# Non-Nuclear Methods for HMA Density Measurements

***Ranjith Kumar Patmala, J.Vikranth and Dr. Divakar C***

**ABSTRACT: on-nuclear methods for the measurement of hot-mix asphalt (HMA) density offer the ability to take numerous density readings in a very short period of time, without the need for intensive licensing, training, and maintenance efforts common to nuclear gauges. The Pavement Quality Indicator™ (PQI) and the Pave Tracker™ use electrical impedance to estimate density. Early models of these gauges were deemed inadequate for quality control and quality assurance testing, but improvements have been made to each. In this project, a number of field sites were used to evaluate the non-nuclear gauges in terms of ruggedness, accuracy, and precision. A thorough investigation of calibration methods was also performed. In the ruggedness study, three pavement sites were used to determine potential procedural factors that significantly affected the non-nuclear density results. Moisture, the presence of sand or debris, gauge orientation, gauge type, and presence of paint markings were determined to significantly impact the accuracy of non-nuclear gauge readings. Four calibration methods were investigated, including screed offset, core offset, two-point, and data pair techniques. None were found to possess all of the necessary components for generating significant correlations with field core densities. A screed-core method was developed as a method to more comprehensively adjust the magnitude of the offset as well as the sensitivity of the device over a large range of true densities. Overall, neither non-nuclear gauge was able to predict core densities as accurately or precisely as the nuclear gauge. Of the non-nuclear devices, the PQI generated more consistent results but was less sensitive to actual changes in density. The Pave Tracker was more sensitive to actual changes in density, but exhibited a higher level of variability. Existing specifications for use of non-nuclear devices should be edited to include guidance on gauge orientation during testing, as well as calibration procedures for a screed-slope type of technique**

## I. INTRODUCTION

In-place density is a key indicator used to judge the quality of hot-mix asphalt (HMA) pavements. Traditionally, this property has been measured by determining the density of cores cut from the compacted pavement, or by the use of a nuclear gauge. Core densities are typically believed to provide the most accurate results, but this process is destructive to the newly compacted pavement. Nuclear technology offers a non-destructive method for density measurements, but is burdened with intense regulations associated with the handling, storage, and transportation of radioactive materials.Within the last decade, non-nuclear technology has been developed for the purpose of measuring the density of in-place HMA materials. These devices operate based on the principles of electrical impedance for a current passing through the HMA material. These devices have many advantages in that they are capable of providing density measurements very quickly and in a completely non-destructive manner, are easy to handle, and are not subject to complicated regulations. In order to adopt a new test method, certain advantages must be realized. The accuracy of the new method should be equivalent to, or better than existing technology. Other justifications relate to efficiency, in terms of time, effort, and money. There are a number of practical reasons to move toward the non-nuclear technology, but the method must first be proven to perform adequately. In this project, the use of two non-nuclear gauges, the Pavement Quality Indicator™(PQI) and the PaveTracker™ were investigated in order to determine whether non-nuclear technology was appropriate for use in quality control and quality assurance (QC/QA) applications. A ruggedness study was performed in order to determine the effects of a number of factors on the results obtained by the non-nuclear devices including temperature, moisture, gauge type, gauge orientation, and presence of debris. The accuracy and precision of the gauges were assessed by comparisons with traditional methods of density measurement, including field cores and the nuclear gauge. In addition, a thorough consideration of calibration procedures was conducted, and suggestions were made for incorporation into existing specifications.

## II. BACKGROUND

In-place density of asphalt pavement is a vital property which can indicate the long-term performance of a flexible pavement. It is also a primary characteristic used to measure quality during construction. Traditionally, the in-place density of HMA pavements was measured from core samples cut from the pavement after compaction. While this method offered a measure of density that was believed to be accurate, the process was time-consuming, labor-intensive, and destructive to the pavement. Nuclear technology was later developed as a non-destructive alternative for density determinations.Thisadvancement was significant because a nuclear density measurement could be completed in less than five minutes, which provided the contractor with reasonably accurate information for "real-time" quality control. The greatest disadvantage of the nuclear device was that it contained radioactive materials, which required significant efforts relating to training, licensing, calibration, maintenance, handling, storage, and transportation. During the last decade, non-nuclear technology has been developed, which uses the impedance of an electrical current to measure dielectric constant and estimate pavement density. These devices do not require intensive safety procedures, are lightweight and easy to handle, and provide density measurements within a few seconds. Early models of these devices demonstrated poor correlations with traditional density measurements, and were significantly affected by factors such as temperature and moisture.


*Figure 2. Troxler Model 3430 Nuclear Gauge*

*Figure 1. AASHTO T 166*

coarse-graded and large NMAS mixes; however, this test is still the most commonly specified method for QA measures of field density.

## III. NUCLEAR METHOD

Nuclear density gauges measure density by emitting gamma rays from a Cesium source. These rays pass through the compacted material to detectors. For a densely compacted material, the gamma rays do not easily pass through to the detector, resulting in a low number of counts. Lower density materials allow the gamma rays to pass through to the detectors more readily, resulting in a higher number of counts. The density of the mat is inversely proportional to the counts, and can be expressed as a unit weight or as a percentage of MTD. Standard procedures for tests performed on HMA pavements are outlined in ASTM D 2950. *(2)* A Troxler Model 3430 nuclear gauge is shown in Figure 2. Although the nuclear method is a relatively quick and non-destructive method for obtaining field densities, poor correlations between nuclear and core densities have been documented. *(3, 4, 5)* As a result, most states require field cores for QA purposes.

## IV. NON-NUCLEAR METHODS

Non-nuclear gauges estimate density by measuring the change in electromagnetic field when an electrical current is transmitted through an asphalt pavement. Specifically, an electrical current passes from the transmitter, is forced around an isolation ring, through the pavement, and is detected by the receiver. The impedance, or resistance to electrical flow, is measured and used to determine the dielectric constant. *(6)* A schematic of this process is shown in Figure 3.

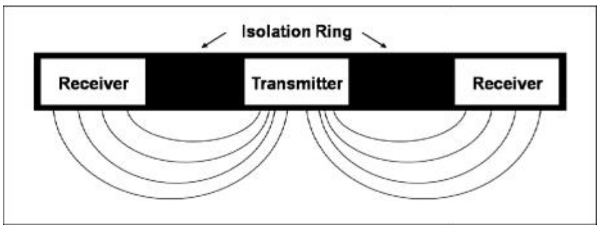


*Figure 3. Schematic of Non-nuclear Gauge Function*

The overall dielectric constant of an asphalt pavement is directly proportional to its density. *(6)* The dielectric constant of air is approximately 1.0, and that for aggregate and asphalt cement is in the range of 5 to 6. Because air has a smaller dielectric constant than the other HMA components, higher air void levels (i.e., lower densities) are indicated by a lower overall dielectric constant. Water has a very high dielectric constant (approximately 80), and small amounts of water can significantly impact the measured overall dielectric constant, such that densities estimated by dielectric constant are higher when water is present. Because the dielectric constant of air is less than that of HMA, and that of water is greater than HMA, the presence of a small amount of water can have the same numerical effect as a large decrease in air void spaces. *(7)*The first impedance-type density gauge, the Pavement Quality Indicator (PQI), was developed by TransTech, Inc. in 1998 as part of the NCHRP-IDEA Program. *(6, 8, 9, 10)* The earliest model of the device, the PQI 100, did not have a moisture sensor, which created obvious problems with accuracy. This gauge did not correlate well with other measures of density and was not recommended for use. The next model (PQI 200) was capable of measuring moisture and temperature, and improved accuracy was reported. Subsequent improvements have been made to the PQI since that time, resulting in the PQI 300, PQI 301, PQI 302, and PQI 303. The PQI 301 is shown in Figure 4. Additions to the device have included settings for layer type, depth settings for layer thickness, and updated algorithms.

*Figure 4. Pavement Quality Indicator*

The PaveTracker is another non-nuclear density gauge, which was developed in 2000 and is currently marketed by Troxler Electronic Laboratories, Inc. *(8, 12)* This device is based on the same principles as the PQI, and is shown in Figure 5. Continues until the density no longer increases, and the number of roller passes is recorded. The second method is a screed calibration, in which the density behind the screed is estimated and used to generate an offset for the mix. The density behind the screed is typically in the range of 75 to 85 percent, and the actual value is usually based on operator experience. The third method involves a core calibration, and is the method recommended by AASHTO. In this procedure, one to five locations are chosen and impedance gauge readings are taken at each location. The offset is calculated based on the average differences in the gauge and core densities.

*Figure 5. Troxler PaveTracker™*

A method for non-nuclear density measurements has also been published as ASTM D 7113, "Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods". *(18)* This specification acknowledges that a number of calibration methods are available, but recommends a core calibration method in which three to ten locations are selected. A minimum of four non-nuclear gauge readings are taken at each location and compared to corresponding core densities. The average of the differences serves as the calibration offset.

Manufacturer's instructions for each gauge also provide insight to appropriate calibration procedures. Trans Tech recommends a core calibration procedure using five core locations and five gauge readings at each location. *(19)* A one point method is also described, which utilizes an offset based on the estimated density of the mat immediately behind the screed. An offset is determined based on the difference in the estimated screed density and the average of five gauge readings. In addition, a two-point method is described, which utilizes an estimate of density behind the screed as well as an estimate of density after the mat has been 'peaked' (i.e., the density no longer increases with additional roller passes). TransTech suggests that the density of an HMA pavement behind the screed is approximately 82 percent, and that the typical density of a peaked mat is approximately 95 percent. Based on linear modeling, the estimated and measured values are used to generate slope and intercept calibration constants.Troxler recommends either a density offset method or a mix calibration method. *(12)* For Non-nuclear gauges have primarily been used for determining mat density during construction, and results have been varied. *(6, 8, 13, 14)* Additional uses for these gauges have also been investigated, including density profiling, longitudinal joint density testing, and the quantification of segregation in compacted pavements. *(15, 16, 17)*

## V. CALIBRATION

A critical step in using impedance gauges effectively is to calibrate them in a manner that will increase the accuracy of results. Density measurements are relative measures of compaction, and can thus be adjusted mathematically in order to more accurately represent the "true" density of the pavement. Although an "absolutely true" measure of pavement density cannot be reasonably achieved, the most accurate measures are typically believed to result from the bulk specific gravity measurement of a pavement core cut from the compacted mat. Therefore, an alternative measure of density is believed to be accurate if it can produce results similar to those generated by core densities. A number of methods are available for use in calibrating impedance gauges. The AASHTO TP 68 method, "Density of In-Place Hot-Mix Asphalt (HMA) Pavement by Electronic Surface Contact Devices", outlines three such methods. *(1)* The first is a relative method, which is recommended primarily for establishing rolling patterns during field compaction. In this method, the density of the mat is recorded after each of a series of roller passes. This process the offset method, a series of readings can be taken with the non-nuclear gauge and compared to values generated by some other method, such as core densities, nuclear gauge densities, or gyratory-compacted core densities. The average difference is taken to be the offset. The mix calibration method involves taking pairs of density readings at a series of three to ten locations such that the range of density is at least 3 pcf. The non-nuclear gauge densities are paired with density readings from another method (in which the other method is assumed to provide 'true' results) such as core densities or nuclear gauge density readings, and linear modeling is employed as a means to generate slope and intercept calibration constants. A calibration method seeks to reconcile the differences between two measures of the same property. In graphical form, if two measures are plotted against each other and agree perfectly, then the resulting relationship will follow the line of equality, which is a straight line having an intercept at the origin and a slope of 1 (see Figure 6). In most cases, perfect agreement is not present, and coefficients of regression (i.e., slope and intercept values) are used to transform measurements by one method to an equivalent measure by the second method.

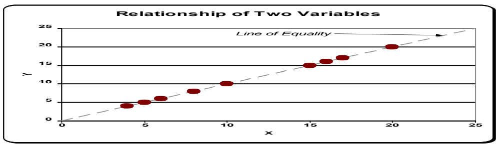


*Figure 6. Relationship of Two Variables Having Perfect Agreement*

An offset method of calibration is used to shift data vertically in order to create a dataset that most closely follows the line of equality. In Figure 7, the relationship of the original data is shown, as well as the corrected data after an offset calibration has been applied. In order to correct data using an offset calibration, a constant is added to the original data value.

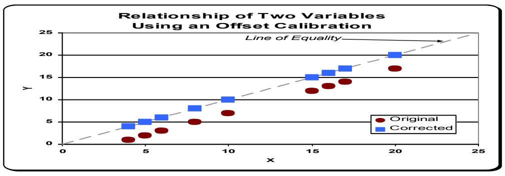


*Figure 7. Relationship of Two Variables Using an Offset Calibration*

A slope calibration is used to change the slope of a relationship to create a dataset that most closely follows the line of equality. In essence, the slope calibration will "twist" the relationship about the origin. In Figure 8, the relationship of the original data is shown, as well as the data after a slope calibration has been applied. In order to correct data using a slope calibration, the original data value is multiplied by a constant.

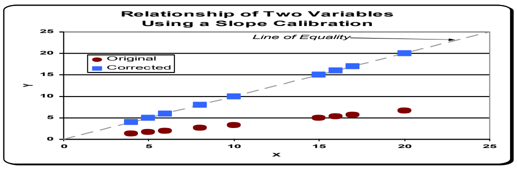


*Figure 8. Relationship of Two Variables Using a Slope Calibration*

To account for errors in the vertical position and slope of the relationship concurrently, a slope-intercept calibration should be used. This type of calibration method will "twist" the data to match the line of equality, and then apply an offset, or intercept, to shift the data vertically toward the line of equality. By including the both the slope factor and vertical offset, the data appears to be twisted about a point other than the origin. In Figure 9, the relationship of the original data is shown, as well as the data after a slope-intercept calibration has been applied. In order to correct data using a slope-intercept calibration, the data value is multiplied by a factor (slope) and then a constant (offset) is added to the result. The slope-intercept is the most difficult method to compute, but is usually able to provide a more complete adjustment to a dataset.

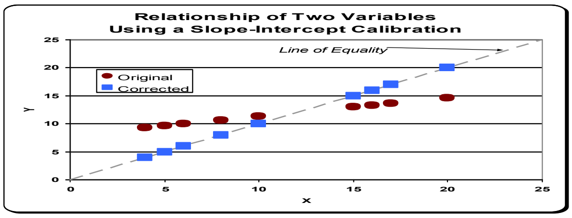


Figure 9. Relationship of Two Variables Using a Slope-Intercept Calibration

### *A. Cost*

The costs associated with performing field density tests vary according to method. The term "cost" can include money, time, or effort, but these factors are typically assessed by some equivalent monetary value. In general, the non-nuclear devices have been advertised to provide significant savings as compared to the nuclear gauge. The initial cost of the non-nuclear devices is similar or slightly less than a nuclear gauge (depending on the model), but the majority of the savings is generated through the elimination of costs associated with licensing, training, and maintenance. One source reported that the annual operating cost of the PQI was $210 per year, as compared to $3075 per year for the nuclear gauge. *(7)* Another source reported that over a 5 year period, the non-nuclear devices could save as much as $50318.

## VI. LITERATURE REVIEW

### *A. Rogge and Jackson*

A number of studies have been performed to determine the ability of the non-nuclear devices to accurately and precisely measure in-place density of asphalt pavements. One of the earliest was performed in Oregon in 1999. *(21)* In this study, a Humboldt nuclear gauge and the original PQI model were compared to field cores in order to assess the compaction and field density for open-graded asphalt pavements having a nominal maximum aggregate size (NMAS) of 25mm and a typical air void range of 17 to 26 percent. Six projects were tested such that nuclear and non-nuclear densities were measured in 45 locations for each. Cores were also cut in each location, resulting in 270 cores and corresponding density measurements. Although a large amount of data was collected, it was reported that neither nuclear nor non-nuclear densities correlated well with core densities, and neither method was determined to be adequate for controlling field compaction.

### *B. Sully-Miller*

In 2000, the Sully-Miller Contracting Company reported on a study in which the PQI was compared to a Troxler 3440 nuclear gauge. The variability was compared for the two gauges, and standard deviations of 0.95, 0.79, and 0.84 were reported for the PQI, and standard deviations of 1.51, 2.12, and 0.90 were reported for the nuclear gauge. The results of the nuclear gauge were widely varied, and it was concluded that these effects were due to surface texture. The PQI, however, did not appear to be affected by surface texture. Overall, it was determined that the PQI was reliable and accurate for measuring the in-place density of compacted HMA.

### *C. Henault*

In another early study, the PQI 300 was evaluated in conjunction with the nuclear gauge in thin-lift mode, and the two were compared to field core densities with the intention of determining whether the PQI could be used for quality assurance (QA) testing. *(6)* Ten sites were tested, and a 5-core offset method was used to calibrate the PQI. Correlations between the PQI and core densities were poor, averaging 0.28, which was suspected to be due to moisture from the roller. Correlations between the nuclear gauge and core densities were better, but not good, having an average $R^2$ value of 0.55. Additionally, PQI densities did not correlate well with the nuclear gauge. Overall, the QA testing with the PQI was not recommended.

### *D. Pooled Fund Study*

By 2002, the results of several non-nuclear gauge studies were published, including a pooled fund study. *(8)* In this study, laboratory and field evaluations of the PQI 300 were performed. The laboratory study sought to determine the effects of several factors, including density, NMAS, aggregate source, temperature, and moisture. Three aggregate sources and three aggregate sizes were used to compact slabs in the linear kneading compactor at varying densities. The results indicated that PQI readings were sensitive to temperature and moisture, even though improvements to the device had been made in an effort to combat these effects. Small amounts of moisture were not significant provided the moisture level remained fairly constant, and NMAS was not significant. The PQI 300 was recommended for use to indicate changes in density under constant temperature and humidity conditions, as long as a mixture specific calibration was used. A slope and intercept method of calibration was recommended. As part of the pooled fund study, two field evaluations were performed. The first took place during the 2000 construction season, in which a nuclear gauge and PQI were evaluated with respect to field cores. It was found that nuclear gauge density readings provided the stronger correlation to field core densities. Although this relationship was merely fair, it was suggested that PQI readings were probably as reasonable as nuclear gauge readings, which are currently accepted by industry, and many practical reasons for using the PQI were cited. Due to poor correlations, the PQI was not yet recommended for field use; however, updated algorithms were recommended to further improve the device.A second field study was held in the 2001 construction season, with five states participating. The PaveTracker, marketed by Troxler, was available at this time and was included in the study. In Pennsylvania, the PQI 300+ (improved) demonstrated the better performance, providing density values similar to that of cores for 6 of 9 projects. The PaveTracker demonstrated significant similarities to field cores in just 3 of 6 projects. The Pennsylvania project was regarded as highly successful, and part of the success was attributed to the experience of the technicians who made the decision to use a calibration based on an assumed density behind the screed of 87 percent.

In contrast, testing performed in Maryland indicated that the PQI was unable to sufficiently correlate with field cores in two of two projects. The PaveTracker was tested on three projects, and was able to successfully correlate with field cores in two of the three. Minnesota also reported greater success with the PaveTracker, which demonstrated high correlation with field cores for 4 of 7 projects and no poor correlations. Overall, the PaveTracker demonstrated a somewhat better correlation to core densities than did the PQI, but neither performed as well as the nuclear gauge. It was noted that the PQI did not appear to be sensitive to actual changes in density in spite of its recent improvements. The non-nuclear devices were recommended for QC or supplemental testing, but not for QA testing.

*E. Romero*

Because several groups were analyzing the differences in non-nuclear density measurements, Romero offered guidance on the most appropriate ways to statistically analyze a dataset of this type. *(22)* T-tests were demonstrated to be inappropriate for comparing non-nuclear density data because the t-test can be misleading for highly variable data. The correlation coefficient was cited as the most accurate way to compare test methods because it provides an idea of the sensitivity of each parameter; however, small sample sizes can be detrimental to the reliability of this method. This is important to remember because small sample sizes are often an unfortunate side effect of a testing regime that involves destructive testing.

*F. Prowell and Dudley*

In 2002, the results of a similar type of comparison were reported for the PQI and nuclear methods. *(23)* Weak correlations existed between the PQI and field cores, but better correlations were exhibited by the nuclear gauge using the core calibration offset method, which was validated. The PQI readings were very consistent, but perhaps too consistent because PQI densities did not increase proportionally as core densities increased.

*G. Hausman and Buttlar*

Another comparison of the PQI and nuclear density gauge was performed in Illinois, and several factors were investigated in the laboratory portion of the study. *(11)* These factors were base coverage, moisture, slab thickness, and use of mineral filler. Base coverage was defined as the percent area of the base plate that is in contact with the HMA at each of 5 points along the longitudinal centerline of the slab. The results of the analysis showed that the PQI 300 was determined to still be sensitive to moisture, although not to the same extent as the PQI 100. Thus, the previous improvements to the device were beneficial. Mineral filler did not affect the measured density results. The PQI 300 results did not correlate well with core densities. This was partially attributed to the density gradient created by the rolling wheel compactor used in the laboratory. As a result, density tests for pay were specified to be based on core densities tested according to AASHTO T 166, while nuclear gauge readings were deemed acceptable for QC/QA purposes.

*H. Sebasta, Zeig and Scullion*

In Texas, a laboratory study was performed using the Troxler 3450 nuclear gauge and the PQI and PaveTracker non-nuclear devices to evaluate the effects of temperature, moisture and gauge battery voltage on densities generated by the PQI and PaveTracker non-nuclear devices. *(16, 17)* This data was used to assess the ruggedness, repeatability, and accuracy of the gauges. The results indicated that all gauges were sensitive to changes in temperature; specifically, density decreased as temperature decreased. All gauges were also affected by moisture, with the nuclear gauge exhibiting the least sensitivity to this factor. It was noted that unless the mat was excessively wet, both non-nuclear gauges provided stable readings. For the battery voltage analysis, only the PaveTracker was used, and the effects of low voltage were not significant. The PQI was not included in this portion of the study because it performs an automatic shut off when the battery is low. Another observation noted was that the PQI, which requires the user to input the lift thickness, was marginally sensitive to this input value. As the input lift thickness increased, the measured density slightly decreased. The precision of the gauges in the laboratory was determined to be good, with standard deviations below 0.5 pcf for the non-nuclear gauges and less than 1.0 pcf for the nuclear gauge.In the second phase of the project, a field study was performed. A 5-core calibration offset method was used, and data for the various gauges was compared to data generated from corresponding field cores. In terms of accuracy, no gauge consistently performed the best. If all of the gauges were assumed to be unbiased (which was not likely to be true), then the PQI was the better performer. The authors cautioned, however that the PQI did not always adequately reflect true changes in mat density. The non-nuclear gauges were more sensitive to daily changes in the mix, and thus a daily mix calibration was recommended.

Experiments were also performed to determine whether the PQI and / or PaveTracker were suitable for use in density profiling and for testing the quality of longitudinal joints. The PQI was found acceptable for density profiling even without calibration, because the purpose of profiling is to detect relative changes. The PaveTracker was found to require calibration for profiling. The PQI was also found to be suitable for testing longitudinal joint density, but the PaveTracker was not. As a result of the concluding recommendations from this study, the PQI has been implemented by the Texas Department of Transportation for density profiling and longitudinal joint testing.

## VII. ANALYSIS AND DISCUSSION

the PQI™ Model 301and the Troxler PaveTracker Plus™ Model 2701-B were the non-nuclear gauges investigated. A Troxler Model 3430 nuclear gauge was also used. Densities of field cores were determined according to AASHTO T 166.A series of experiments were conducted involving various aspects of the non-nuclear gauges. The first was a ruggedness study, which was used to determine factors that significantly affected non-nuclear gauge results, and what procedures should be followed in order to avoid unintentionally introducing error into density measurements. The second set of considerations involved a number of comparisons of density measurement according to the various test methods. The third topic of investigation involved calibration procedures for non-nuclear devices.

### *A. Ruggedness Study*

A ruggedness study is a designed experiment used to identify potential factors that generate significant effects on a measurement. Several ruggedness-type studies have been performed for non-nuclear gauges, both in the laboratory and in the field. The primary thrust of the field studies, however, was to develop correlations among the various testing methods. Since the non-nuclear gauge is intended for field use, it was believed that a more accurate measure of the ruggedness of the devices could be assessed through a field ruggedness study. Although considerable field work has been done, no single field study had encompassed a comprehensive set of experimental factors likely to be encountered in common practice, and no evidence was found in the available literature regarding the completion of a true ruggedness study performed in accordance with ASTM E 1169.The global objective of this portion of the project was to assess the effects of a considerable number of factors potentially affecting the density measurements generated by two non-nuclear devices. The desired result was to create a statistically robust evaluation of potential influences, and to develop a practical solution for each situation relative to these factors.The ruggedness studies was performed in two distinct phases. In Phase I, seven potential factors were chosen for a ruggedness, or screening, test according to ASTM E 1169, Standard Guide for Conducting Ruggedness Tests. As a result, significant factors were identified for further study. Next, the factors presenting the greatest likelihood for significance were investigated further. Phase 2 of the ruggedness study focused on these factors in a more statistically complete examination.

### B. Phase 1

In the first phase of the ruggedness study, ten separate locations on a 12.5mm dense-graded Superpave mix containing a limestone / sandstone aggregate blend were tested. A calibration offset for each gauge was determined using field cores according to AASHTO TP 68, Method C. Seven experimental factors were chosen that were believed to have the potential to impact the density measurements obtained by the non-nuclear devices. The factor selection was based on information found in the available literature, as well as a consideration of practical and procedural deviations that could take place during field testing (even within the parameters of the state testing procedures). A Plackett-Burman design for N = 8 (fractional factorial) was used, which requires 7 experimental factors. The factors chosen were gauge type, mat temperature, presence of moisture, presence of sand, gauge orientation, number of readings used to generate one test “result”, and gauge placement. Each factor was varied at two levels (termed ‘low’ and ‘high’). A summary of the experimental factors and levels is presented in table below. The experiment was replicated in 10 locations on the compacted HMA mat.

| **Factor** | **Low Level** | **High Level** |
|---|---|---|
| GAUGE | PQI | PaveTracker |
| TEMP | Approx. 100F | Approx. 180F |
| WATER | No Water | Water |
| SAND | No Sand | Sand |
| ORIENT | Parallel | Perpendicular |
| REPS | 1 | 4 |
| PICKUP | No Pick Up | Pick Up |

*Table: Ruggedness Study Phase 1 Experimental Factors and Levels*

### C. Gauge Type

Two gauge types were used – the TransTech PQI 301 and the Troxler PaveTracker Plus. The purpose of including this factor was to determine whether the two gauge models could be used interchangeably. In order to develop a generic construction specification which allows non-nuclear technology, the various gauge models should provide similar results. Other research project have investigated the use of both gauges, and though correlations have been mentioned, most of the analyses have focused on the ability to each to correlate with core densities or nuclear density measurements rather than to correlate with each other.

### D. Mat Temperature

In early studies, the temperature of the mat was shown to significantly affect the performance of the non-nuclear devices. Specifically, decreases in temperature created decreased density readings. *(16)* Although product modifications have been performed to compensate for this factor, it was included in the experiment to ensure that its effects were no longer significant. The high temperature used was the temperature of the mat immediately behind the finish roller (approximately 180 degrees F) and the low temperature was tested after the mat had cooled considerably (approximately 100 degrees F). The exact testing locations were marked so that the same locations could be tested after the mat had cooled. It was recognized that a greater temperature differential could have been more informative. However, testing at higher temperatures (i.e., prior to final rolling) would have been confounded by actual differences in pavement density.

### E. Moisture

Modifications were also made by the manufacturers to compensate for the effects of moisture. This factor was included in the experiment in order to assess the success of such modifications. In the manufacturer's instructions for the PQI, the user is cautioned to ensure that no visible signs of moisture are present on the testing surface. However, the PaveTracker manual does not include a warning of this type. *(12, 19)* Current standard specifications, AASHTO TP68 and ASTM D 7113, state that the surface should be free from excess moisture, but that roller water is allowable. In this study, the "dry" condition was tested when the mat had no visible signs of moisture present. To achieve the "wet" condition, a spray bottle was used to wet the surface until the surface voids were essentially filled with water, then a towel was used to blot the surface. In the "wet" state, the mat resembled a saturated-surface dry (SSD) condition. Basically, the moisture comparison evaluated the effect of excessive roller water on the mat's surface.

### F. Presence of Sand

The non-nuclear gauges rely heavily upon the quality of contact with the surface of the HMA. Therefore, sand particles or debris could disrupt the contact between surfaces. Construction debris is often present at job sites and could affect readings, especially if the density measurements are not taken immediately after paving. If the surface of the mat contains a large number of voids, however, the measured dielectric constant could be excessively affected, indicating a lesser density. To remove the effects of surface defects when using the nuclear density gauge, fine sand is often used to fill the surface voids.

### G. Gauge Orientation

The standard convention for taking nuclear density readings is to place the gauge parallel to the direction of paving. However, the gauge orientation is not specified in the manufacturer's instructions or in AASHTO TP68 or ASTM D 7113. ASTM D 7113 also recommends rotating the gauge to obtain maximum contact between the gauge and the surface. Thus, a technician could place the gauge in any orientation and still abide by the stated procedures. Density readings were taken both parallel and perpendicular to the direction of paving. Because the contact areas of the gauges are round, parallel orientation was defined such that a technician facing the direction of paving could read the gauge display screen directly. Parallel and perpendicular orientations are shown in Figure 10.

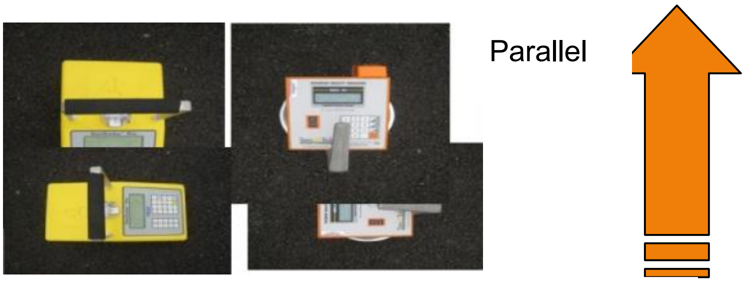


*Figure: Parallel and perpendicular (*

### H. Number of Readings

For calibration purposes, non-nuclear gauge manufacturers recommend using the average of multiple readings (four or five) to generate one reported value. For general use, however, the number of readings required to obtain a reported value is not explicitly stated in the currently specifications. In general, increasing the number of readings is expected to improve the overall results. In this study, one reading and four readings were used to generate a reported value. Because the intention was to assess the gauges' ability to repeatedly measure a density and not to assess the variability of the mat, all replicate readings were taken in the exact same location, thereby removing the confounding effects of variation in mat density.

### I. Gauge Placement

As stated previously, non-nuclear gauges require firm contact with the HMA surface for maximum effectiveness. In addition, it is generally desirable to report the average of multiple readings as the in-place density for a given location. It is reasonable, then, to ask the question: when taking multiple readings for a given location, should the user "pick up" the gauge between readings, or ensure a single firm placement and leave the gauge in place for all readings? This factor was included to assess the effect of picking up the gauge between successive readings.

J. Phase 1 Analysis

The results of the testing performed in this portion of the experiment are given in graphical comparison for each factor as shown in Figures 11 through 17, such that average values are presented for each testing location.

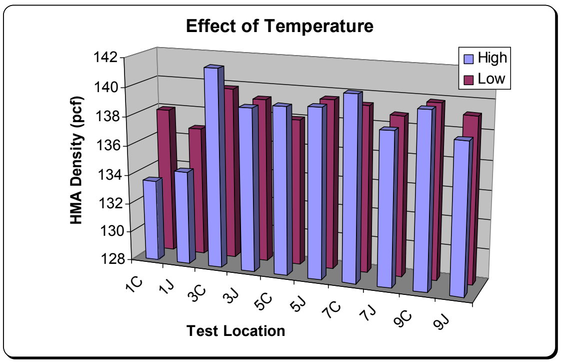


*Figure 11. ASTM E 1169 Analysis – Effect of Temperature*

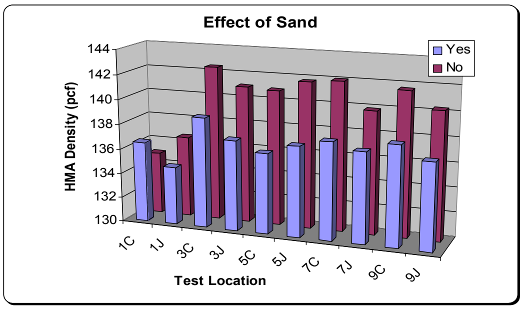


*Figure 12. ASTM E 1169 Analysis – Effect of Sand*

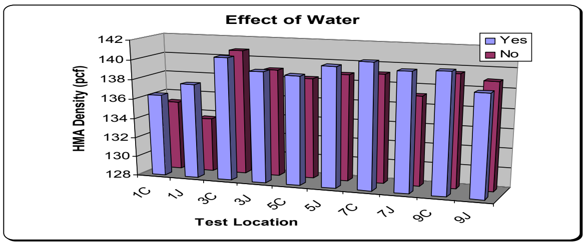


*Figure 13. ASTM E 1169 Analysis – Effect of Water*

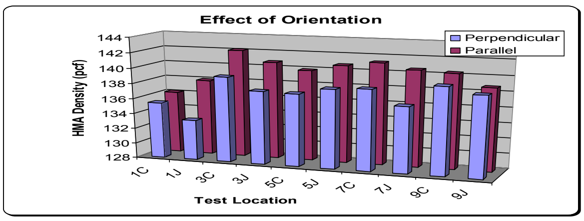


*Figure 14. ASTM E 1169 Analysis – Effect of Gauge Orientation*

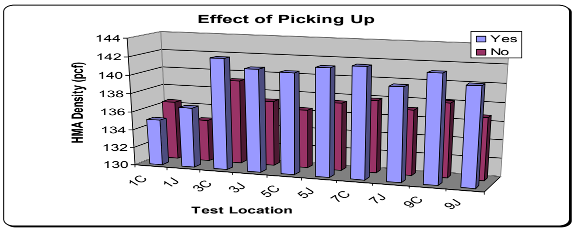


*Figure 15. ASTM E 1169 Analysis – Effect of Picking Up the Gauge*

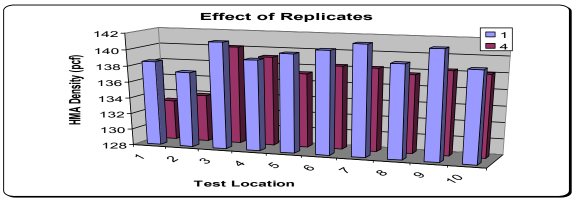


*Figure 16. ASTM E 1169 Analysis – Effect of Number of Replicate Readings*

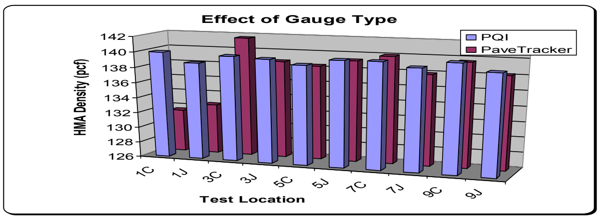


*Figure 17. ASTM E 1169 Analysis – Effect of Number of Gauge Type*

K. Phase 1 Conclusions

Based on the ASTM E 1169 analysis, the following conclusions were made.

1. Non-nuclear density measurements were largely unaffected by the range of temperatures tested. Of the ten locations, temperature was significant for only two, and the average effect was relatively small.

2. Nine of ten locations were significantly affected by the presence of sand. Introducing sand to the mat decreased the average density reading by approximately 3 pcf. Based on this result, it is believed that the sand is more likely to prevent solid contact between the gauge and the mat, than to alleviate the detection of a disproportionate number of surface voids.

3. Water was found to be significant in only 3 of the 10 locations. Thus, blotting surface moisture from the mat (as per specifications) may be an adequate procedure. It was noted that the average effect was greater than 1 pcf.

4. Gauge orientation was significant in 8 of 10 locations. Overall, placing the gauge in a direction parallel to the direction of paving creates a density approximately 2.4 pcf higher than when placed perpendicular to the direction of paving. Thus, rotating the gauge to obtain maximum contact is not acceptable.

5. Picking up the gauge between readings was significant in 9 of 10 locations. Interestingly, placing the gauge repeatedly in the exact location increased the density readings by 3 pcf. It is suspected that the repeated placement may have “seated” the gauge in its place, increasing the quality of the contact with the mat. It could also be due to the operator unintentionally placing slightly more pressure on the gauge each time it was placed.

6. The number of readings used to generate one reported value was significant in 5 of 10 locations. In general, the values consisting of 1 reading were significantly higher than those consisting of 4 readings. Though no explanation for this phenomenon was determined, it was noted that the practical purpose for including this factor was to provide the required number of factors necessary to properly perform the procedures outlined in ASTM E 1169.

7. Overall, gauge type was not found to be significant. In general, the PQI generated slightly higher densities, however the average difference was statistically significant in only one of the ten locations tested. Because the non-nuclear density readings are relative, a proper calibration and offset should be sufficient to create similar density data.

An analysis of variance (ANOVA) was used to evaluate all of the data in a single analysis. However, since each location tested could, in theory, have a different actual density, it was necessary to block on the location factor. And because the dataset did not have the ability to provide full orthogonal contrasts and interactions, only the main effects were tested. While this technique is not sufficiently robust for a detailed investigation, it is acceptable for use in a screening experiment, such as this. The results of the ANOVA are given in Table 3. At the 95 percent level of significance (a = 0.05), all experimental factors are at least marginally significant with the exception of temperature. The presence of moisture was significant at the 92.5 percent level of significance, and was considered to be significant. Overall, these results appeared to be fairly consistent with those derived from the ASTM E 1169 procedure. From these results, the least critical factors were eliminated from further study. Temperature was eliminated from the testing matrix due to the conclusive evidence that non-nuclear density measurements were not significantly affected by changes in that factor for the range tested. The number of readings used to generate a reported value was also eliminated from the testing matrix. Although this factor was significant, it is generally recognized that increasing the number of readings will decrease the overall variability. Because the difference in one reading and four readings was statistically significant, it was concluded that multiple readings should be used for the measurement of density by non-nuclear methods. This evidence was considered sufficient for a conclusive recommendation, and was therefore not included in the phase 2 ruggedness experiment.

| **Source** | **df** | **Mean Square** | **F-Value** | **P-Value** |
|---|---|---|---|---|
| LOCATION | 9 | 21.907 | 2.82 | **0.0074** |
| TEMP | 1 | 2.521 | 0.32 | 0.5707 |
| SAND | 1 | 191.581 | 24.7 | **<0.0001** |
| WATER | 1 | 25.765 | 3.32 | 0.0731 |
| ORIENT | 1 | 114.290 | 14.73 | **0.0003** |
| PICKUP | 1 | 182.468 | 23.52 | **<0.0001** |
| REPS | 1 | 123.654 | 15.94 | **0.0002** |
| GAUGE | 1 | 56.113 | 7.23 | **0.0091** |
| Error | 63 | 7.756 | | |

*Table : ANOVA Table for Ruggedness Experiment*

The gauge placement factor was also removed from the experiment. Although significant, this factor lacked practical significance. In most applications, the gauge is picked up between readings. It was noted that there was very little, if any, variation in readings taken consecutively without moving the gauge. When lifting the gauge between measurements, the variability of consecutive readings was considerably greater. This supports the fact that non-nuclear gauges are very sensitive to the quality of contact between the gauge and the mat.The factors remaining in the experiment included gauge model, gauge orientation, the presence of sand, and the presence of water. Though gauge model was not largely significant in the ASTM E 1169 analysis, it was determined to be significant in the ANOVA. And, both gauges were intended to be used in the study, so this factor was retained. Gauge orientation and the presence of sand were clearly significant in the analysis, and were selected for further testing in phase 2. While the presence of water was only marginally significant in the phase 1 analysis, it has bee reported in several other studies to have a significant effect on non-nuclear density readings. Therefore, it was also included in the phase 2 study.

## VIII. CONCLUSIONS

This study of non-nuclear densities gauges was composed of a number of experiments designed to evaluate ruggedness, accuracy, variability, and calibration methods associated with the devices. TransTech’s Pavement Quality Indicator™ (PQI) Model 301 and Troxler’s PaveTracker™ Plus Model 2701-B were used in conjunction with a Troxler Model 3430 nuclear gauge and field cores.

### *A. Ruggedness*

The ruggedness study was a field study designed to identify factors having a significant effect on density measurements made by the non-nuclear density gauges. Two 12.5mm NMAS mixes and one 37.5mm mix were used to test the effects of gauge type, mat temperature, moisture, presence of sand or debris, gauge orientation, number of readings used to generate one result, and gauge placement. The following conclusions were made.

- The PaveTracker and PQI provided similar results for the 12.5mm mixtures, but significant differences were present for the 37.5mm mix. Thus, the two types of gauges cannot be used interchangeably in all cases.
- The orientation of the gauge was significant in some cases, but appeared to be mixture dependent. A consistent orientation should be implemented to alleviate this problem.
- The presence of sand significantly affected both the PQI and PaveTracker, especially for the 12.5mm mixes. The PaveTracker was more sensitive than the PQI to this factor. All sand and debris should be thoroughly swept from the mat prior to testing.
- The presence of water significantly affected density readings in that the presence of moisture generated increased density readings. Although modifications to the non-nuclear gauges have attempted to account for moisture, they are still significantly affected.
- For the range tested, temperature did not significantly affect the density as measured by the PQI or PaveTracker.
- Paint caused non-nuclear testing devices to produce higher density readings.

### *B. Method Comparisons*

Initial comparisons of the nuclear and non-nuclear gauges indicated weak correlations between them. Both non-nuclear gauges were significantly less sensitive to changes in density than the nuclear gauge. In terms of variability, the PQI was the least variable, followed by the nuclear gauge and PaveTracker devices. When compared to core densities, the nuclear gauge demonstrated the strongest relationships, followed by the PQI and PaveTracker. Again, the non-nuclear gauges appeared to be insensitive to actual changes in density for some mixes. However, it was concluded that proper calibration may be able to account for these differences.

### *C. Calibration*

Four calibration methods were evaluated, including the screed offset method; the core offset method, the two-point method, and the data pair method. None of these methods were able to provide non-nuclear devices with a way to estimate densities equivalent to core densities with respect to both magnitude and sensitivity. The following reasons were cited.

The screed offset method provided values that were acceptable at very low densities, but was unable to accurately estimate high densities. An additional difficulty of this method was the fact that it is based on operator experience.

The core offset method was successful at predicting high density levels, but was not sensitive to decreases in density. This could be detrimental a QC/QA application.

The two-point method provided, reasonable estimates of density, and was sensitive to changes in density. However, it was based on operator experience.

The data pair method considered the largest number of factors, but was dependent upon the nuclear gauge. Since the intended purpose of the non-nuclear gauge is to serve as a *replacement* for the nuclear method, this style of calibration does not provide a long-term solution.

The variability of non-nuclear gauges increased as NMAS increased.

## REFERENCES


1. Density of Bituminous Concrete in Place by Nuclear Methods", ASTM D 2950, *Annual Book of ASTM Standards*, Volume 04.03, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 2007.
2. Choubane, B., Musselman, J.A., Page, G.C., Sholar, G.A., and Upshaw, P.B., "Nuclear Density Readings and Core Densities – A Comparative Study", *Transportation Research Record #1654*, Transportation Research Board, Washington, D.C., 1999.
3. Bradbury, R.L., "Comparison of Density Test Methods on Project IM-95-6596(00)E Old Town-T2R8", *Final Report*, State of Maine Department of Transportation, 1998.
4. Brown, E.R., "Density of Asphalt Concrete – How Much Is Needed", Transportation Research Record #1282, Transportation Research Board, Washington, D.C., 1990.
5. Henault, J.W., *Field Evaluation of a Non-Nuclear Density Pavement Quality Indicator*, Report No. 2227-F-01-3, Connecticut Department of Transportation, Bureau of Engineering and Highway Operations, Division of Research, June 2001.
6. Sargand, S.M., Kim, S., and Farrington, S.P., A Working Review of Available Non-Nuclear Equipment for Determining In-Place Density of Asphalt, Final Report for State Job Number 147960, Ohio Research Institute for Transportation and the Environment, Columbus, Ohio, December, 2005.
7. Romero, P., *Evaluation of Non-Nuclear Gauges to Measure Density of Hot-Mix Asphalt Pavements*, Pooled Fund Study, Final Report, University of Utah, Department of Civil and Environmental Engineering, July 2002.
8. Sawchuk, P., and Sovik, R., NCHRP-IDEA Program Project Final Report: Testing and Trial Deployment of a Cost-Effective and Real-Time Asphalt Pavement Quality Indicator System, Transportation Research Board, Washington, D.C., 1997.
9. TransTech Systems, Inc., *TransTech Systems' Pavement Quality Indicator™ (PQI) Application Brief*, Schenectady, New York, January, 2003.
10. Hausman, J.J., and Buttlar, W.G., *Analysis of TransTech Model 300 Pavement Quality Indicators: Laboratory and Field Studies for Determining Asphalt Pavement Density*, Transportation Research Record #1813, Transportation Research Board, Washington, D.C., 2002.
11. "A Summary of Operational differences Between Nuclear and Non-Nulcear Density Measuring Instruments", Sully-Miller Contracting Company, Quality Control Department, October 2000.
12. Mohammad, L.N., Wu, Z., Zhang, C., Khattak, M.J., and Abadie, C., "Variability of Air Voids and Mechanistic Properties of Plant-Produced Asphalt Mixtures",

*Transportation Research Record #1891*, Transportation Research Board, Washington, D.C., 2004.

13. Larsen, D.A., and Henault, J.W., Quantifying Segregation in HMA Pavements Using Non-nuclear Density Devices: Data Collection Report for Connecticut, Final Report, SPR-2238, Connecticut Department of Transportation, November 2006.
14. Sebesta, S., Zeig, M., and Scullion, T., "Evaluation of Non-Nuclear Density Gauges for HMAC: Year 1 Report", *Report No. FHWA/TX-04/0-4577-1*, Texas Transportation Institute, Texas A&M University System, October, 2003.
15. Sebasta, S., Estakhri, C., Scullion, T., and Liu, W., "New Technologies for Evaluating Flexible Pavement Construction: Year 1 Report", *Report No. FHWA/TX-06/0-4774-1*, Texas Transportation Institute, Texas A&M University System, June, 2006.
16. "Standard Test Method for Density of Bituminous Paving Mixtures in Place by the Electromagnetic Surface Contact Methods", ASTM D 7113, *Annual Book of ASTM Standards*, Volume 04.03, American Society for Testing and Materials, West Conshohocken, Pennsylvania, 2007.
17. "Pavement Quality Indicator Model 301 Operator's Handbook", TransTech Systems, Inc., Schenectady, New York, 2003.

## AUTHOR'S INFORMATION

**Ranjith Kumar Patmala** Student of Masters of Engineering in Civil Engineering Department in Pydah College of Engineering & Technology Gambheeram, Visakhapatnam.

***J.Vikranth*** ASSOC.PROFESSOR Department Civil Engineering, Anil Neerukonda Institute of Technology&SciencesVisakhapatnam

**Dr. Divakar C** M.Tech Ph.D, Principal, Pydah College of Engineering&Technology Gambheeram, Viskhapatnam