inspectors, laboratory technicians and most importantly, radiation safety officers (RSO) who have the responsibility to oversee the NDG training, certification, and operations. The interviews were used to collect actual cost data on the NDGs currently in deployed throughout the state and verified by checking equipment purchase invoices and other data maintained in the MoDOT central office in Jefferson City.

Data Collection Methods

Data collection and gathering of hard numbers was considerably easier for the NDG (MoDOT standard compaction testing device) because of existing records, experience, requirements and procedures. Records for NDG usage were readily available from required sign-out/check-in registers maintained at the project offices. The MoDOT RSO provided costs for NDG devices, calibration costs and frequency as well as the costs to dispose of spent nuclear material. Costs for testing alternatives and consumables came from invoices for purchased items or from the producers or distributors of rented or borrowed devices.

Simple time and motion studies were run in the field for each alternative method as it was applied during normal usage. Times were collected in the same location by the same technicians on the same portion of compacted fill. The results of the time and motion studies were validated by other agencies that use or routinely use the alternative devices for compaction testing that MoDOT is considering adopting.

NDG field usage was determined by the project office survey mentioned above. The questionnaire was developed from the literature review and assembled in accordance with the protocol established by Oppenheim (Oppenheim 1992). The questionnaire was sent to all 29 project offices to gather information on amount of usage. The questionnaire asked the respondents to determine two usage rates: during the construction season (March to November) and during the construction off season (November to March). Nineteen of the 29 project offices returned the survey, which yields a 66% response rate. The summary of the responses are shown in Table 3. From the project office survey, the following results were obtained:

- Average number of times NDG used per week during construction season: 1.16 times
- Average time NDG used per week during construction season: 1.26 hours
- Construction season: 8 months = 32 weeks
- Total Average NDG usage: 37 times each construction season.

- Total duration: 46.65 hours per office
- 29 Project offices
- Total annual duration for MoDOT= 1353 hours

Table 3. Nuclear Gauge Usage from MoDOT Project Offices for 2013.

Project Office	**District**	**Number of gauges**	**Usage per week during construction season**	**Duration of testing period construction season (hrs)**	**Usage per week during off season**	**Duration of testing period during off season**
St. Joseph	NW	2	2	Unknown	1	Unknown
Chillicothe	NW	2	2	Unknown	0	0
Maryville	NW	2	7	Unknown	0	0
Troy	NE	3	0.25	Unknown	0	0
Hannibal	NE	3	0.75	Unknown	0	0
Nashua	KC	2	3	1	0	0
Marshall	KC	2	0.5	0.5	0	0
Lee Summit	KC	3	1	0.5	0	0
St. James	CD	1	0.25	0.33	0	0
Jefferson City	CD	2	5	1	0	0
Camdenton	CD	1	0.25	1	0	0
Columbia	CD	2	2	Unknown	0	0
Chesterfield	SL	1	0.1875	Unknown	0	0
Clinton	SW	1	0.5	Unknown	0	0
Branson *	SW	0	0.1	Unknown	0	0
Joplin	SW	2	0.367	Unknown	0	0
Jackson	SW	2	0.5	2	0	0
Poplar Bluff	SE	2	1	4	0.5	2
Willow Springs	SE	2	0.03	1	0	0
*Branson uses the Springfield Project Office Nuclear Gauges						

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LCCA Assumptions

In determining EUAC for the alternative soil compaction test devices, a number of assumptions had to be made since the systems being evaluated that are not currently in standard use with MoDOT. The major assumptions are as follows:

- Two test devices are to be assigned to the project offices in the same manner as the nuclear density gauges. This assumption is very conservative as the possibility exists that after the contractors take over the much of the compaction testing responsibility, MoDOT may not need both devices.
- Since an average of 37 compaction tests using the NDG were run by each project office in the 2013 construction season, the same number of tests for the alternative test methods was assumed.
- The costs associated with personnel time and transportation to receive the required calibration procedures was not included.
- No residual value for the equipment was assumed at the end of its useful life.
- Training costs and times were assumed to be constant for each testing alternative. While these times and costs should decrease over the lifetime of the device, they are also dependent on personnel turnover in the project offices.
- Construction inspectors and construction technician currently conducting NDG tests would be conducting compaction tests using possible alternate devices for the NDG.

Life Cycle Cost Analysis Results

The life cycle cost results expressed as the EUAC for the NDG and competing alternative testing devices are shown in Figure 2. The EDG was the most expensive to own and operate over its life cycle followed by the NDG. The DCP and the SC had EUACs lower than the NDG.

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Figure 2. EUAC to MoDOT for Each Compaction Testing Device.

The cost comparison shows the fifteen year cost for owning and operating nuclear gauges costs MoDOT Construction approximately 30 million dollars. But cost projections predict the EDG could cost the Department an additional 20 million dollars over the cost of the NDG. Table 4 provides the MoDOT ownership cost totals for the period analysis. It shows the input data for the eight cost categories discussed in a previous section. The major difference between the NDG and the alternatives under analysis is that the only costs beyond the initial procurement and training of personnel are for labor and consumable supplies; whereas, the NDG has significant ownership costs throughout its useful life.

Table 4. EUAC for 56 units and training for 28 Project Office Locations

Ownership Cost Category	**NDG**	**EDG**	**SC**	**DCP**
Purchase (P)	$436,800	$772,800	$11,200	$84,000
Training (T)	$92,135	$60,904	$31,327	$17,332
Consumable (C)	NA	NA	$672	$1,736
Labor (M)	$29,064	$144,157	$112,000	$151,132
Disposal (D)	$44,800	NA	NA	NA
User Cost (U)	$13,407	NA	NA	NA
Verification/ Calibration (V)	$6,785	NA	NA	NA
Storage (S)	$2,751	NA	NA	NA
Licensure (L)	$6,400	NA	NA	NA

Table 5 illustrates an analysis that compares each devices ownership costs as a percentage of total EUAC. Its purpose is to measure the effect of device specific ownership costs. Given the assumption that MoDOT will conduct the same number of compaction tests each year without regard to the device in use, the labor costs will be roughly equivalent for all four devices when taken as an annual lump sum. Therefore, the relative difference in the labor costs and purchase cost taken as a percentage of EUAC provides another measure of cost effectiveness. One can see that the NDG’s and EDG’s purchase costs are over 90% of its EUAC whereas the SC’s largest cost is the labor in actually running the compaction test.

Table 5. Percent of EUAC for Compaction Test Devices

Device	P Purchase	T Training	C Consumable	M Labor	D Disposal	U User Cost	V Calibration	S Storage	L Licensure
NDG	89.6	4.7	0	1.5	2.3	0.7	0.3	0.6	0.3
EDG	93.8	1.8	0	4.4	0	0	0.00	0	0
SC	23.7	16.6	0.4	59.3	0.0	0.0	0.0	0.0	0.0
DCP	66.4	3.4	0.3	29.9	0.0	0.0	0.0	0.0	0.0

Cost Index Results

The cost index number analysis provides a “bang for the buck” evaluation of cost effectiveness. The results are shown in Table 6. The EUAC/Test index highlights the cost or potential cost for MoDOT every time an inspector or construction technician leaves the project office to perform a compaction test. For the EUAC/Test index, the decision makers for choice of compaction test device should be noting the lesser numbers, which for this study is the sand cone and density drive sampler. The testing time per EUAC underscores the relationship of time to perform the test to its cost. The decision makers need to consider the larger numbers because the EUAC‘s magnitude is large to the testing time in minutes. This index may need to be looked at an individual device basis to lower the magnitude of the EUAC to testing time.

Table 6. Cost Index Summary

Device	EUAC/Test	Testing Time/ EUAC (Min/$)
NDG	1883	0.00531
EDG	3182	0.00786
SC	182	0.10975
DCP	489	0.02047

Conclusions

The LCC and cost indexes for the differing test methods and devices are tools that will factor into MoDOT’s decision to eventually select a compaction testing alternative to the NDG. Costs along with accuracy, repeatability, and testing performance in differing soils, and ease of use in testing will all be used in determining the best compaction testing system or device for quality assurance and control practices on MoDOT projects. The conclusions drawn from this pilot study are as follows:

- Both the NDG and the EDG have a greater annual life cycle cost than the SC and the DCP. The EDG’s EUAC is greater than the NDG’s EUAC.
- The life cycle cost per test index show the SC and DCP to be the most cost effective.

- The fact that MoDOT has shifted the bulk of the annual compaction testing program to the contractor shifts those tests taken by MoDOT technicians to a QA verification testing role and reduces the advantage of having immediate feedback that is the major advantage of the NDG and the EDG.

Therefore, given all of the above discussion and analysis, the pilot test has confirmed the that replacing the NDG with an alternative testing device will accrue tangible long-term benefits to MoDOT and release scarce operations and maintenance funding for other purposes.

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Figure 1 Break Even LCC Comparison from Choe et al. (Cho et al. 2011)

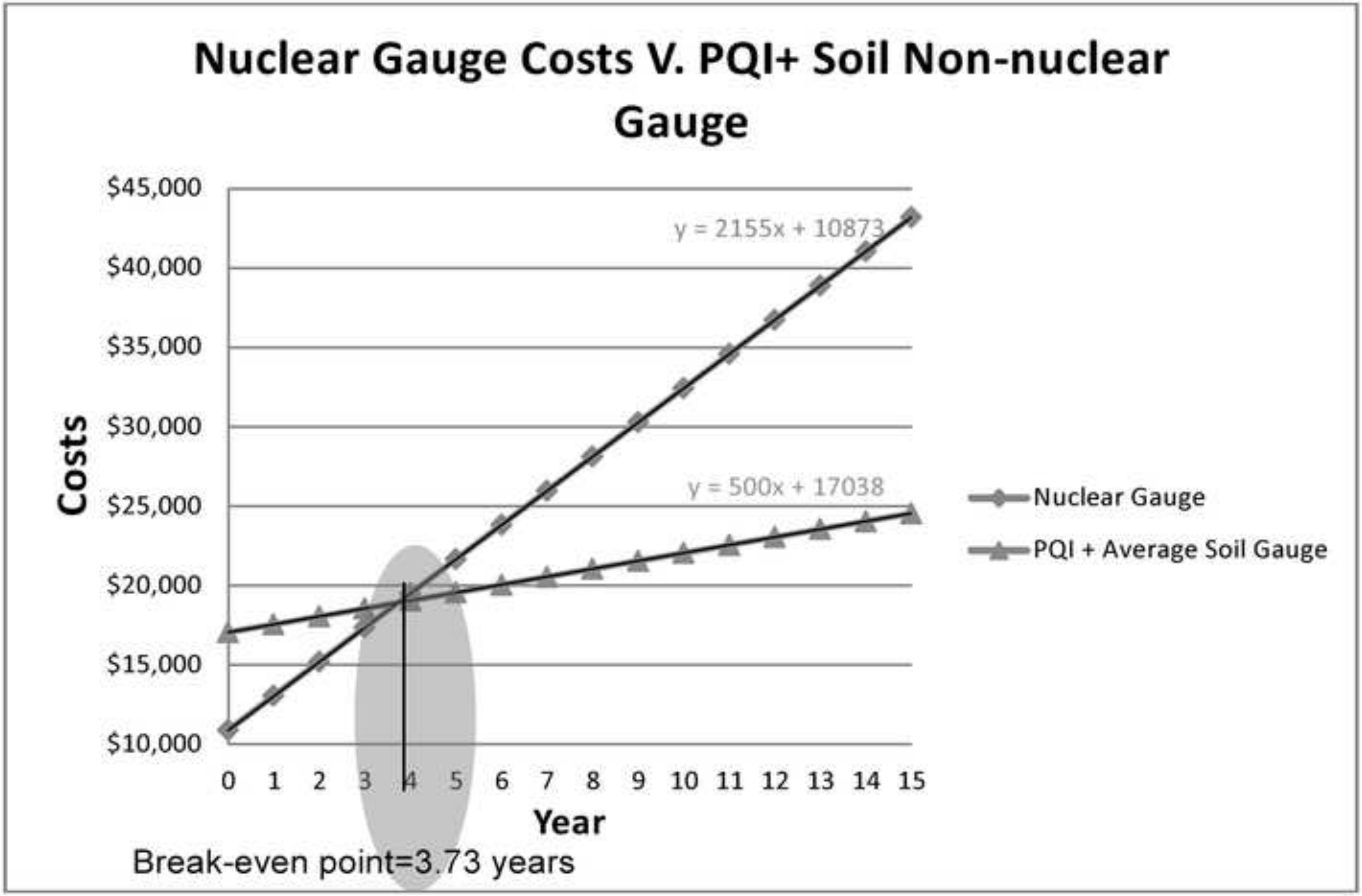

Figure 2 EUAC to MoDOT for Each Compaction Testing Device