# Correlation of Nuclear Density Readings with Cores Cut from Compacted Roadways

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16. Abstract

Developed a field procedure for use of the nuclear density gauge resulted in nuclear gauge density data that closely resembles in-place density obtained from cores. Made procedural recommendations intended to improve its accuracy. The nuclear gauge data were collected on seven sites during Connecticut Department of Transportation pavement construction projects in 2003 and 2004. The findings indicate that the six individual nuclear gauge density units used for this study do not produce similar results and do not consistently correlate with core densities. The differences between the core density values obtained by the three laboratories and the nuclear gauge readings were significantly higher than the 0.1% MTD (maximum theoretical density) reported accuracy currently used by ConnDOT for acceptance on projects. Significant variation was also found between the results of core density samples obtained by three different laboratories on the same samples. In addition, the variability of the nuclear density gauge error differed not only from gauge to gauge, but also from location to location and is present for both nuclear gauge density testing modes (backscatter versus thin lift). The effect of the nuclear gauge orientation during testing with respect to the new mat was statistically different but very small; the mean difference was 0.05 percent of MTD. When the nuclear gauge was in the longitudinal direction, the density reading was slightly higher than those taken in the transverse direction. The time recording interval for the nuclear gauge was found to be relatively significant with respect to minimizing the difference between the nuclear gauge densities and core densities. The longer the recording time interval for the nuclear density gauge, the smaller the difference between the core density values and nuclear gauge densities. If the nuclear gauge continues to be used for project Quality Assurance, it is recommended that the recording time interval be 1-minute and that the acceptance reported accuracy be set to 1% of MTD. A new project-by-project nuclear gauge density correction procedure that requires 10 cut cores to improve accuracy is presented in this report.

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# 1 INTRODUCTION

Maintenance, rehabilitation, and management of Connecticut's network of roads is challenging due to the aging of the roads and the limited budgets of various agencies. Ensuring the pavement is constructed properly helps to ease this burden as proper construction will tend to extend the service life of the pavement. The long-term quality of hot mix asphalt (HMA) pavement can be controlled by implementing an appropriate Quality Assurance Program. Specified mix properties are tested during plant inspection and specified compaction levels are tested during paving inspection. The following definition of Quality Assurance is now accepted by AASHTO and the FHWA:

"QUALITY ASSURANCE is defined by AASHTO as:

'All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.' " [27]

Asphalt compaction measurements have been traditionally used as an indicator of future pavement performance and quality [1-6]. Inadequate compaction results in a pavement with decreased stiffness, reduced fatigue resistance, accelerated aging, and decreased durability. All of these may lead to rutting, raveling, and moisture damage of the roadway [3]. There are numerous methods of measuring the extent of pavement compaction or pavement density. These methods can be classified into two main categories: destructive and non-destructive. The destructive method for measuring density is coring, where a cylinder is cut from the compacted asphalt mat and subsequently tested in the laboratory. The most common non-destructive method for measuring density involves the use of a nuclear density gauge. Other methods of non-destructive density measurement include deflectometers, ground pavement radar (GPR), microwaves and non-nuclear density indicators. Many of these alternate methods of non-destructive testing are still under development and in the future may prove to be viable options for the field measurement of the density in HMA pavements.

In Connecticut, two primary methods have been used to measure the density of a compacted asphalt mat [7]: the laboratory measurements of cores and the use of a nuclear gauge. Although the core measurement results provide what many feel are the most accurate and precise measure of compaction, these results are not available in real time to make in-process corrections to the paving operation during construction. This procedure requires several days to produce core density measurements. However, many professionals question the alternative to cores, especially the nuclear gauge field method [4, 8, 9]. The general observation is that measuring density with a nuclear gauge in the field is not as accurate as measuring the density of cores in the laboratory. Many variables are known to impact nuclear gauge readings and it is speculated that changes in technique could improve accuracy. The Connecticut Department of Transportation (ConnDOT) began to use the nuclear gauge density measurements in the 1970s and is currently using it as an exclusive method for Quality Assurance and Acceptance of projects for payment.

The objective of this study is to develop a field procedure for use of the nuclear density gauge that will result in nuclear gauge density data that closely resembles in-place density obtained from cores and to make procedural recommendations that could improve its accuracy. Four datasets were used in this study. First, real world density data was analyzed from seven Connecticut sites during multi-day paving operations on interstate and state secondary highways to evaluate the level of agreement between the nuclear gauge density readings and core densities. At each site, multiple random locations per day were selected to perform nuclear density measurements, and later, core samples were extracted from the same random locations. For each random location, up to three different nuclear gauges were used and each core sample was tested to determine its bulk density by up to three different agencies at their respective laboratories. The minimum number of core samples was twenty-eight and the maximum was fifty-five per site. The overall dataset contains three hundred forty-four total locations.

To evaluate the correlation between the nuclear gauge and core samples, the following comparisons were undertaken. First, the values of core densities measured by the three laboratories were compared. Second, densities from the nuclear gauges for each sample location were compared. (Each agency collected four nuclear gauge measurements per test location.) The nuclear gauge devices were set on the pavement and after the first reading the gauge was rotated 180 degrees. After the second reading the gauge was rotated 90 degrees. After the third reading the gauge was then rotated 180 degrees. This allowed for a comparison between nuclear density readings taken in the transverse and longitudinal directions. Finally, a comparison between each nuclear gauge and the average core density for an individual location was undertaken.

In addition, three smaller data sets were collected on the 2004 projects. Every day during sampling, a random location was selected to perform ten repeated measurements without moving the nuclear density gauge. The CAP Lab performed these measurements utilizing two different nuclear gauge modes: thin lift and backscatter. These observations were compared to determine if the mode significantly affected the gauge readings.

Second, all three agencies made four measurements of nuclear density each day at the same location which was designated on the first day of paving for site. The nuclear gauges were set on the pavement and after each reading the gauge was rotated as described above. This allowed investigation of variations that exist within each gauge due to external factors such as the possible drift in accuracy of the nuclear density gauge readings over time. Last, measurements were taken on three existing parking surfaces with three different aggregate sources used in the HMA. For this dataset, 10 measurements per nuclear gauge and time recording interval were taken without moving the gauge. Up to four recording intervals were used depending on the individual gauge capabilities; 15 seconds, 30 seconds, 60 seconds, and 90 seconds. This allowed for determination of the impact of the recording time interval on the gauge variability.

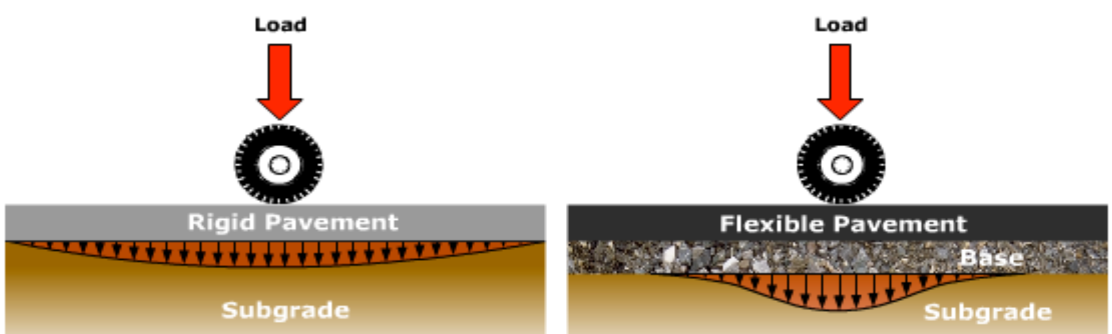
This report is divided into six chapters. Following this chapter, the background section covers the general background on HMA pavement structures and the need for a correlation factor between the two density measurement methods. The background section also discusses the findings of other studies attempting similar investigations. The methodology portion of the report (chapter three) describes the field procedures used to collect the data and the data analysis methods. The results section is followed by a discussion of the methodology used to develop a correction factor (chapter five) which includes recommended field procedures that will optimize the correlation between density from the nuclear gauge and the core samples. The final chapter discusses the recommendations and conclusions

# 2 BACKGROUND

This background section contains three types of information: 1) a general section on pavement characteristics and structure including a discussion of factors affecting pavement density, 2) procedures for nuclear gauge use and factors affecting its accuracy, and 3) previous studies on factors affecting nuclear density gauge readings and the relationship between these readings and the core densities obtained in the field.

### *2.1 PAVEMENT CHARACTERISTICS AND STRUCTURE*

Pavements can be divided into two main categories: flexible and rigid [10]. The primary differences between these types of pavements are the material they are made of and the manner in which they distribute the load over the sub-grade [10]. The wearing surface of a rigid pavement is constructed of Portland cement concrete. Therefore it acts like a beam lying over any irregularities in the underlying supporting material. Rigid pavements, because of the concrete's rigidity and stiffness, distribute the load over a relatively wide area of the sub-grade [10] as illustrated in Figure 2.1.




(Muench, et al. 2002).

**Figure 2.1: Load Distribution in Rigid and Flexible Pavements**

Flexible pavements, as the name implies, bend and flex due to the traffic loads [11]. Flexible pavements are constructed with asphalt that is inherently weaker and less stiff as compared with Portland cement concrete. Therefore, flexible pavements do not distribute vehicle loads as well as Portland cement concrete. The traffic loads are transferred by slight deflection of the bituminous or asphalt wearing surface to the underlying support layer which spreads the load further and passes the loads on to the next sub-layer [10] as shown in Figure 2.1. Thus, the bottom layer carries the smallest load in terms of stress or force per area. Flexible pavements usually require more layers and greater thickness for optimal transmission of loads to the sub-grade [11].

### 2.1.1 Flexible Pavement: Structure

The most common type of flexible pavement surface in the U.S. is hot mix asphalt (HMA). Hot mix asphalt is known by many different names including “hot mix”, asphalt concrete (AC or ACP), asphalt, blacktop, hot top or bitumen. A typical Connecticut highway constructed using a full depth HMA flexible pavement structure consists of 4 layers, a wearing surface course, binder course, base course and sub-base. The wearing surface course is the top layer that is in direct contact with traffic loads. It provides several functions including friction, smoothness, rut resistance, and drainage [10]. This layer is the focus of this study. The compacted thickness of the wearing surface in Connecticut usually varies between 1.5 to 2 inches. The binder course is placed beneath the wearing surface and is intended to increase the structural carrying capacity of the pavement. The layer immediately beneath the binder course of asphalt is the base course. The base course usually consists of a HMA mix with a larger nominal aggregate size. The base course is intended to provide support to the pavement structure and is typically 3 to 6 inches thick after compaction. The sub-base is a granular material such as crushed stone, gravel and sand. This material is selected according to guidelines for gradation, strength and plasticity. This layer provides the additional load distribution and contributes to the drainage and frost resistance. The sub-base is located immediately above the sub-grade, or existing soils if they are granular in nature, and directly below the base course.

HMA in the United States can be divided into two general categories: standard mixes and Superpave (SUperior PERforming PAVEment) mixes. All mixes, standard or Superpave, are prepared by heating the aggregate and other materials to temperatures ranging from 250º F (121° C) to 400º F (204° C), depending upon the aggregate type, asphalt binders and the mix design. This project uses data from re-surfacing projects where Superpave mix designs were used. Superpave was created in 1992 by the Strategic Highway Research Program (SHRP) to make the best use of asphalt paving technology and to present a system that would optimize asphalt mixture resistance to permanent deformation, fatigue cracking and low-temperature cracking [12]. The mixes produced under this system are still composed of the same materials as standard mixes, but they are more precisely designed. A particular Superpave HMA design is selected to match traffic loads as well as the temperature extremes expected for the given location [13].

### 2.1.2 Flexible Pavement: Distress

There are three basic categories of HMA pavement distress: fracture, distortion, and disintegration [14]. These three categories can be further subdivided. Fracture can be seen as cracks or spalls. Cracks come in many shapes and sizes. There are six types of cracks that can be observed on the HMA surface; transverse, longitudinal, fatigue, joint reflection, and block cracking and edge cracking [25]. Cracking can be caused by excessive loads, fatigue of pavement over time, low temperatures, an inability of the asphalt binder to expand and contract with temperature or moisture infiltration. Spalling is caused by fewer mechanisms: excessive stresses at joints/cracks caused by infiltration of incompressible materials and subsequent expansion, heavy traffic loadings, thermal changes, moisture infiltration and poor bonding between the surface HMA and adjacent layers in the pavement structure. Pavement with minor cracking or spalling can provide years of satisfactory service. In some cases, pavement cracks are sealed. But, for extensive damage of this type a new overlay is needed after removal of the fractured pavement.

Distortion can also be divided into two subcategories; rutting and shoving [25]. Rutting is caused by traffic loads and presents itself as longitudinal depressions in the wheel paths. Shoving is caused by braking or accelerating vehicles and presents itself as lateral and/or vertical displacement of the pavement surface. Insufficient compaction during construction, soft asphalt binders, excessively high asphalt contents, and over consolidation of HMA layers during construction often result in this type of distress [14]. Pavement with minor distortion can be paved over, but for extensive damage, the distorted pavement must be removed prior to resurfacing.

Disintegration of HMA pavement surfaces is referred to as raveling. Raveling occurs as individual aggregate particles dislodge from the pavement surface and asphalt binder is lost [25]. Raveling can also be caused by water stripping of asphalt/aggregate bond. A raveling pavement will initially lose fine aggregate particles, leaving a pock-marked surface texture, followed by the loss of larger aggregates, leading to a rough surface texture with large, exposed aggregate. This will eventually result in the loss of the entire lift of asphalt pavement [14]. This type of deterioration is exponential. It is a result of a combination of the following factors: poor mix design, inadequate production practices, or construction practices including poor compaction and aggregate segregation.

The solution is to remove the affected pavement and patch or place a new overlay for larger distress areas. Unfortunately, this type of distress can occur early in the HMA life cycle.

Proper compaction of HMA can prevent certain types of distress. Achieving proper compaction during construction is essential as proper compaction results in longer pavement life, lower pavement maintenance costs, and better all-around pavement performance. There is a direct correlation between improper compaction and the categories of distress described above.

#### 2.1.3 The Compaction and Density of Flexible Pavement

Hot Mix Asphalt compaction measurements are used at the time of construction as a predictor of pavement performance and quality [1-6]. Inadequate compaction results in a pavement with decreased stiffness, reduced fatigue resistance, accelerated aging, and decreased durability, which can lead to the pavement distresses discussed above.

To ensure proper asphalt compaction during construction, the percent of voids in the HMA is closely monitored. This indicator is quantified as a percentage of maximum theoretical density (MTD) by volume, which is calculated by comparing a test specimen's density with the density that it would theoretically have if all the air voids were removed. The percent of air voids present is computed by subtracting the percent of MTD from 100 percent. Although the percent air voids is the HMA characteristic of interest, measurements are usually reported as the measured density of the HMA material in relation to a reference density. For example, the percentage of MTD, percentage of a laboratory-determined density, and percentage of a control strip density [3] are commonly used. In Connecticut, all density measurements utilized for construction Quality Control and Quality Assurance are presented as percent of MTD [7]. In this report, percent of MTD is used. The MTD is calculated from the theoretical maximum specific gravity of the particular bituminous pavement mixture ($G_{mm}$) multiplied by the unit weight of water. The $G_{mm}$ is a ratio of the mass of a given volume of voidless HMA at a stated temperature (usually 25 °C) to a mass of an equal volume of water at the same temperature. The percent of MTD is equal to the actual density of the sample, divided by MTD and multiplied by 100. For example, if the pavement is compacted to 95% of MTD, 5% of the volume is air voids.

"There has been much work that has shown that the initial in-place voids should be less than approximately 8 percent and [that] the in-place voids should never fall below approximately 3 percent during the life of the pavement." [3] This corresponds to a compaction ratio of 92-97 percent of MTD. A rule of thumb for initial compaction is that for every 1 percent increase in air voids (above 7 percent), about 10 percent of the pavement life may be lost [24]. HMA pavements that are properly compacted will contain enough air voids to prevent rutting due to plastic flow, but low enough air void content to prevent permeability of air or water. The remaining 3% of the allowable compaction of 98% is left assuming that additional compaction occurs under traffic loading [3].

There are two methods to compact pavement during construction. First, a weight can be applied to the HMA surface and the material underneath the contact area is compressed. Second, a shear stress can be created between the compressed area and adjacent uncompressed areas. These methods are dependent on three types of available equipment: the paver screed, the static or vibratory steel wheeled roller, and the pneumatic tire roller.

The paver screed is mostly utilized to distribute the HMA at a correct thickness and provides initial mat compaction to approximately 75 to 85 percent of the MTD of the HMA. Hence, use of the paver screed must be followed by another means of compaction. Steel wheeled rollers are compaction devices that use the weight of steel drums to compress the underlying HMA and can be used for final compaction. Some of the steel wheel rollers are equipped with vibratory drums that assist in the compactive effort. Drum vibration adds a dynamic load to the static roller weight and thus overcomes aggregate interlock during compaction by moving the aggregate particles to final positions that produce greater friction and interlock. By using an appropriate drum vibration frequency, a better compaction can be produced in the mat while providing a smoother mat in a shorter length of time. As an alternative to the steel wheeled rollers, pneumatic tire rollers utilize a set of smooth tires, typically four to five on each axle. The arrangement of the multiple tires on the axles compresses and kneads the mat. Unlike the steel wheel rollers, with the pneumatic tire rollers the densification is achieved in multiple areas at once and in addition to being compressed, the mat is also kneaded. When the milled surface of a roadway is uneven, a pneumatic tire roller provides a more uniformly compacted surface due to the independence of each individual pneumatic tire.

The equipment used and the amount of the compactive effort affects the compaction achieved. The final compaction is dependent on other factors such as the sequence and number of roller passes, roller speed, pattern that each roller uses on the mat as well as the rigidity of the underlying base material. In general, a pattern must be established such that it will receive uniform compaction through the entirety of the newly placed mat. This pattern will also specify the sequence and number of roller passes needed to achieve compaction. There are numerous variables that may effect the compaction of the pavement during construction and the lifetime of pavement. These variables include the HMA placement methods described above, weather, HMA temperature, uniformity of the milled surface, and the aggregate used in the mix which varies by location.

Weather components such as ambient temperature, cloud cover, humidity, and wind speed affect the cool-down rate of the HMA, which is directly proportional to compaction [10]. HMA generally compacts best between 175 and 320F. HMA temperature has a direct effect on the viscosity of the asphalt binder and thus the workability of the mix. "As HMA temperature decreases, its asphalt binder becomes more viscous and resistant to deformation, which results in a smaller reduction in air voids for a given compactive effort. As the mix cools, the asphalt binder eventually becomes stiff enough to effectively prevent any further reduction in air voids regardless of the applied compactive effort" [12]. Therefore, the warmer the air temperature the slower the cool down rate of the mat, thus the total time available to apply the compaction effort increases. Low wind speeds also reduce the mat heat loss due to convection.

Physical, as well as chemical properties, of the HMA may effect the compaction and resultant density of the pavement [15, 16]. These physical characteristics of the aggregate include: the nominal size, shape, texture and its mineral content [17]. These properties affect the way aggregates interlock and thus the ease with which the aggregate can be rearranged under roller loads. Rough surface textures, cubical or block shaped aggregate (as opposed to round aggregate) and highly angular particles (high percentage of fractured faces) will all increase the required compactive effort to achieve a specific density [17]. A rough surface texture on the aggregate gives the asphalt binder a higher adhesive capacity, producing a stronger bond, increasing the friction between particles, and thus creating a stronger HMA. The fine midsize, rounded aggregate (natural sand) can cause a mix to displace laterally or shove under roller loads thus producing a less desirable pavement mat. The density result for HMA pavement with midsize, rounded, fine aggregate will be higher than with course aggregate, but the strength of the pavement could be lower because of the reduced internal friction between the aggregate particles.

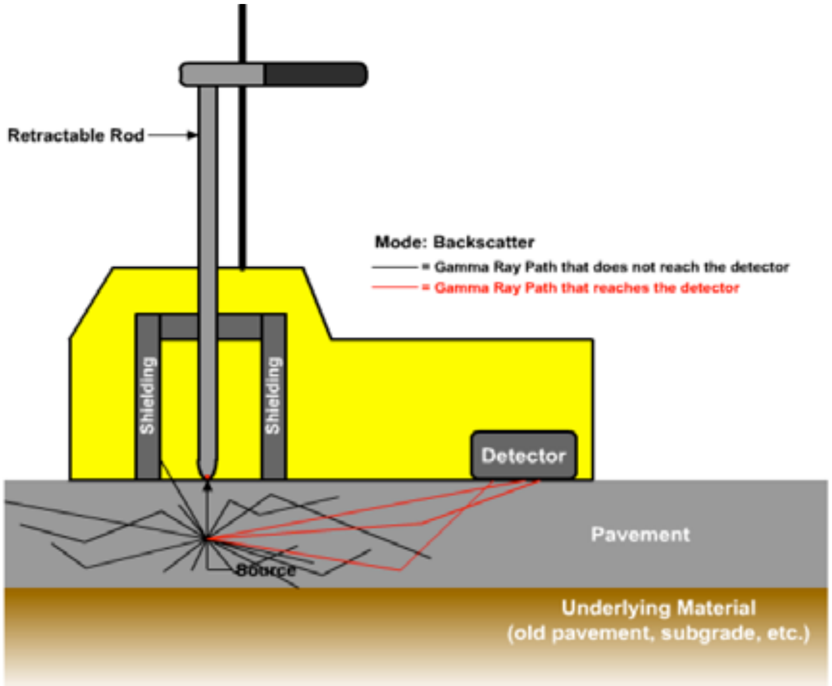
Depending on the source of the aggregate, the type of material used, and the characteristics of the aggregate, the composition and density of the HMA will vary. In addition to variations in the physical composition of the aggregate, the chemical composition or specific minerals in the aggregate also vary. Each mineral has different strength properties. Knowledge of the minerals in the aggregates provides information on the strength of the aggregate before mixing it with other materials to make HMA. Typically the stronger the tensile strength of aggregate, the stronger the HMA mix because the HMA is able to withstand greater compactive effort. While the mineralogy of the aggregate does not affect the actual compaction per se, it is possible that it affects nuclear gauge readings.

The asphalt binder grade (or stiffness) also affects compaction through its viscosity. The asphalt binder is combined with the aggregate to make a HMA mat. A binder that is higher in viscosity will generally result in a mix that is more resistant to compaction. Additionally, the more a binder hardens (or ages) during production or storage, the more resistant the mix is to compaction [17]. The selection of the binder is considered to be an integral part of the mix design process.

### *2.2 THE NUCLEAR GAUGE FOR DENSITY MEASUREMENT*

During the last forty years the nuclear gauge has been the instrument of choice for the non-destructive measurement of HMA compaction. Many agencies and commercial firms have made use of the nuclear gauge density values because this method does not include delay as required if one cores the pavement to perform the laboratory density measurements. The California Division of Highways conducted the first recorded study using nuclear gauges in 1954. At that time, the primary use of the nuclear gauge was to determine the density and moisture content of soils. With time, the nuclear gauge was introduced as a method to measure the density of pavements and Portland cement concrete. The earliest documentation of nuclear gauge devices being used for asphalt pavements is 1964 [18].

Nuclear density gauges have not changed in principle of measurement or calibration for the last thirty years [18]. As the name suggests they utilize a radioactive isotope, such as gamma photon emitter Cesium 137 or 241-Beryllium. Nuclear density gauges used for measuring pavement density operate by measuring the amount of backscattered gamma radiation (photons) as shown in Figure 2.2.




(Muench, et al. 2002).

**Figure 2.2 Nuclear Gauge Measurement of Pavement Density**

The nuclear density gauge must be calibrated, preferably against actual core densities obtained from the same material it will be used to measure [19]. Usually, nuclear gauges are calibrated at the factory by establishing a relationship between the counts and known density blocks [20]. The gauge calibration will change with time due to rugged use, the rough construction industry environment, changes in the gauge's mechanical geometry, degradation of the radioactive source or the electronic drift of the gauge's components [20]. In Connecticut, the DOT verifies their nuclear gauges on a set of granite and concrete blocks of known density and thickness. Currently, all nuclear gauges used for determination of payment on Connecticut DOT projects must be verified annually on the ConnDOT blocks to establish their bias. This bias is then added to all measurements made by that individual gauge.

Even with perfect calibration, the nuclear gauge can show misleading HMA density values resulting from the influence of the environment surrounding the equipment as well as variations in the material, surface texture, aggregate types, temperature, and moisture [1-6, 17, 19, 21]. Proper field adjustments can compensate for most of these factors, but questions regarding the overall accuracy and consistency of the nuclear gauge remain.

The mat thickness is one factor that is speculated to affect the nuclear gauge accuracy. In order to obtain nuclear density results, some gauges require a thickness value be keyed into the instrument. The value that is keyed into the instrument is the specified project thickness and does not necessarily reflect the exact thickness of the test location. Such conditions may influence the nuclear gauge readings [8, 9, 21]. Even if the actual thickness were known with certainty, it is speculated that each nuclear gauge model measures a different depth of the pavement, which may cause variability in the resultant density measurement [2]. For example, the radioactivity may travel through two layers when the top layer is 2 inches thick and the bottom layer is 4 inches thick producing an average of the two layer densities. In order to avoid these problems, only the partial value of top layer thickness can be entered into the gauge to ensure only the top mat density is measured [21]. Other research groups have proposed mathematical equations to account for this discrepancy, but only as a post construction solution [21].

To account for mat thickness a new nuclear gauge mode known as “thin lift” can be used. The backscatter method is the more conventional mode of density measurement. The mechanics of these two modes of measurements are basically the same. The difference arises in the algorithm each nuclear gauge uses to calculate a density based on the measurements at the receptor on the nuclear gauge. Variations in the algorithms depend on the manufacturer and the nuclear gauge model. For example, thin lift gauges, such as the model of gauges most commonly employed by ConnDOT, use an algorithm that does not require the user to input pavement thickness, while the gauge from the CAP Lab uses an algorithm based on the pavement thickness entered into the gauge. Some studies intended to determine if there is a correlation between the type of mode used have been inconclusive [21]. On the other hand, one California study determined that "the densities determined by the thin lift gauge are often much lower than the densities indicated by the standard backscatter nuclear gauge" [2].

It has also been suggested that proper pre-construction surface treatments such as milling may reduce the variability in nuclear density readings caused by inconsistencies in the existing pavement layer if it is performed properly and no rip outs occur. Milling old pavements removes ruts and other surface irregularities, which should reduce variability in the overlay thickness and density [8]. Milling is particularly helpful in maintaining uniform overlay thickness when correcting for cross slopes deficiencies.[8]. When a new surface layer of HMA is placed, the nuclear density measurements taken (in any mode) may include the sub-base layer in the calculation of the density as explained in previous section. Hence, the variation of nuclear density results may be reduced if milling is used.

Finally, the surface texture of the rolled material may affect nuclear gauge density readings. "When testing by nuclear methods, the gauge is supported by the highest points of the surface. Thus, any surface voids and depressions become an integral part of [the] pavement being tested" [2]. In other words, the surface on which the nuclear gauge rests may have aggregates raised above the mean pavement surface thus creating higher air void content in the calculation of density. A California study found there is no need to utilize known density material, such as rubber pads, to eliminate protrusion or irregularities on the surface of HMA. The results from the nuclear gauge when a material of known density and thickness was used as an interlayer between the gauge and the surface were not improved [2]. Currently, nuclear gauge operators have to pay close attention to the surface on which the nuclear gauge rests to ensure maximum surface contact between the nuclear density gauge and the pavement surface.

### *2.3 COMPARISON OF NUCLEAR GAUGE AND CORE SAMPLE DENSITY RESULTS*

Previous studies performed in California, Pennsylvania, Virginia, Nevada, Texas, and Maine have had similar conclusions for the use of nuclear density gauge readings. They all determined that the nuclear gauge should not be used for Quality Assurance and should remain only as a Quality Control tool in the field. [2, 3, 5, 8, 9, 16].

In California, the studies of HMA density using the nuclear gauge and core pavement sampling methods yielded inconclusive results. They utilized a total of 24 locations on paving projects where 8 different nuclear gauges took density measurements followed by core sampling [2]. The results from all gauges were inconclusive and statistically different from each other. The principle investigators suggest further data collection for statistically conclusive results [2]. This study concentrated on developing new procedures for calibration of nuclear gauges to achieve better correlation between the nuclear gauge density values and core sample density values [2]. In addition, they tried to determine if the thin lift mode provides better results than the backscatter. The results for this comparison were also inconclusive [2].

A Pennsylvania study also recommended only utilizing the nuclear gauge density readings for compaction Quality Control during construction. In order to reduce the variation in nuclear gauge density readings, this study concluded that the gauges must be calibrated based on numerous factors for each site and project tested [16]. This study utilized a total of 1041 test locations (on 8 sites) where both nuclear gauge and core samples were taken at the same location. The study included the continuation of existing pavement projects where nuclear gauges were used for Quality Control and Quality Assurance. In some cases, the pavements showed considerable distress within a short period of time. This study uses average results on "numerous gauges" used throughout the study period of two years [16]. The factors that researchers speculate affected their results were the season during which construction occurred, poor and non-uniform compaction procedures, excessive fine material content, and asphalt binder content [16]. Furthermore, the correlation coefficient between nuclear gauge and core samples ranged from 0.30 (poor) to 0.82 (good). One concern that the researchers did not address was the large number of gauges used and the differences in density measurements between them.

The Stroup-Gardiner and Newcomb study included the use of nuclear gauges in three states: Texas, Virginia, and Nevada [9]. These efforts resulted in some conclusive results. First, they determined that the length of time used to take a nuclear gauge reading has little or no effect on the accuracy of the density value. They illustrated that a 15 second reading generated a similar density reading to either the 1 minute or the 4 minute readings. A total of 3 state projects with 10 test sites each were used to compare 31 nuclear gauges to core samples. Their study included a total of 34 core samples (4 extra cores that were used in statistical calculation), and a minimum of 8 nuclear gauges used at each site. The nuclear gauges results were statistically different. “Further statistical analysis showed variances generated by each test location to be dependent on each specific set of test conditions” [9]. In addition, they determined that when the gauges were considered as a group, they failed to generate accurate regression equations. Thus, the accuracy of the nuclear gauge appeared to depend on the test conditions. However, “correlations between $R^2$ values and standard counts, date of last calibration, and average differences between cores and gauges showed no apparent trends” [9]. Thus, while a single nuclear gauge was consistent over time, they were not consistent with each other.

Another study performed by the Federal Aviation Administration in the Eastern Region of the United States, also attempted to determine possible correlations between the nuclear gauge accuracy based on core results [4]. “The results indicated that the correlation between the core and gauge results varied from gauge to gauge and from project to project. There was a higher degree of correlation among the gauges than there was between the core densities and the gauge results” [4]. This was presumably caused by the methods employed in the study, where the core samples were not taken directly at the location of nuclear gauge measurements. Furthermore, this study only had 4 cores per project (8 cores total) to compare with 3 nuclear gauges density measurements, a total of 30 density results per project. The study sample size was only 60 nuclear gauge density values.

Similar conclusions were found in a study in Florida where the authors also stated that the correlation between the core and gauge results varied from gauge to gauge and from project to project [5]. Their findings also indicated that the nuclear gauge density measurements did not always produce similar results and did not consistently correlate with the core densities [5]. Their sample size was also small. They utilized a total of 10 cores samples and 3 measurements per core location with five different nuclear gauges. This is a very small sample to make any conclusive statements that could be extrapolated to other pavement projects.

A study conducted by Dr. Jack Stephens at the University of Connecticut as part of a Joint Highway Research Advisory Council (JHRAC 63-6) project determined that surface texture of the pavement largely influenced the density measurement by the nuclear gauge [26]. Dr. Stephens indicated that the nuclear gauge measures the density of a certain volume underneath the gauge and any voids under the gauge would therefore be included in that volume thus decreasing the density. In this study, Silly Putty® was used to quantify the surface texture of the pavement. The surface texture was taken as the volume of voids per unit area at the surface of the road. The voids would fill with Silly Putty under a plate with a load on it. The diameter of the resulting patty of Silly Putty was correlated to blocks of known density and scribed surface textures. The correction could then be applied to subsequent readings taken with the nuclear gauge. The research showed an improved correlation between the nuclear readings and the cores. Further research is needed regarding the influence of surface texture on the accuracy of nuclear density readings.

This study, which includes multiple mixes and conditions, is based on a comprehensively larger dataset than previous work that has been reviewed by the study team.

### *2.4 SUMMARY OF BACKGROUND INFORMATION*

The literature review included a significant amount of research which aimed to determine the correlation between nuclear gauge density readings and density based on core samples. Furthermore, the statistical analyses have included several external factors that may affect the nuclear gauge readings. Most studies could not find causal relationships and concluded that the nuclear gauge should not be used for Quality Assurance but rather kept as Quality Control measure in the field. In Connecticut, the nuclear gauge is currently used for Quality Assurance. The overall objective of this study is to find methods and procedures that will allow for more accurate and consistent nuclear density results. This study is based on a comprehensive larger dataset than previous work that includes multiple mixes and conditions. This study did not directly examine surface texture, although using cores to develop a correction factor does account for general differences in surface texture between projects.

# 3 DATA COLLECTION AND TABULATION

This report makes use of data from four experiments conducted by the CAP Lab at the Connecticut Transportation Institute in 2003 and 2004 in cooperation with the Connecticut Department of Transportation and members of the HMA industry in Connecticut. The largest of these experiments was conducted on seven paving projects in six different towns in the state of Connecticut as shown on Figure 3.1. Note that the village of Mystic is in the town of Stonington and each had a separate paving project on I-95 included in the study. The second and third of the four datasets was collected on a subset of four of the paving projects studied in 2004, while the last dataset was collected on three parking lots in 2004. In total, there were four field experiments that resulted in the four datasets described in the subsections of this chapter: 1) the coring dataset, 2) the repeated location dataset, 3) the mode dataset; and 4) the recording time interval dataset. Figure 3.2 illustrates the seven research questions addressed in this report with these datasets. Section 3.1 includes a description of the methods used to take core samples in the field as well as the procedures used with the individual nuclear gauges that were used for all four datasets.

CAP Lab staff utilized Filemaker® software to organize the incoming data from the three agencies in various formats. The Filemaker software, was used to re-tabulate the data into cohesive datasets aggregated by the appropriate unit to perform the statistical tests Minitab®.

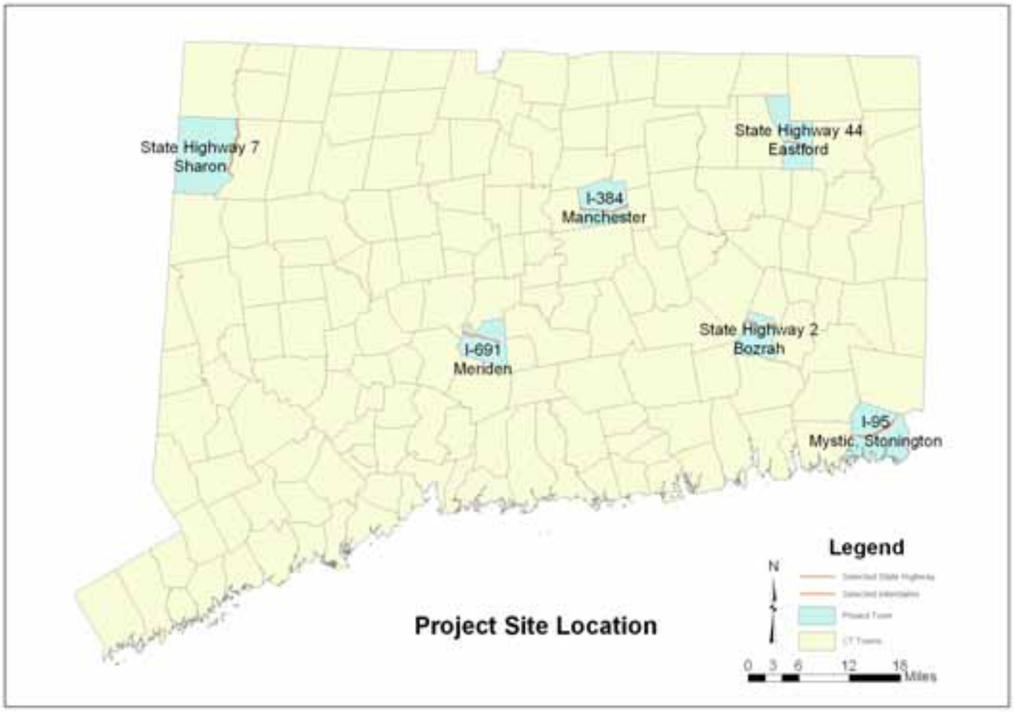



**Figure 3.1: Map of Project Site Locations.**

**Coring Dataset** Questions[1] (data collected during 2003 and 2004 on seven paving projects)

1. The comparison of core densities from three different labs.
2. The comparison of nuclear gauge density from seven instruments.
3. The comparison of average core density to nuclear gauge density.
4. The comparison of average transverse and longitudinal nuclear gauge density measurements at a given location.

[1] This dataset was also utilized with the fourth dataset for the seventh research question

**Repeated Location Dataset**, (data collected during 2004 on four paving projects)

5. Variation of nuclear gauge density readings as a function of external variables (aggregate source, temperature, thickness, drift of time).

**Mode Dataset** (data collected during 2004 by CAP Lab on only four paving projects)

6. The comparison of backscatter versus thin lift nuclear gauge mode

**Recording Time Interval Dataset** (data collected in 2004 on three parking lots by three agencies)

7. The effect of recording time interval on nuclear gauge density accuracy.

**Figure 3.2: Seven Main Research Questions**

### *3.1 THE CORING DATASET*

Seven sites were selected in consultation with the project's technical committee from the paving projects in the State of Connecticut in 2003 and 2004 based on the construction schedule and the schedule of the CAP Lab field crew as well as to ensure a range of geographic locations. Each paving project in 2003 and 2004 was required to have a minimum of 5 days of paving to be considered for inclusion in the study [6]. This limitation was imposed to ensure sufficient density readings per site to reduce the confounding impact of differences in project-based HMA design on nuclear gauge accuracy. Table 3.1 provides the seven project site locations, state project numbers, the number of days when the study team was on the construction site taking measurements, and number of core samples taken on each project.

**Table 3.1: Site Locations and Project Numbers**

| Site | Project | US/State Route | Town | Number of Days on Site | Date Range | Number of Core Samples |
|---|---|---|---|---|---|---|
| 1 | 171-306A | I-384 | Manchester | 14 | 8/7/03-8/18/03 | 83 |
| 2 | 172-345A | Route 2 | Bozra | 10 | 6/30/03-7/18/03 | 28 |
| 3 | 172-346A | I-95 | Stonington | 14 | 6/19/03-8/4/03 | 66 |
| 4 | 58-300 | I-95 | Mystic | 6 | 6/24/04-7/8/04 | 35 |
| 5 | 172-349A | Route 44 | Eastford | 7 | 7/20/04-8/2/04 | 40 |
| 6 | 79-219 | I-691 | Meriden | 10 | 8/17/2004 | 55 |
| 7 | 174-319D | Route 7 | Sharon | 8 | 9/14/04-9/17/04 | 45 |

For the seven sites, test locations were identified at random by generating random numbers using an Excel® worksheet and the predicted length of the mat to be placed every day. On the first day of paving for each site, 10 locations were randomly selected for testing. On the following days during the 2004 data collection only 5 random test locations were selected. During the 2003 data collection, one random location was tested each day following the first day of data collection. On several occasions during the 2003 data collection 10 additional random locations were tested. Nuclear gauge density readings were measured at these spots before cores were cut to allow laboratory testing. The core samples were obtained utilizing a combination of contractor and ConnDOT equipment. Tests for density of the cores were conducted in accordance with the applicable AASHTO standards (TP69) [6]. The standard measurements of the samples were performed by at least two of the three agencies (CAP Lab, Contractor, and ConnDOT) at their own labs, to test for consistency during the 2004 projects. The validity of the core measurements made by the various agencies was validated in accordance with AASHTO TP 69. Core densities that could not be validated were excluded from the computations. During the 2003 projects, only core density measurements made by ConnDOT were used. The 2003 cores were also tested by the contractor but the draft protocol developed by the CAP Lab, required the cores to be tested and turned over to ConnDOT within 24 hours. This did not allow sufficient time for the cores to dry thereby invalidating the contractor's data. Four nuclear gauge density measurements were also taken using the gauge orientation described in Chapter 1. These were then recorded by at least two of the agencies (if the Contractors nuclear gauge was not available on the project that day only two sets of measurements were taken). The information and results of the data collected on each site were stored in two databases created and managed by CAP Lab. Each method of density measurement is described in detail in the following two sub-sections.

Each of the 966 raw data records in this field database corresponds to a particular nuclear gauge density reading. Therefore, each row of data contained 4 nuclear gauge density measurements and one core corresponding to the density result from the lab for that given agency. Table 3.2 provides the total number of nuclear gauge records collected on each site by each agency. In addition, other valuable information was stored in this database. Each record contains: nuclear gauge identification number, day on the project, and core test results such as density, specific gravity, air voids, and maximum theoretical specific gravity. The core specific gravity was converted to percent of maximum theoretical density (MTD) for presentation in this report.

**Table 3.2: Number of Validated Measurements Taken by Each Agency**

| Site | Project | US/State Route | Town | CAP Lab Number of Records | ConnDOT Number of Records | Contractor Number of Records | Total Number of Records |
|---|---|---|---|---|---|---|---|
| 1 | 171-306A | I-384 | Manchester | 82 | 63 | 65 | 210 |
| 2 | 172-345A | Route 2 | Bozra | 28 | 28 | 28 | 84 |
| 3 | 172-346A | I-95 | Stonington | 52 | 53 | 55 | 160 |
| 4 | 58-300 | I-95 | Mystic | 35 | 34 | 32 | 101 |
| 5 | 172-349A | Route 44 | Eastford | 39 | 35 | NA | 74 |
| 6 | 79-219 | I-691 | Meriden | 52 | 36 | 44 | 132 |
| 7 | 174-319D | Route 7 | Sharon | 41 | 36 | NA | 77 |
| | | | TOTAL | 329 | 285 | 224 | **838** |

This preliminary dataset was reformatted such that every observation or row corresponded to a single core location. In total, there were 6 columns with nuclear gauge readings as a percentage of MTD. Each nuclear gauge column is a mean of the four measurements made at 90 degrees to one another by one model gauge at a single location. Furthermore, in 2004 each agency performed individual compaction tests on the core samples. These results were also stored in separate columns for each agency for each of the 175 core locations in 2004. The mean of the valid core measurements (as determined by AASHTO TP 69) was calculated to use as the standard for determination of individual nuclear gauge error. This coring dataset was used to answer the first three research questions listed in Figure 3.2 and as an additional source of data to answer the seventh research question in Figure 3.2.

The original 966 raw data records of the field dataset were re-structured a second way for use to compare the transverse and longitudinal nuclear density readings. For the statistical analysis, a mean of the four density readings in each direction was calculated for all nuclear gauges. Due to missing observations, this dataset had only 936 observations. In this dataset, a single row represented a particular set of four nuclear gauge readings as opposed to all measurements for a single core location. When 2 or 3 sets of nuclear gauge readings were taken on one core location, this dataset had two or three rows of observations.

### 3.1.1 Nuclear Density Gauges

A total of six nuclear gauges were used in this study. CAP Lab utilized a Troxler-3450 model on all seven sites. The contractor used a Seamans L-540 on five sites. Sites 5 and 7 were not tested with a nuclear gauge by the contractor. ConnDOT utilized a total of four gauges over the course of this study. ConnDOT's CPN-990 was used on four sites, and different gauges measured the remaining sites. Table 3.3 contains a list of the make and model of each nuclear gauge used in the study.

**Table 3.3: Nuclear Gauge Make and Model Used by Project.**

| Site | Project | US/State Route | Town | CAP Lab's Model | ConnDOT's Model | Contractor's Model |
|---|---|---|---|---|---|---|
| 1 | 171-306A | I-384 | Manchester | Troxler-3450 | CPN-354 | Seamans L-540 |
| 2 | 172-345A | Route 2 | Bozrah | Troxler-3450 | CPN-990 | Seamans L-540 |
| 3 | 172-346A | I-95 | Stonington | Troxler-3450 | CPN-559 | Seamans L-540 |
| 4 | 58-300 | I-95 | Mystic | Troxler-3450 | CPN-559 | Seamans L-540 |
| 5 | 172-349A | Route 44 | Eastford | Troxler-3450 | Troxler-17269 | NA |
| 6 | 79-219 | I-691 | Meriden | Troxler-3450 | CPN-990 | Seamans L-540 |
| 7 | 174-319D | Route 7 | Sharon | Troxler-3450 | CPN-990 | NA |

The nuclear gauge units had different sources of radiation but all were operated in the thin lift mode unless otherwise specified. Although a better accuracy may have been obtained with longer recording time intervals, a 30-sec reading time was adopted for the 2003 data collected by ConnDOT and the Contractor and 1-min readings for the CAP Lab (the CAP Lab gauge cannot perform 30 second readings). This short time interval was chosen because this is the current Connecticut DOT nuclear gauge specification standard. Keeping recording time intervals short is desirable for safety and in order to not impede the ongoing paving operations. In 2004, the recording time interval was changed to 1-min readings for all agencies because in the 2003 study, the CAP Lab's nuclear density gauge was the most consistent and exhibited less variation in density readings on each project.

For the coring data set, each core location was selected at random distances using

**Figure 3.3: Nuclear Gauge Measurement Location Outline**

a random number generator from the start of the new mat prior to mat placement. The locations were marked with “lumber crayon” as showed in Figure 3.3. Each agency collected four nuclear gauge measurements per test location. The nuclear gauge devices were set on the pavement and after each reading the gauge was rotated as described in Chapter 1. The first nuclear gauge measurement was always made in the longitudinal direction on the mat.

All data were recorded by three agencies and stored in one data file created and managed by CAP Lab. Each of the participating parties created a spreadsheet for each day of data collection. The spreadsheet record contained agency identification, nuclear gauge identification number, day on the project, and core identification that identified the location of nuclear gauge measurement. In addition, CAP Lab collected the temperature of the mat using an infrared temperature gun during the nuclear gauge reading at each test location in 2004. The location of each measurement was also recorded using a GPS device whenever possible.

### 3.1.2 Collection of Core Samples

Core samples were obtained as soon as the pavement cooled sufficiently so the cores did not distort during cutting. To expedite the cooling process on some projects, ice was applied at the test locations after all nuclear testing was completed. The cutting of cores was performed with a water-cooled masonry saw with a diamond-tipped blade. Figure 3.4 illustrates the coring process. All cores were then labeled, air dried and transferred to either the DOT’s Materials Testing Laboratory or the contractor’s laboratory. In the laboratory, the cores were further oven or air dried and tested for density according to AASHTO TP69 [6]. Once the first laboratory performed all of the tests to determine the density, thickness and air void content the core samples were further shipped to the second laboratory and then to CAP Lab for similar testing. The maximum theoretical specific gravity testing was performed by ConnDOT personnel and the average of the day's test results were used for that day's cores. In addition, the three laboratories measured the thickness of the HMA and their average was used in the analysis of the density.

**Figure 3.4: Core Cutting**

### *3.2 REPEATED LOCATION DATASET*

The second dataset consists of nuclear gauge measurements from the four Connecticut paving projects performed in 2004. (No repeated measurements were taken on the 2003 sites.) Four nuclear density readings were taken at the single locations on each project site and were repeated once each day for the duration of the paving at that site. The purpose of this analysis was to observe and quantify variation in nuclear gauge readings at exactly the same locations due to external factors over a period of time. The measurements were performed by three agencies utilizing the same measurement mode as was used for the field testing of the core locations using 1-minute intervals. In total, there were 201 observations recorded by CAP Lab, ConnDOT, and the Contractors. This dataset contained the following additional information: project number, route number, and a countdown of days spent on each site. A mean of the four density values was calculated and evaluated over time and by project.

### *3.3 MODE DATASET*

The third dataset also only contains data collected on the 2004 paving projects. A total of 10 measurements were performed twice at random locations once a day during the construction on each site. Only the CAP Lab nuclear gauge repeated these measurements: once in the thin lift mode and once in the backscatter mode. The other two agencies could only perform measurements in one mode and therefore were not used for this experiment. These observations are compared to determine if the mode significantly affects the gauge readings. The differences between the two modes arise in the algorithm each nuclear gauge uses when determining the density of pavement. Variations exist in the algorithms depending on the manufacturer and the nuclear gauge model. This dataset was imported into Minitab for comparison of mode of nuclear gauge (backscatter versus thin lift) and factors affecting its readings.

### *3.4 RECORDING TIME INTERVAL DATASET*

The fourth dataset contains repeated nuclear gauge measurements taken on three existing parking surfaces with three different aggregate sources in the HMA. For this data, 10 measurements for each nuclear gauge and each time recording interval were taken without moving the gauge. Four recording intervals were used; 15 seconds, 30 seconds, 60 seconds, and 90 seconds. Where possible, each agency was asked to perform these measurements in two modes with different gauges: backscatter and thin lift. CAP Lab only performed the nuclear gauge measurements for two time intervals due to a nuclear gauge limitation: 15 and 60 seconds. The contractor only performed measurements in backscatter mode for four time intervals of 15, 30, 60, and 90 seconds.

ConnDOT also performed measurements for only two time intervals: 60 and 90 seconds. The worksheets obtained by the three agencies, and a fourth worksheet containing core density values provided by a contractor, were combined. The resultant database allowed for the evaluation of the recording time interval on the nuclear gauges variability. The variables available for modeling included: agency performing the measurement, location, time interval, and mode (thin lift versus backscatter). The mean and standard deviation of each set of ten measurements was used to calculate the covariance of the nuclear gauge density. Covariance was modeled as a function of recording time interval, site, mode and agency.

In addition to this dedicated recording time interval dataset, the large coring dataset described in section 3.1 was used to conduct an additional comparison of nuclear gauge variation as a function of recording time intervals. Recall that a 30-second recording time was adopted for all of the 2003 data collected by ConnDOT and the Contractor, but the CAP Lab performed 1-minute measurements. In 2004, the recording time interval was changed to 1-minute readings for all agencies (ConnDOT, Contractor, and CAP Lab). The variance in observations was compared for the two recording time intervals.

# 4 ANALYSIS AND RESULTS

Several statistical tests were used to evaluate the seven main research questions posed: pair t-tests, ANOVA, and linear regression. The statistical analysis procedures are presented in this chapter together with the results for each research question in a separate subsection.

## *4.1 COMPARISON OF CORE DENSITIES FROM THE THREE LABORATORIES*

ConnDOT provided the core density values for three of the seven projects. On the other four projects, different pairs of labs conducted the tests. In order to compare the core densities determined in the labs, a series of nine (three sets of three) paired t-tests were performed. The core densities were expressed as percent of MTD for these comparisons. The tests allowed us to determine if the average differences in core density values were statistically different from zero. These tests also allowed for estimation of the reported accuracy level of the differences between the laboratory densities at the 95% confidence level and the probability that the difference was less than 0.1% MTD.

Each of the 3 sets of paired t-tests had a different number of observations as shown in Table 4.1. In total, the contractor performed 91 core densities out of which only 56 cores have corresponding ConnDOT core density values after validating the results in accordance with AASHTO TP69. 69 of the 91 cores had a corresponding CAP Lab core density value. The participating contractor was only present for 2 of the 4 projects conducted in 2004 as those projects were being constructed by that contractor. ConnDOT and CAP Lab had 129 core density pairs in common to compare after the cores were validated using tolerances set by AASHTO [22]. The core data that came from ConnDOT were the only laboratory values used in 2003. The reasoning for this is that it was established in the 2003 project protocol that the contractor turn the cores back over to ConnDOT within 24 hours of that nights data collection. There was some doubt that the cores had enough time to dry adequately before the contractor measured the density and as such the data from the cores was suspect. ConnDOT however, had sufficient time to measure the cores in the lab and one of the methods they used on the 2003 cores was the vacuum sealing method (AASHTO TP69) which was then adopted for the remainder of the project.

**Table 4.1 Comparison of Core Samples.**

| I | II | III | IV | V | VI |
|---|---|---|---|---|---|
| X1-X2 | Number of Observations | Mean Difference % of MTD | p-value for Paired t-test where Ho: x1-x2 = 0 | Mean Difference* where P=0.05 for Ho: x1-x2 = * (Pair t-test) | p-value for Paired t-test where Mean Diff. < 0.1% |
| CAP Lab - ConnDOT | 129 | 0.059 | 0.763 | 0.38 | 0.538 |
| ConnDOT- Contractor | 56 | 0.125 | 0.047 | 0.23 | 0.344 |
| CAP Lab - Contractor | 69 | 0.289 | 0.293 | 0.75 | 0.246 |

When evaluating the mean difference between the core densities, ConnDOT values were slightly higher than CAP Lab's and 0.125 percent higher than the contractor. The mean difference in core densities between the CAP Lab and Contractor was also small, 0.289 percent.

The right hand columns in Table 4.1 are the results of the paired t-tests. Three types of comparisons for the 3 agency pair combinations were made. The initial comparison is the typical paired t-test where the null hypothesis is that the difference between the pairs of core density observations is zero. The p-value results are shown in column four of Table 4.1. The p value indicates the probably of the null hypothesis being true. In this case the null hypothesis is that the lab values from different labs are equal. At a 95 percent confidence level, this hypothesis could only be rejected for the second comparison, the difference between ConnDOT's cores and the Contractor cores. In the other two cases, the variability in the cores results in an inability to conclude the labs are different and the assumption that the measurements are therefore equal.

These lab density pairs are also considered another way in column five. The objective of this test was to estimate the 95% confident level for the mean difference. In other words, the values in the column are the maximum difference or upper reported accuracy level between core density values. All three reported accuracies were greater than the 0.1% MTD currently used by ConnDOT. Two of the three were close to 1%.

Further analysis was conducted to determine the probability that the difference between the paired core measurements was less than 0.1%. The 0.1% is of a particular interest because it is the level of accuracy at which contractor payment penalties are enforced in Connecticut. For example, if the contractor's average density for the day is 92.0% of MTD then they will get paid 100% but if the average density is 91.9% for the day the contractor will be penalized. These results are shown in column six of Table 4.1. The numbers in this column represent the probability that the differences are greater than 0.1%. For the comparison of ConnDOT to contractor, the probability that the difference is greater than 0.1 % is equal to 0.99, for comparison of ConnDOT to CAP Lab the probability that the difference is greater than 0.1 % is equal to 0.34 and finally, for the comparison of CAP Lab to contractor the probability that the difference is less than 0.1 % is 0.67%. These results indicate very low confidence in the appropriateness of the 0.1% reported accuracy for the nuclear gauge readings.

Since the results of core densities vary by the laboratory performing the test; an error is introduced in the subsequent analysis in this study where we intended to use the core densities as the standard against which nuclear gauge densities were compared. Because we cannot say which agency has the most accurate core density value, the mean of the three values is used as the accuracy standard in subsequent comparisons provided they can be validated in accordance with AASHTO TP69. The values that could not be validated in accordance with AASHTO were then discarded. Section 4.3 of this chapter will utilize the mean of the validated core values for comparison with the individual nuclear gauges.

### *4.2 COMPARISON OF DENSITY FROM DIFFERENT NUCLEAR GAUGES*

A series of paired t-tests were again used for this comparison between individual nuclear gauges. Within the main coring dataset, six individual nuclear gauges were used on the 2003 and 2004 state paving projects. For each of the six nuclear gauge models, a mean of the four density measurements made at one location was calculated. T-tests were used for the three types of comparisons for each of the nine agency pair combinations shown in Table 4.2. These comparisons were made between every pair of nuclear gauges used on the same core location on the project. Each pair has a different number of observations ranging from 21 to 323. The mean difference between two nuclear gauge density values ranged from 0.3% of MTD for the ConnDOT nuclear gauge CPN-990 and CAP Lab Troxler-3450 to 1.4% of MTD for ConnDOT nuclear gauge CPN-354 and CAP Lab Troxler-3450.

**Table 4.2 Comparison of Nuclear Gauge Density**

| I | II | III | IV | V | VI |
|---|---|---|---|---|---|
| **X1-X2** | Number of Observations | Mean Difference % of MTD | p-value for Paired t-test where Ho: x1-x2 = 0 | Mean Difference* where P-value=0.05 for Ho: x1-x2 < * | p-value for Paired t-test where Mean Diff > 0.1 |
| ConnDOT (990) – CAP Lab | 107 | 0.300 | 0.015 | 0.502 | 0.948 |
| ConnDOT (354) – CAP Lab | 28 | 1.355 | 0.000 | 1.610 | 1.000 |
| ConnDOT (17269) – CAP Lab | 39 | 0.802 | 0.004 | 1.245 | 0.999 |
| ConnDOT (559) – CAP Lab | 119 | 0.536 | 0.000 | 0.696 | 1.000 |
| Contractor (Troxler) – CAP Lab | 25 | 0.931 | 0.000 | 1.094 | 1.000 |
| Contractor (L540) – CAP Lab | 323 | 1.211 | 0.000 | 1.337 | 1.000 |
| ConnDOT (990) - Contractor (L540) | 68 | 0.528 | 0.013 | 0.875 | 0.978 |
| Contractor (L540) - ConnDOT (599) | 125 | 0.616 | 0.000 | 0.775 | 1.000 |

The results of the initial comparison using a paired t-test where the null hypothesis is that the mean difference between a pair of nuclear gauge density observations is zero are shown in column four of Table 4.2. In all cases, at a 95% confidence level, the difference in paired density value means was statistically different from zero. In other words, the densities from different nuclear gauges are not equal. The second t-test determined the upper reported accuracy range (maximum mean difference at 95% confidence level). In other words, this column represents calculations of the level of difference where we are 95% certain the true difference is below. For example, for row 1, the data indicates we are 95% certain that the true difference between these gauges is less than 0.502%. The last column of the table provides the probability that the difference between the two gauges is smaller than 0.1% of MTD. Column 6 of Table 4.2 indicates a very high probability that all mean differences are smaller than 0.1% of MTD.

In summary, the nuclear gauge density results vary significantly between the nuclear density gauges performing the measurements. The CAP Lab density values were always lower than the core densities. The contractor’s nuclear density readings were either greater or lower than the core densities depending on the project. ConnDOT's results varied based on the nuclear gauge model used and the particular paving project. This is problematic especially given that no two nuclear gauges produced statistically similar results.

### 4.3 COMPARISON OF MEAN CORE DENSITY TO NUCLEAR GAUGE DENSITIES

The main coring data set was also used for the comparison of the nuclear gauge density to the mean of the lab core densities. Table 4.3 contains a summary of the sets of paired t-tests used to evaluate whether or not mean core densities are statistically different from the nuclear gauge density values. In total, there were six comparisons for the six individual nuclear gauge devices used in this project. The average difference is shown graphically for each gauge in Figure 4.1. The number of observations, indicated in column two of Table 4.3, varied depending on the extent of use of the given nuclear gauge model on individual construction sites.

**Table 4.3: Comparison of Nuclear Gauges to Mean Core Values**

| I | II | III | IV | V | VI | VII |
|---|---|---|---|---|---|---|
| X1-X2 | Number of Observations | Mean Difference % of MTD | Standard Deviation Difference | p-value for Paired t-test where Ho: x1-x2 = 0 | Mean Difference where P=0.05 for Ho: x1-x2 = 0 (Pair t-test) | p-value for Paired t-test where Mean Diff. > 0.1% |
| Mean Core – CAP Lab | 321 | 1.213 | 1.053 | 0.000 | 1.31 | 1.000 |
| Mean Core - ConnDOT (990) | 75 | 0.289 | 1.289 | 0.056 | 0.53 | 0.896 |
| Mean Core - ConnDOT (354) | 63 | 0.477 | 1.050 | 0.001 | 0.70 | 0.997 |
| ConnDOT (17269) - Mean Core | 36 | 0.519 | 0.986 | 0.003 | 0.80 | 0.992 |
| Mean Core - ConnDOT (559) | 82 | 1.253 | 1.279 | 0.000 | 1.49 | 1.000 |
| Mean Core - Contractor (L540) | 230 | 0.366 | 1.490 | 0.000 | 0.53 | 0.996 |

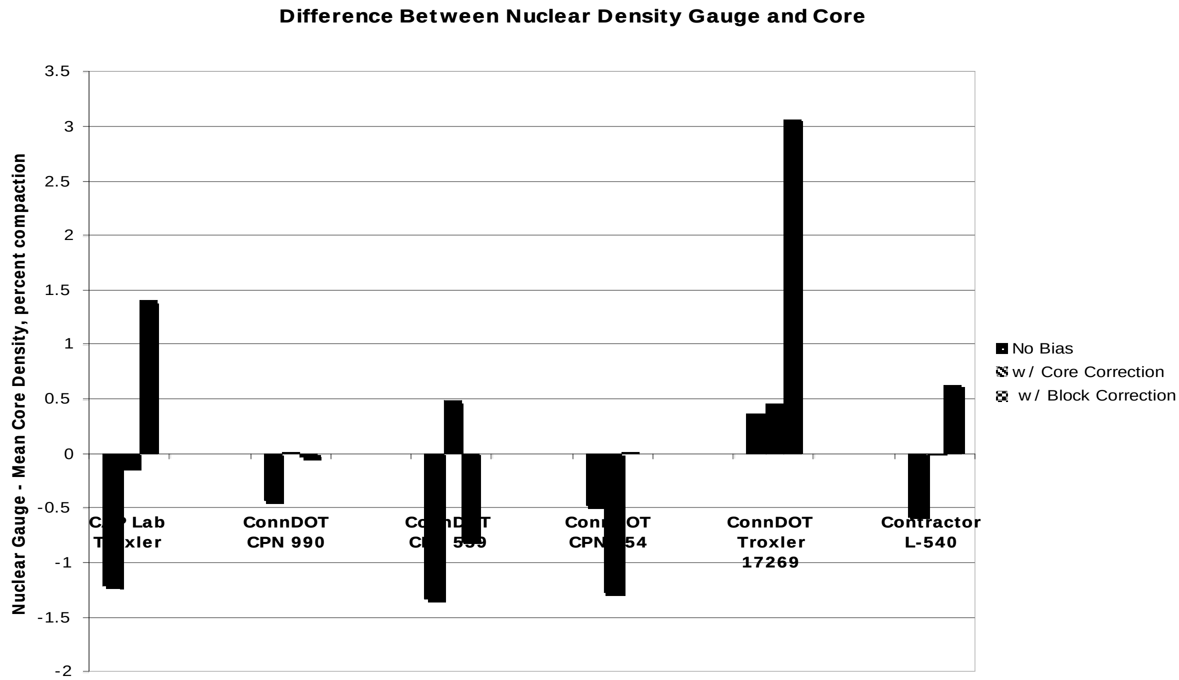



**Figure 4.1: The Mean Difference between the Mean Core Sample Density and Nuclear Gauges**

The mean difference in densities as a percent of MTD are shown in Figure 4.1 for all gauges with no bias applied, with the block bias applied and also with the core correction factor applied. The average errors generated through use of the block bias are large in comparison to the errors with the core correction as well as with no bias at all as is evident in the figure.

The first set of paired t-tests in Table 4.3 (column 5) indicates that the average gauge errors are statistically different from zero at the 95% confidence level for all but one gauge: ConnDOT's CPN-990. The second paired t-tests, to obtain the 95 percent confidence error level indicates the nuclear gauge error only falls below 1% for 4 gauges: All other nuclear gauge 95% confidence level errors were higher than 1% of MTD. The last series of paired t-tests indicate a very high probability that the nuclear gauge error is greater than the 0.1% reported accuracy level currently used by ConnDOT. These mean core values were compared and tested with each nuclear gauge in an identical manner as described above. In summary, all gauges had larger errors than desirable. Since the mean cores had both lower and higher density values, external factors might have had an effect on the nuclear gauge readings. These external factors include temperature and mat thickness, which are investigated below. Another hypothesis for explaining the variation, which was not tested, is that the volume of the sample tested by the nuclear gauge measurement is larger than the core sample. The core sample is only six or eight inches in diameter compared to nuclear gauge which tests a larger volume depending upon the gauge's measurement system geometry. The nuclear value is then an average density over a larger area.

Further analysis focused on nuclear gauge error which was estimated as the difference between individual nuclear gauge value and mean core value (Nuclear gauge density minus mean core density. Note that negative values indicate the core value was higher than the nuclear density gauge). The thickness of the core was used to approximate mat thickness. Temperature is the measurement of pavement surface temperature measured with an infrared temperature gun during nuclear gauge density testing. The temperature values ranged from 90 degrees Fahrenheit (32.2º C) to 156 degrees Fahrenheit (68.8º C). The mat thickness ranged from a low of 1.370 inches in Mystic to a high of 2.796 inches in Eastford. One-dimensional regressions were performed to estimate the effect of individual factors on the nuclear gauge error. A summary of the regression results is shown in Table 4.4. The R-square values are very low indicating poor correlation of nuclear gauge error to mat thickness and pavement temperature. The following generalization can be made based on the regression results: as the thickness of the HMA mat increases, the trend of the error of density measurement decreases. Also, the temperature of pavement at which the measurements were taken had no effect on nuclear gauge density readings. Note that this generalization is nuclear gauge and project specific. The equations cannot be applied at other construction sites.

**Table 4.4: Regression Results of Nuclear Gauge Error to Mat Thickness and Pavement Temperature**

| Nuclear Gauge | Mean Core Thickness (inches) | | | | Temperature (degrees F) | | | |
|---|---|---|---|---|---|---|---|---|
| | y-Intercept | Slope | P-Value | R-square | y-Intercept | Slope | P-Value | R-square |
| CAP Lab | 0.76 | -0.94 | 0.00 | 5.6% | 0.31 | -0.01 | 0.023 | 2.1% |
| ConnDOT (990) | 0.23 | -0.26 | 0.66 | 0.0% | -2.08 | 0.02 | 0.491 | 0% |
| ConnDOT (354) | 1.78 | -0.99 | 0.12 | 4.8% | -1.14 | 0.006 | 0.575 | 0% |
| ConnDOT (17269) | 1.52 | -0.49 | 0.44 | 0.0% | 3.70 | -0.026 | 0.054 | 0% |
| ConnDOT (559) | 1.83 | -1.52 | 0.01 | 6.3% | -0.34 | -0.003 | 0.818 | 0% |
| Contractor (L540) | 0.82 | -0.57 | 0.11 | 0.7% | 1.64 | -0.01 | 0.214 | 0.4% |

In addition to the regression analysis, ANOVA tests were also performed to consider the variance in nuclear gauge error as a function of aggregate source in the HMA. In total, only three ANOVA results were obtained for three nuclear gauges. The other three nuclear gauges were only used on single sites. Figure 4.2 provides a summary of the ANOVA results. The results indicate that for all three compared nuclear gauges, the aggregate source is a significant factor affecting the density error. For the two nuclear gauges used with Montville aggregates the error increased significantly. Furthermore, note that the difference between these projects can be assumed to be a function of aggregate source but may not be. Other systematic differences may be present between projects.

**CAP Lab nuclear gauge error by source of aggregate**

```
F = 33.40    P = 0.000    R-Sq = 33.61
Individual 95% CIs For Mean Based on Pooled Standard Deviation

Level           N     Mean   StDev  ------+---------+---------+---------+---
Killingly      39  -0.0576  0.6495                                (---*----)
Massachusetts  41  -0.6569  0.6723                      (---*---)
Montville      27  -1.8175  0.5876  (-----*----)
New Britain    52  -0.7672  1.0486                    (---*---)
Newington      82  -1.5287  1.1010         (---*--)
Wauregan        80  -1.8226  0.6592   (---*--)
                                    ------+---------+---------+---------+---
                                       -1.80     -1.20     -0.60      0.00
```

*ConnDOT CPN-990 nuclear gauge error by source of aggregate*

```
F = 0.23     P = 0.635    R-Sq = 0.00
Individual 95% CIs For Mean Based on Pooled Standard Deviation

Level           N    Mean  StDev    -+---------+---------+---------+--------
Massachusetts  36  -0.215  0.696        (----------------*----------------)
New Britain    39  -0.358  1.668    (----------------*---------------)
                                    -+---------+---------+---------+--------
                                  -0.75     -0.50     -0.25      0.00
```

**Contractors Seamans L-540 nuclear gauge error by source of aggregate**

```
F = 43.03    P = 0.000    R-Sq = 35.5%
Individual 95% CIs For Mean Based on Pooled Standard Deviation

Level         N    Mean  StDev  ---+---------+---------+---------+------
Montville    27  -1.828  0.703  (----*---)
New Britain  53   0.689  1.840                             (--*--)
Newington    69   0.246  1.144                         (-*--)
Wauregan      81  -1.090  0.757           (--*--)
                                ---+---------+---------+---------+------
                                -2.0      -1.0       0.0       1.0
```

**Figure 4.2: Analysis Of Variance (ANOVA) for Nuclear Gauge Error by Source of Aggregate**

#### *4.3.1 Comparison of longitudinal to transverse nuclear gauge density measurements*

For the coring dataset, each agency collected four individual nuclear gauge measurements per test location. The nuclear gauge devices were set on the pavement with the source rod end pointing in the direction of paving and after the first reading, the gauge was rotated 180 degrees. The first and second reading provided measurements with the gauge orientated longitudinally. After the second reading the gauge was rotated 90 degrees for the third reading. The gauge was then rotated 180 degrees for the final reading. The third and fourth readings provided measurements with the gauge orientated transversely. To compare the nuclear density readings taken in the transverse and longitudinal directions, an average of the two readings was made for each location and each gauge. In total, there were 937 paired records available for use in a series of t-tests.

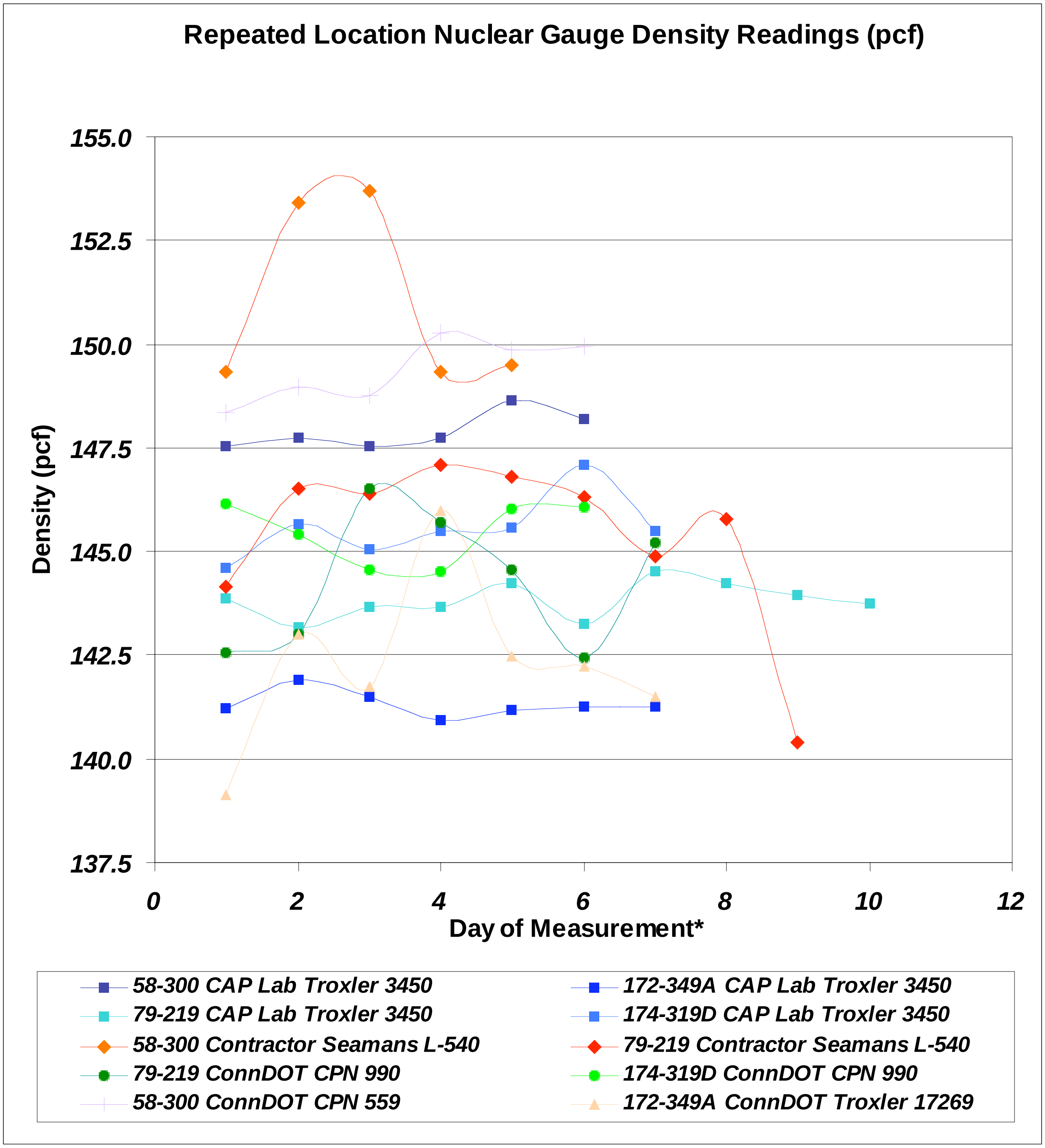
When comparing the longitudinal to transverse nuclear measurements we found that the mean difference between the two directions of measurements was 0.048%. Using the same three paired t-tests described above for each paired set of data, several conclusions can be drawn. The initial comparison is the typical paired t-test where the null hypothesis is that the difference between the pairs of core density observations is zero. The p-value result was 0.33, which implies that at a 95% confidence level, this hypothesis could not be rejected; the measurements are statistically equal. This was followed by a second comparison, where the objective of the test was to estimate the 95% confidence level for the mean difference (or the upper reported accuracy level of the difference). In other words, 0.011 is the maximum difference between the longitudinal and transverse nuclear measurement values corresponding to a probability of 0.05 that the two densities are statistically different from each other. Further analysis was conducted to determine the probability that the difference between the directions was greater than

0.1 % of MTD. This probability is only 0.013. Based on these results, we can conclude that the difference between the longitudinal and transverse direction measurements is minimal and insignificant. The orientation of the nuclear gauge on the new HMA mat should not be considered a factor that affects the density measurements.

### *4.4 Deviation of nuclear gauge density as a function of external variables*

The purpose of this analysis was to observe and quantify variation in nuclear gauge readings at exactly the same locations due to external factors over a period of time (days). For the repeated location dataset, similarly to core dataset, each agency collected four individual nuclear gauge measurements per test location for the projects completed in 2004. The nuclear gauge devices were set on the pavement and after each reading the gauge was rotated as previously described. Figure 4.3 and Table 4.5 contains mean values of the four measurements per day at the same location through out the period of site construction. The number of days during which such measurements were collected varied between six and ten days.

Table 4.5 and Figure 4.3 suggest that the CAP Lab nuclear gauge had the least variation over each project period. The range of values for each site was less than 2.5 pcf for CAP Lab gauge, and as high as 6.8 pcf for ConnDOT's Troxler 17269 nuclear gauge.




* Day 1 indicates day of placement

**Figure: 4.3 Summary of Repeated Location Nuclear Gauge Density Readings by Project and Agency**

**Table 4.5: Summary of Measurements Repeated Daily for each Site by Nuclear Gauge Used.**

| Town | Project Number | Agency | Gauges Used | # of Days | Date | # of Obs. per gauge | Repeated Location Nuclear Gauge Density Readings (pcf) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Mystic | 58-300 | CAP Lab | Troxler 3450 | 6 | 6/24/04-7/8/04 | 6 | 147.5 | 147.7 | 147.6 | 147.8 | 148.6 | 148.2 | | | | |
| Mystic | 58-300 | Contrctor | Seamans L-540 | 6 | 6/24/04-7/8/04 | 5 | 149.4 | 153.4 | 153.7 | * | 149.4 | 149.5 | | | | |
| Mystic | 58-300 | ConnDOT | CPN 559 | 6 | 6/24/04-7/8/04 | 6 | 148.4 | 149.0 | 148.8 | 150.3 | 149.9 | 150.0 | | | | |
| Eastford | 172-349A | CAP Lab | Troxler 3450 | 7 | 7/20/04-8/2/04 | 7 | 141.2 | 141.9 | 141.5 | 140.9 | 141.2 | 141.3 | 141.3 | | | |
| Eastford | 172-349A | ConnDOT | Troxler 17269 | 7 | 7/20/04-8/2/05 | 4 | 139.2 | 143.0 | 141.7 | 146.0 | 142.5 | 142.3 | 141.5 | | | |
| Meriden | 79-219 | CAP Lab | Troxler 3450 | 10 | 8/17/04-9/2/04 | 10 | 143.9 | 143.2 | 143.7 | 143.7 | 144.2 | 143.3 | 144.5 | 144.3 | 143.9 | 143.7 |
| Meriden | 79-219 | Contractor | Seamans L-540 | 10 | 8/17/04-9/2/04 | 9 | 144.2 | 146.5 | 146.4 | 147.1 | * | 146.8 | 146.3 | 144.9 | 145.8 | 140.4 |
| Meriden | 79-219 | ConnDOT | CPN 990 | 10 | 8/17/04-9/2/04 | 7 | 142.6 | 143.0 | 146.5 | 145.7 | 144.6 | * | * | 142.5 | 145.2 | * |
| Sharon | 174-319D | CAP Lab | Troxler 3450 | 8 | 9/14/04-9/23/04 | 7 | 144.6 | 145.7 | 145.1 | * | 145.5 | 145.6 | 147.1 | 145.5 | | |
| Sharon | 174-319D | ConnDOT | CPN 990 | 8 | 9/14/04-9/23/05 | 6 | 146.2 | 145.4 | 144.6 | * | 144.5 | 146.0 | 146.1 | | | |

Given that for each project the gauges were set on the same location each day, one would expect that the density values would be the same. This was not the case. The mean of density measurements for each project by individual gauge vary by up to 7 pcf as shown in Table 4.5. Note core densities were not taken. The percent of MTD entered into the database is the average of all the MTD tests performed on that day determined from testing conducted at the HMA plant to determine MTD. This is an indication of the instrument error of the nuclear gauge. Figure 4.3 illustrates no time trend or drift in the data suggesting these variations may be random. External variables may affect the accuracy of the gauge. If external variables did not affect the gauge, the standard deviation of the same gauge would be the same from project to project. In an ideal situation, the standard deviation for a nuclear gauge would remain the same from project to project suggesting an inherit error in the gauge and no possibility of external factors effecting its readings. For all gauges, the standard deviation varied for each site and did not constantly increase or decrease suggesting no drift over time. The standard deviation does vary from project to project suggesting that external variables do affect nuclear gauge measurements. The ConnDOT CPN-990 nuclear gauge, based on its use on only two projects, varies the most. The contractor's nuclear gauge Seamans L-540, also based on only two projects, shows some limited drift with time. The Troxler 17269 was only utilized on one site; therefore a comparison is not made.

**Table 4.6: Repeated Location – Summary of Results**

| Project Number | Town | Agency | Gauges Used | Date | # of Days | # of Obs. Per gauge | Mean Density (pcf) | Mean % of MTD | Stand. Dev. % of MTD | Stand. Error Mean of MTD |
|---|---|---|---|---|---|---|---|---|---|---|
| 171-306A | Manchester | | | 8/7/03-8/18/03 | 9 | No Data Collected | | | | |
| 172-345A | Bozrah | | | 6/30/03-7/18/03 | 10 | No Data Collected | | | | |
| 172-345A | Stonington | | | 6/19/03-8/4/03 | 15 | No Data Collected | | | | |
| 58-300 | Mystic | CAP Lab | Troxler 3450 | 6/24/04-7/8/04 | 6 | 6 | 147.892 | 93.048 | 0.307 | 0.125 |
| 172-349A | Eastford | CAP Lab | Troxler 3450 | 7/20/04-8/2/04 | 7 | 7 | 141.318 | 90.641 | 0.340 | 0.128 |
| 79-219 | Meriden | CAP Lab | Troxler 3450 | 8/17/04-9/2/04 | 10 | 10 | 143.820 | 86.268 | 0.247 | 0.078 |
| 174-319D | Sharon | CAP Lab | Troxler 3450 | 9/14/04-9/17/04 | 8 | 7 | 145.563 | 88.761 | 0.551 | 0.225 |
| 58-300 | Mystic | Contractor | Seamans L-540 | 6/24/04-7/8/04 | 6 | 5 | 151.060 | 95.118 | 1.690 | 0.756 |
| 79-219 | Meriden | Contractor | Seamans L-540 | 8/17/04-9/2/04 | 10 | 9 | 145.367 | 87.196 | 1.215 | 0.430 |
| 79-219 | Meriden | ConnDOT | CPN 990 | 8/17/04-9/2/04 | 10 | 7 | 144.293 | 86.541 | 0.911 | 0.456 |
| 174-319D | Sharon | ConnDOT | CPN 990 | 9/14/04-9/17/04 | 8 | 6 | 145.454 | 88.659 | 0.485 | 0.243 |
| 58-300 | Mystic | ConnDOT | CPN 559 | 6/24/04-7/8/04 | 6 | 6 | 149.358 | 93.969 | 0.161 | 0.066 |
| 172-349A | Eastford | ConnDOT | Troxler 17269 | 7/20/04-8/2/04 | 7 | 7 | 142.304 | 91.273 | 1.309 | 0.495 |

### *4.5 Comparison of backscatter versus thin lift nuclear gauge mode*

Utilizing a third dataset, the nuclear density gauge mode dataset, an analysis was performed to determine if the nuclear gauge mode (backscatter or thin lift) affects the consistency of the density readings. A series of three t-tests comparing the two modes for only the CAP Lab nuclear gauge were performed. Note there were only 24 pairs of density values to compare.

The thin lift density measurements were on average 0.33% of MTD higher than the density values measured in backscatter mode in the same location. When comparing the backscatter to thin lift mode measurement we found that their density values were statistically different (P-value = 0.008.) The second test estimated the maximum mean difference between the modes density values with 95% certainty. The result was that the modes are within 0.52% of MTD of each other. The last t-test performed was used to determine the probability that the difference between the two modes was greater than 0.1 % of MTD. This probability was estimated to be 0.97 indicating that the difference between the modes is almost certainly greater than the current reported accuracy being used by the DOT. Backscatter mode and thin lift mode both receive the exact same measure of radiation however the algorithm for computation of density is different from one mode to the next. This is an indication that thickness may have a greater impact on variation from one mode to the next.

The results suggest that although the density values for the two modes are considered to be statistically different, there is not enough evidence to support that thin lift mode is a better and more accurate method of obtaining density values for all gauges. A larger sample size could produce more reliable and significant results. In addition, the results are only representative of the CAP Lab nuclear gauge. Further analyses of factors affecting the range of the difference between the two nuclear gauge modes were studied using ANOVA as a test method. In this sample of 24 locations, the only documented factor that varied was aggregate source. Table 4.7 lists the source of aggregate for each of the 2004 projects. Figure 4.4 illustrates the range of differences in density between the type of mode the nuclear gauge was set in for each project. The Sharon project stands out with a larger mean difference compared to the other three projects as shown in Figure 4.4. This could be related to the source and type of aggregate as well as the construction conditions that were not monitored during the study. In general, project by project conditions may affect which mode performs best.

**Table 4.7 Aggregate Sources**

| Site | Project | US/State Route | Town | Aggregate Source |
|---|---|---|---|---|
| 4 | 58-300 | I-95 | Mystic | Wauregan |
| 5 | 172-349A | Route 44 | Eastford | Killingly |
| 6 | 79-219 | I-691 | Meriden | New Britain |
| 7 | 174-319D | Route 7 | Sharon | MA |

```
F = 3.37            P = 0.039    R-Sq = 33.59%
Individual 95% CIs For Mean Based on Pooled StDev

Project#    Town     N    Mean   StDev   ------+---------+---------+---------+---
172-349A   Eastford  7   .3006   0.3981        (-------*-------)
174-319D   Sharon    4   .0013   0.7697                    (---------*---------)
58-300     Mystic    5   .2537   0.5846      (--------*--------)
79-219     Meriden   8   .0644   0.3055    (------*------)
                                         ------+---------+---------+---------+---
                                             0.00      0.50      1.00      1.50
```

**Figure 4.4: Analysis of Variance (ANOVA) for Type of Mode by Project Number**

### *4.6 Effects of nuclear gauge time recording interval on density accuracy*

The next analysis of this chapter focused on determining the optimum recording time interval at which nuclear gauge density measurements should be performed. In total there were four time recording intervals, three agencies, two modes and three locations. Based on the four recording intervals measured, with three gauges, on three surfaces, linear regression was used to first explore one dimensional correlations between the coefficient of variation (COV) of density and four recording intervals: 15 seconds, 30 seconds, 60 seconds, and 90 seconds. The effects of the individual gauge, location, and mode (thin lift versus backscatter) on the coefficient of variance were also examined with this dataset. Recording time interval was modeled as a continuous variable, while the others were converted to dummy variables. Note that for every factor there were 53 observations.

A summary of the regression results is shown in Table 4.8. The slopes and intercepts for the regression lines are presented with the Student's T-statistic for testing the hypothesis that the parameter values (slope and intercept) are equal to zero. The $R^2$ values presented in the table are measures of the amount of total variation of the dependent variable that is explained by the variation in the independent variable. Overall the independent variables explain very little of the variance in density error. Only three factors/variables are statistically significant: time interval, ConnDOT as an agency grouping, and nuclear gauge mode (thin lift and backscatter). The location, considered a measure of aggregate source, did not affect the coefficient of variance of the density values in this dataset. In addition, the agency grouping (synonymous with make and model of nuclear gauge), with exception of ConnDOT, did not have an effect on the coefficient of variance.

**Table 4.8: Regression Results of Coefficient of Variance to Time Recording Interval, Agency Performing the Measurements, and Mode of the Nuclear Gauge.**

| Grouping | Factors | Predictors values | | | | | |
|---|---|---|---|---|---|---|---|
| | | y-Intercept | P-Value | Slope | P-Value | F-value | R- Square |
| Time | (sec) | 0.808 | 0.000 | -0.005 | 0.001 | 13.07 | 20.40% |
| Agency | CAP Lab | 0.63 | 0.000 | -0.104 | 0.168 | 1.96 | 3.70% |
| | ConnDOT | 0.52 | 0.000 | 0.197 | 0.011 | 7.01 | 12.10% |
| | Contractor | 0.61 | 0.00 | -0.113 | 0.223 | 1.52 | 2.90% |
| Mode | Thin Lift | 0.65 | 0.000 | -0.155 | 0.040 | 4.42 | 8.00% |
| | Backscatter | 0.49 | 0.00 | 0.155 | 0.040 | 4.42 | 8.00% |
| Location | Groton | 0.58 | 0.000 | 0.022 | 0.788 | 0.07 | 0.10% |
| | Newington | 0.59 | 0.000 | 0.013 | 0.870 | 0.03 | 0.10% |
| | Branford | 0.59 | 0.00 | 0.92 | 0.008 | 0.10 | 0.00% |

Based on these results a final multivariate regression was estimated. The resulting regression equation is shown in equation 1.

**COV%MTD=0.878 + 0.218*Mode + 0.353*ConnDOT(agency) - 0.00674*Time(sec) [1]**

**Where:** COV%MTD = the coefficient of variance expressed as percent of MTD.
Mode = the mode setting on nuclear gauge (1 when backscatter and 0 when thin lift)
ConnDOT (agency) = 1 when the agency performing the test is ConnDOT, 0 otherwise
Time (sec) = time recording interval (in seconds)

The $R^2$ for this equation was 62.8 % and the p-values for the coefficients of the independent variables are less than 0.005. The F-value is high, 27.62, therefore we can conclude that the variables are independent of each other. The $R^2$ is moderate, but not excellent, indicating other factors have an effect on the error in the density measurement. Two out of three of the independent variables have positive values: mode and agency (both dummy variables). Therefore, if the measurement is performed in backscatter mode (1) and by ConnDOT (1) then the coefficient of variance expressed as percent of MTD will be higher indicating larger error. The last independent variable, time recording interval, has a negative value. This means as the recording time increases, the value of the coefficient of variance is smaller. In summary, the coefficient of variance expressed as percent of MTD will be smaller as the recording time increases, the measurements are conducted in thin lift and not by ConnDOT's nuclear gauges. The agency variable could be a result of constant change of nuclear gauge by ConnDOT, hence introducing an additional variation to nuclear gauge density reading when looked at in aggregate.

In addition to the fourth data set, the time recording interval dataset, collected expressively to answer the seventh research question, the main coring data set was also utilized as an additional means to investigate the effects of time recording interval on nuclear gauge density accuracy. Utilizing the original coring dataset a comparison of 30-

sec to 60-sec recording time interval was made. Recall that a 30-sec reading time was adopted for the 2003 data collected by ConnDOT and the Contractor. The CAP Lab nuclear gauge was incapable of performing 30-sec measurements; hence CAP Lab's nuclear gauge was set at 1-min time recording interval. In 2004, the recording time interval was changed to 1-min readings for all agencies. (ConnDOT, Contractor, and CAP Lab.) To compare the two recording intervals additional data manipulations had to be performed. A dummy variable was assigned to differentiate the two intervals. In total there were 321 30-sec recording time measurements and 645 60-sec recording time measurements. The mean error in this data set comparing the nuclear gauge accuracy to core density differences as percent of MTD was -1.05% for 30-sec observations and -0.60% for the 60-sec observations. This provides further evidence that as the time interval increases the accuracy increases. An accuracy gain of 0.45% of MTD may be worth the extra 30-sec for the observation to be recorded.

### *4.7 Effect of Thickness on Nuclear Density Readings*

All of the projects used for this research had a target compacted thickness of two inches. Cores with a thickness of less than 2 inches had an average percent compaction of 91.4%. Cores with a thickness of greater than 2 inches had an average percent compaction of 91.7%. These numbers are what would be expected to occur as it is generally considered easier to get compaction with a slightly thicker mat. The results for the nuclear density gauges don't reflect this. The average error for all nuclear gauges on locations where cores were less than 2 inches thick was -0.54%. The average error for all nuclear gauges on locations where cores were greater than 2 inches thick was -0.94%. The nuclear density gauge readings were actually lower where cores were thicker than 2 inches as compared to the readings taken where cores were less than 2 inches thick. When the wearing surface is thinner from a relative standpoint, the density reading will be more affected by the underlying layer than when the wearing surface is thicker.

# 5 DEVELOPMENT OF A NUCLEAR GAUGE CORRECTION PROCEDURE

Even though the magnitude of uncertainty in nuclear gauge readings was unknown at the start of this project, the primary objective in measuring the uncertainty and finding correlations or patterns was to develop a procedure to correct or improve nuclear gauge accuracy. The use of such a procedure would allow for continued field use of the nuclear gauge for quality control given its benefits in terms of time to obtain results and its non-destructive nature.

The data analyzed in this project and the combined results of Chapter 4 indicate that any correction procedure will be gauge and project specific. This requires testing locations at the beginning of a project with each nuclear density gauge and then coring these locations to determine their in-place bulk densities using a lab procedure. To avoid problems with excessive water absorption as part of bulk specific gravity determination in AASHTO T 166, it is recommended that AASHTO TP69 be used. AASHTO TP69 utilizes a vacuum sealing device which eliminates the problems associated with excessive water absorption. This chapter of the report describes the determination of the recommended number of cores per project, as well as an evaluation of the improvement in accuracy that results from applying the correction factor to the nuclear gauge readings. This chapter also addresses the use of the ConnDOT test blocks and the potential to transfer correction factors from gauge to gauge. Finally, the chapter concludes by considering the level of error when the correction factors for one gauge are used with another.

### *5.1 Establishing the Optimum Number of Cores Required*

The findings of this study indicate that in order to determine a correction factor, cores must be cut from the compacted roadway on each project on the first day of paving. These locations must also be tested by all of the nuclear density gauges to be used on the project prior to cutting the cores. This is a labor intensive process that can at times interfere with the construction of the pavement. It was therefore the goal in this portion of the research project to determine the minimum number of cores required to determine a correction factor with an acceptable level of error.

During the field work for this project, ten locations were tested with the nuclear density gauges as well as being cored on the first day of paving for each paving site. Ten locations were deemed to be the maximum number of locations that could be tested reasonably during a single day. On subsequent days during 2004, only five locations were tested. During 2003, only a single location was tested following the original ten locations. Therefore the 2004 data were used exclusively for this analysis as it more closely simulated the effect of testing all of the locations on a single day as it only required data from the first three days of tests to achieve 20 locations. The running average error between the nuclear density gauges and cores was determined for the first twenty locations of the 2004 projects. The results of this calculation can be seen in Figures 5.1- 5.4.

**Figure 5.1- Eastford Route 44**
**Running Average Error vs. Number of Cores**

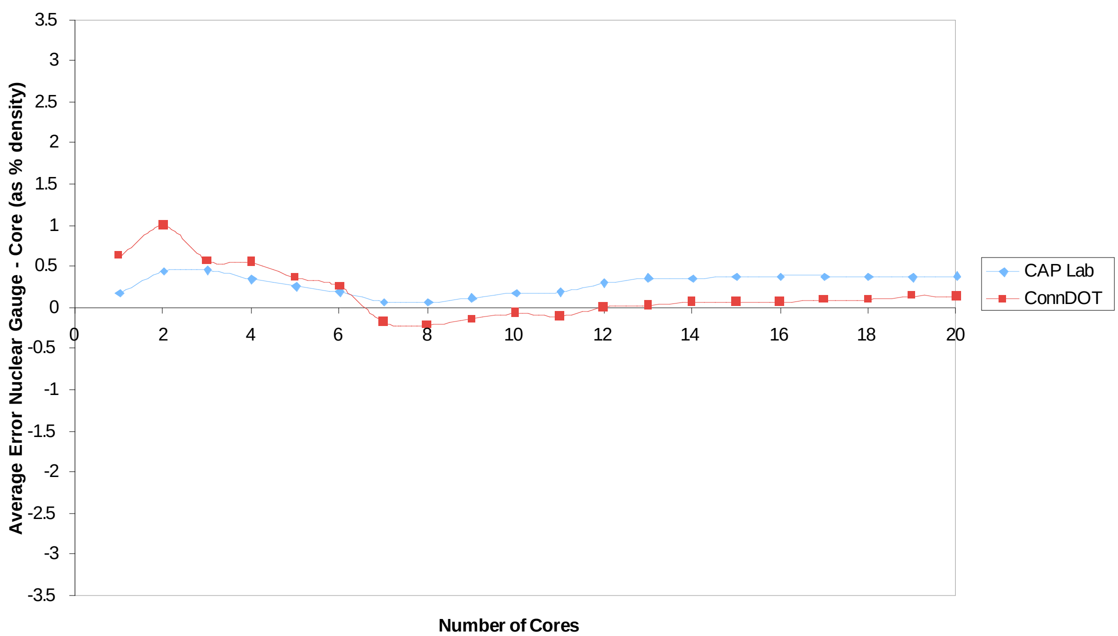



**Figure 5.2 - Meriden I-691**
**Running Average Error vs Number of Cores**

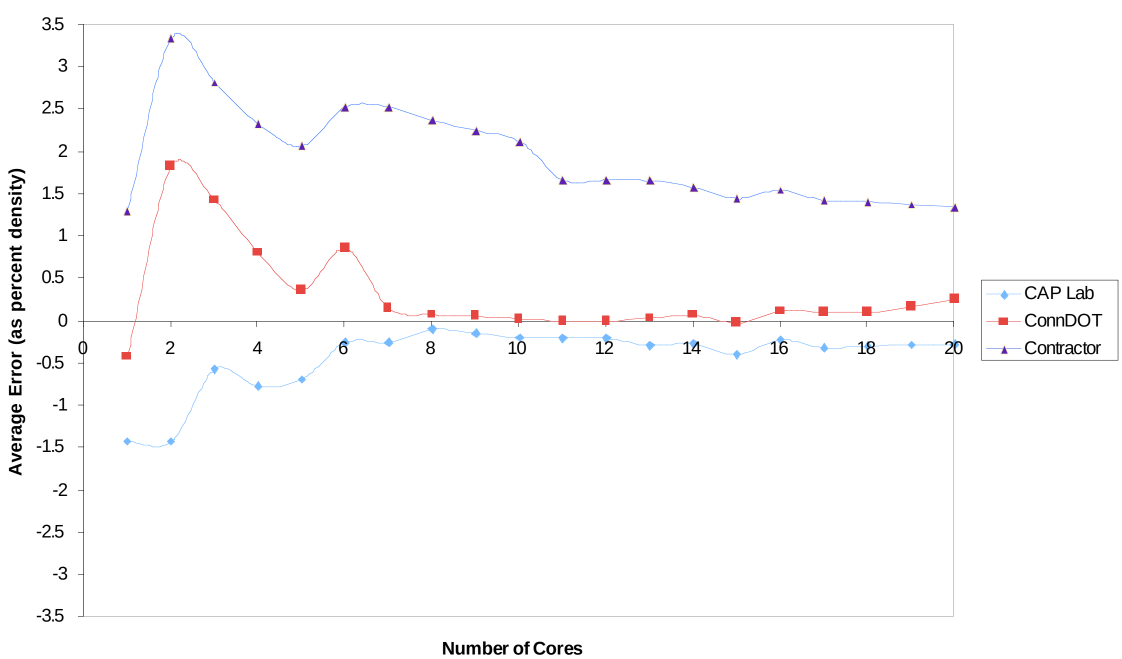


**Figure 5.3 - Mystic I-95**
**Running Average Error vs Number of Cores**

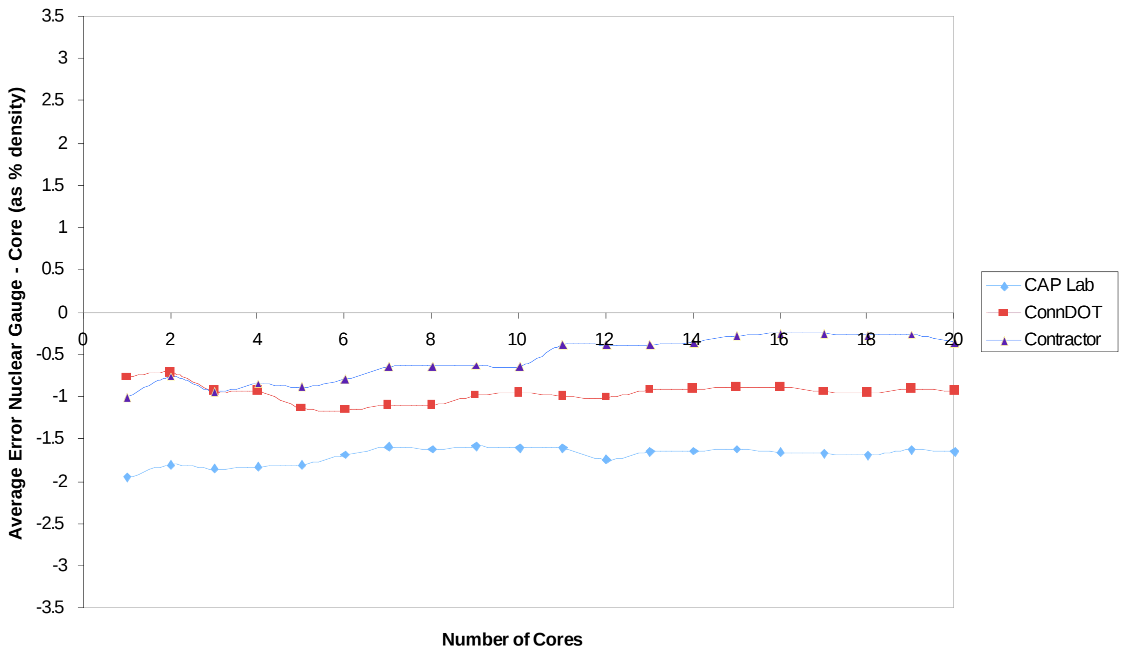
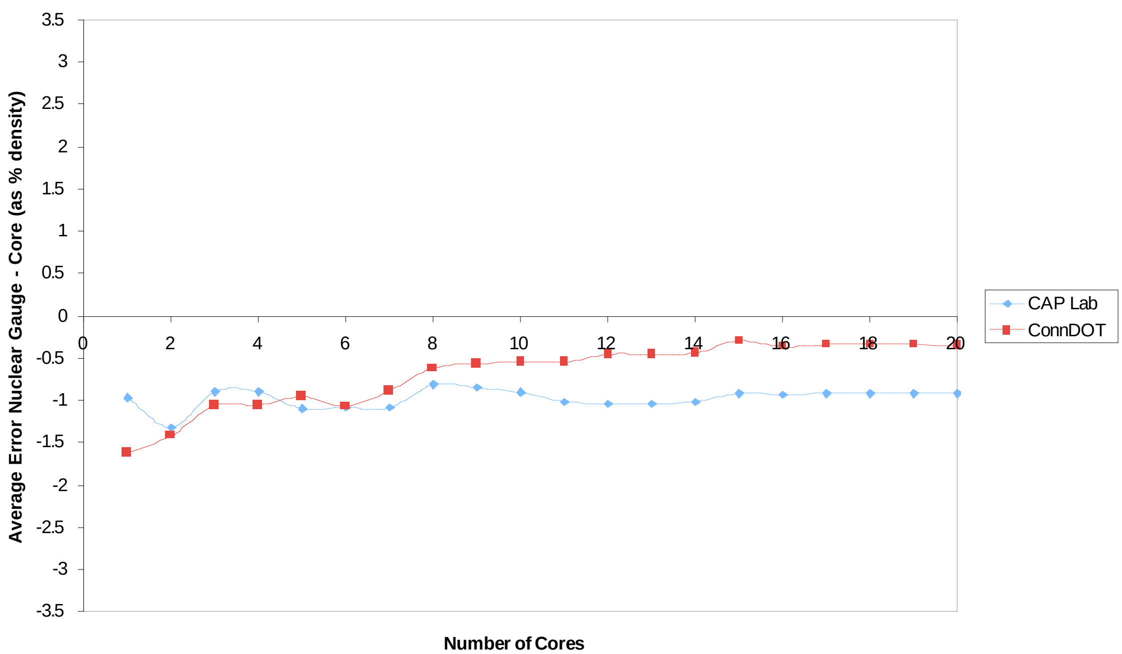



**Figure 5.4 - Sharon Route 7**
**Running Average Error vs Number of Cores**



Each point in Figures 5.1-5.4 is the average error of the nuclear gauge as measured against the first "X" average core densities. These graphs show that the average error (nuclear gauge – core density) decreases as the number of cores increases. The differences in the lines for projects with multiple nuclear gauges further supports the assertion that correction factors must be gauge specific. Overall the error based on the average cores becomes relatively stable between eight and twelve cores. Based on these findings, we recommend that the average density error of ten locations where nuclear density testing and cores were cut on the project be used for determination of the correction factor. The advantage of using ten locations was that in the event the results from a location were deemed to be unacceptable, those results could be removed without jeopardizing the stability of the correction factor (in other words a mean of 8 would also be acceptable).

### *5.2 Calculating the Correction Factor*

The correction factor is determined as the mean error, the difference between the nuclear density gauge percent compaction and the core percent compaction, for the ten locations tested on the first day of paving. Optimizing the accuracy of the correction factor determination requires additional field considerations. First, each of the core locations within the travel lanes should be determined randomly throughout the first day's paving as they were in this research project using random numbers in a spreadsheet program. Second, results where the nuclear density gauge percent compaction was significantly greater (more than 2%) than the core percent compaction was indicative of a core that was damaged in either removing it from the roadway or in transit between laboratories. These results were not included in the calculation of the correction factor. For instances where the nuclear gauge percent compaction was significantly lower (more than 2% but less than 5%) than the core percent compaction, it was deemed to be acceptable as the nuclear gauges observed on these projects tended to have a bias where they under estimated the in-place density.

After elimination of inappropriate cores, the average difference between nuclear readings and core lab values of the acceptable core locations can be computed and used as the correction factor for the given gauge on a specific paving project. The correction factor is then subtracted from all readings made with that nuclear density gauge on the project. The calculated correction factor was expressed as a percent of compaction. This was done to account for variations occurring in the maximum theoretical density during production.

Figures 5.5-5.7 show the percent compaction as determined by the nuclear density gauge plotted against the percent compaction determined from the cores cut at the same location. The nuclear density gauge readings were taken without any correction factor applied. Figures 5.8-5.10 plot the same data as was plotted for Figures 5.5-5.7 but the core correction factor has been applied. Note the reduction in scatter when the correction factor has been applied.

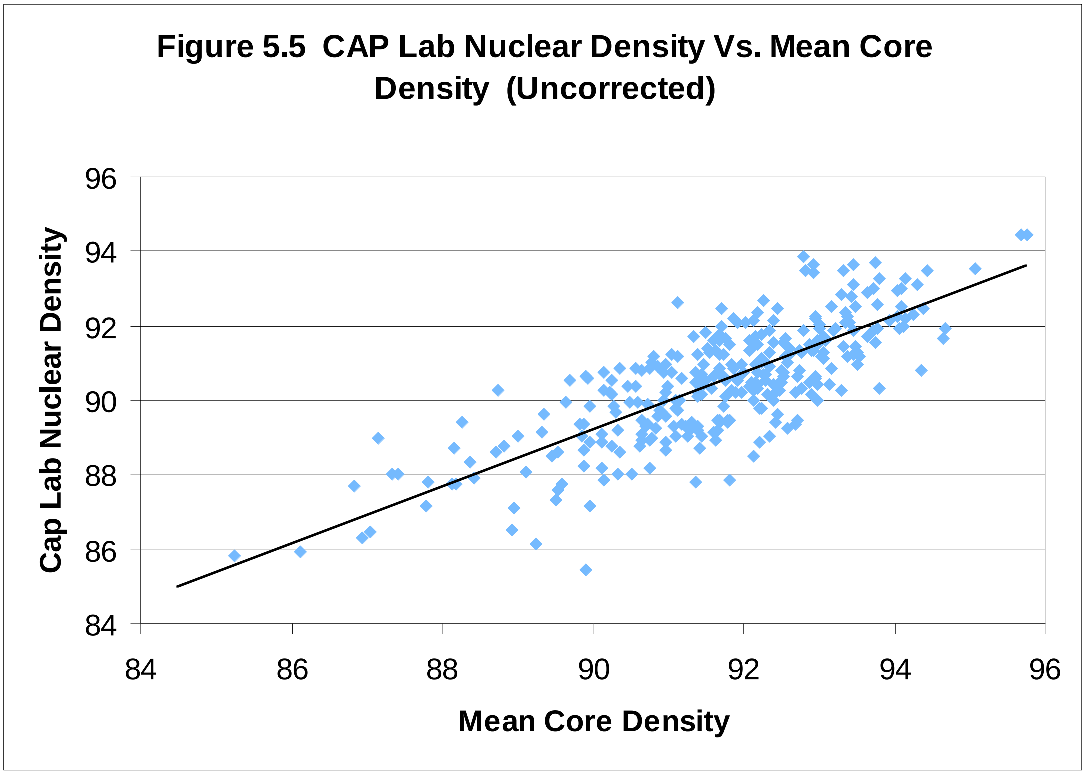


Figure 5.5 CAP Lab Nuclear Density Vs. Mean Core Density (Uncorrected)
Cap Lab Nuclear Density
Mean Core Density
84
86
88
90
92
94
96

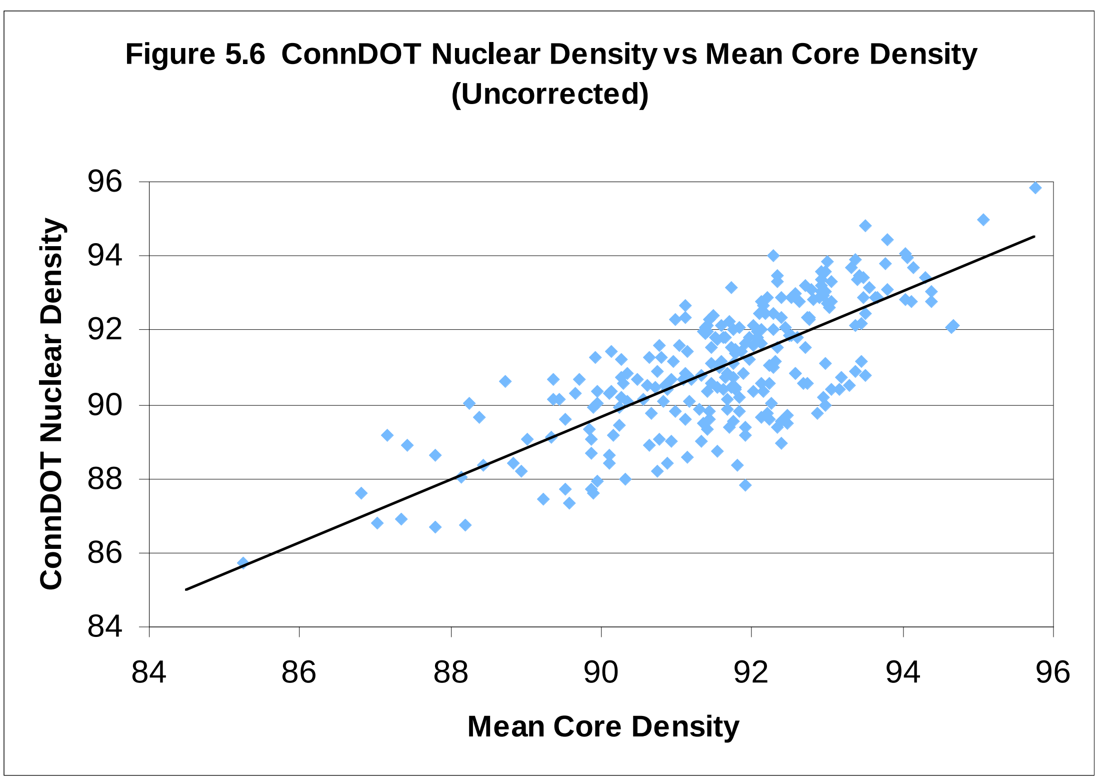


Figure 5.6 ConnDOT Nuclear Density vs Mean Core Density (Uncorrected)
ConnDOT Nuclear Density
Mean Core Density
84
86
88
90
92
94
96

**Figure 5.7 Contractor Nuclear Density Vs. Mean Core Density (Uncorrected)**

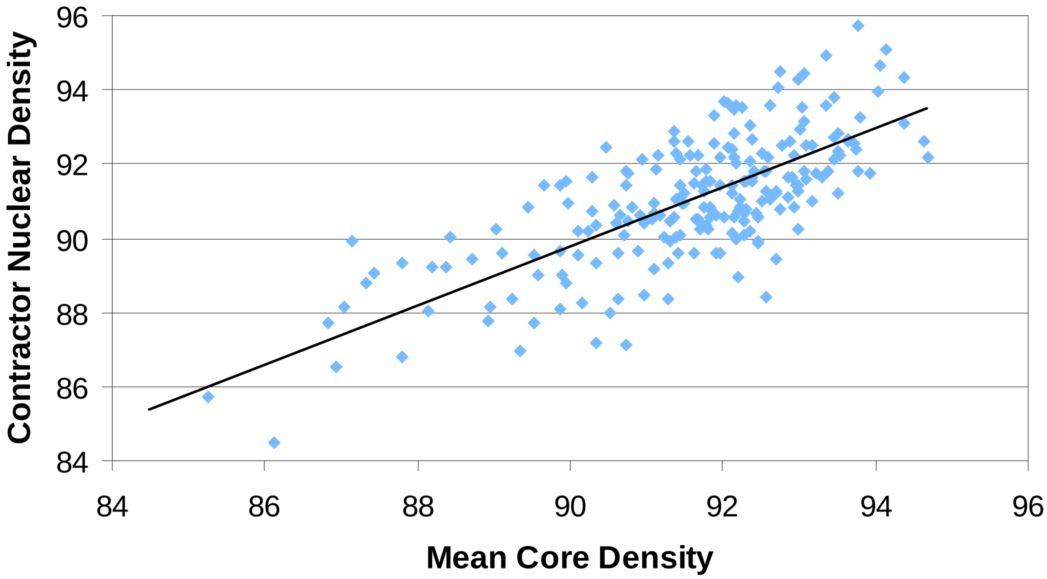
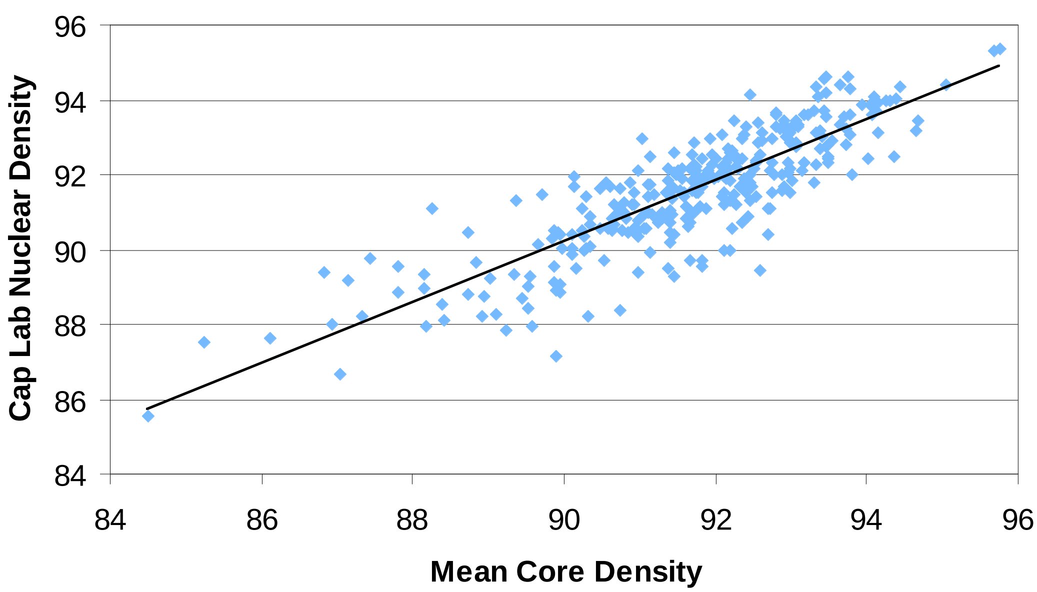



**Figure 5.8 CAP Lab Nuclear Density Vs. Mean Core Density (Corrected)**



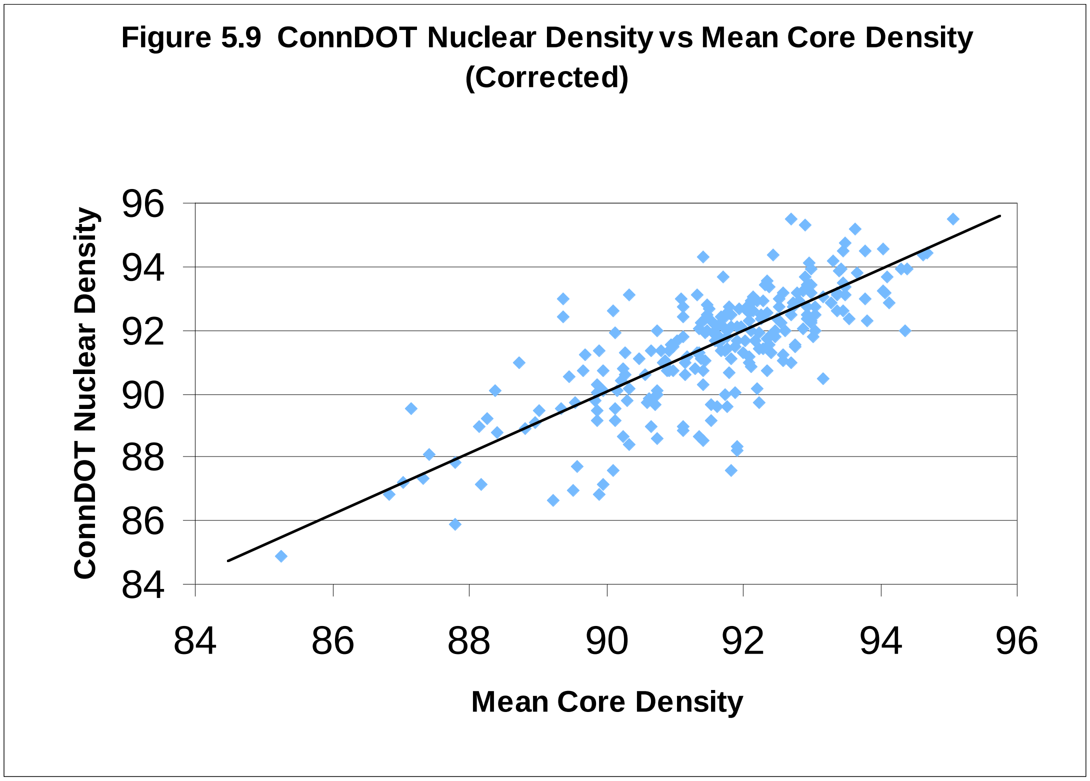


Figure 5.9 ConnDOT Nuclear Density vs Mean Core Density (Corrected)
ConnDOT Nuclear Density
Mean Core Density
84
86
88
90
92
94
96

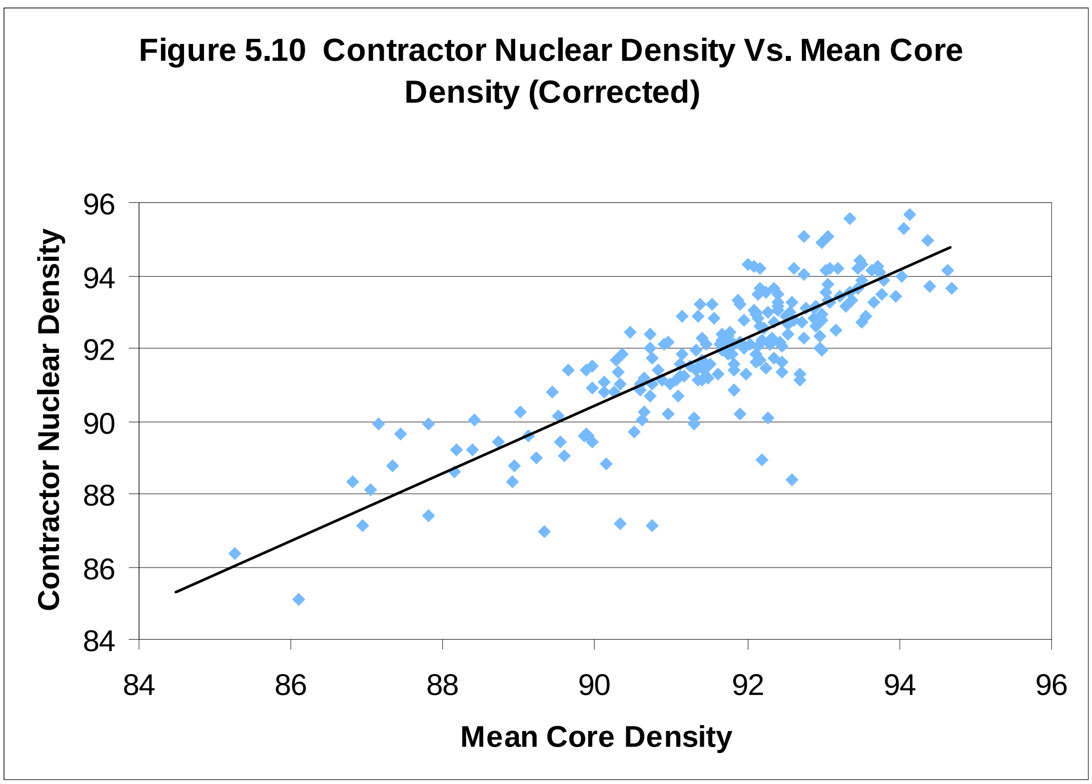


Figure 5.10 Contractor Nuclear Density Vs. Mean Core Density (Corrected)
Contractor Nuclear Density
Mean Core Density
84
86
88
90
92
94
96

The results in Table 5.1 show that the application of the correction factor significantly improves the R Squared values for the CAP Lab and Contractor nuclear gauges using a linear regression. A perfect correlation between the nuclear density gauge and the cores would have a R Squared value of one. The ConnDOT gauges did not show the same level of increase. This is most likely the effect of multiple gauges being used by ConnDOT as compared to a single nuclear density gauge used on all projects by the CAP Lab and Contractor. As many of the ConnDOT gauges were only used on a single project it was not reasonable to conduct a single linear regression on these gauges independently.

Table 5.1 – R Squared Values for Uncorrected and Corrected Nuclear Density Readings

| Agency | Uncorrected | Corrected |
|---|---|---|
| CAP Lab | 0.6324 | 0.7239 |
| ConnDOT | 0.5889 | 0.6174 |
| Contractor | 0.5595 | 0.7093 |

Graphical depictions of the error reduction as a result of the application of the correction factors are displayed in figures 5.11-5.18. It can be seen that application of the core correction factor as outlined in this research limited all of the errors to less than 1% of the core density with the exception of the contractors gauge on I-691 on day 2 where the error was just slightly greater than 1%. The other 38 out of the 39 averages were within one percent of the densities of their respective cores. The application of the bias generated through use of the ConnDOT blocks to the nuclear readings resulted in a much larger margin of error. On the Rt. 44 project the average error was at least 2% for both gauges on each day of testing. On a per project basis the average error was always reduced significantly when the core correction procedure was used as opposed to the block bias as seen in the figures below.

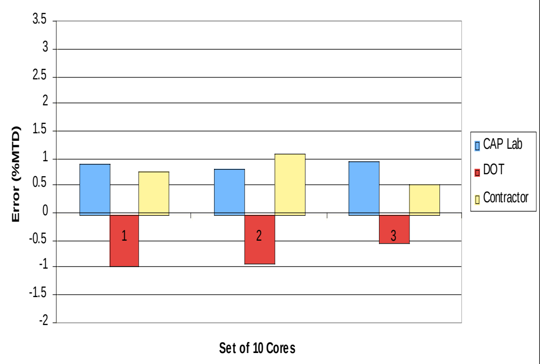


Figure 5.11 I-95 Comparison (block bias)

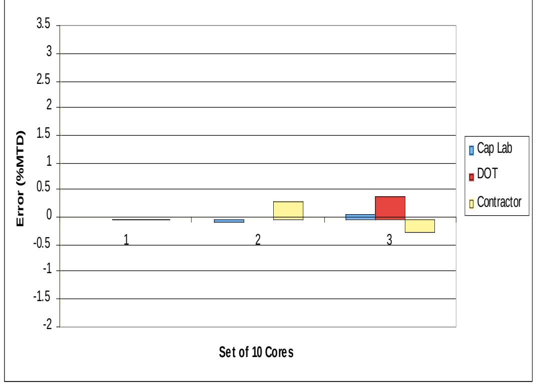


Figure 5.12 I-95 Comparison (core correction)

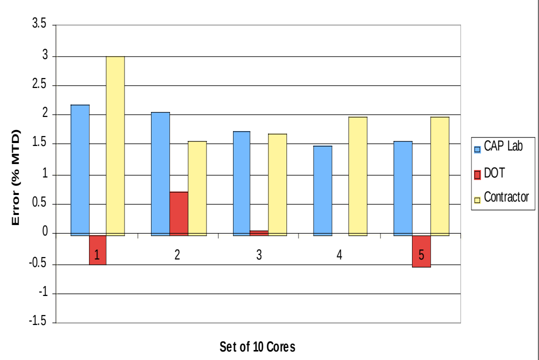


Figure 5.13 I-691 Comparisons (block bias)

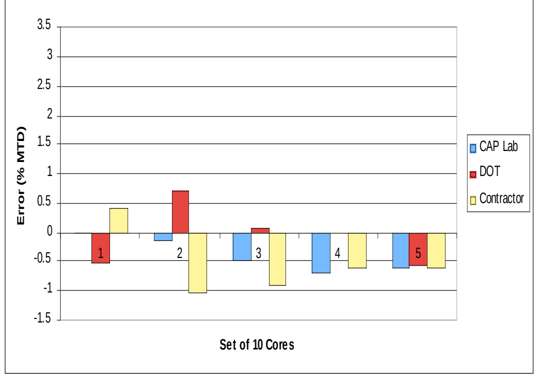


Figure 5.14 I-691 Comparisons (core correction)

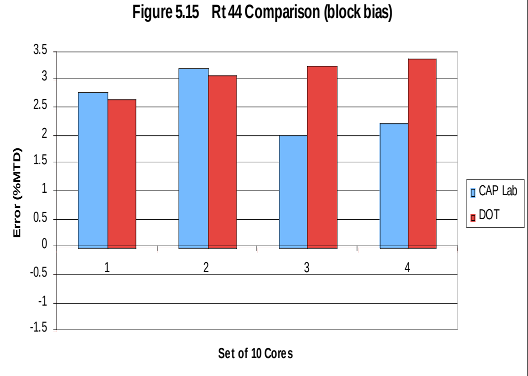


Figure 5.15 Rt 44 Comparison (block bias)

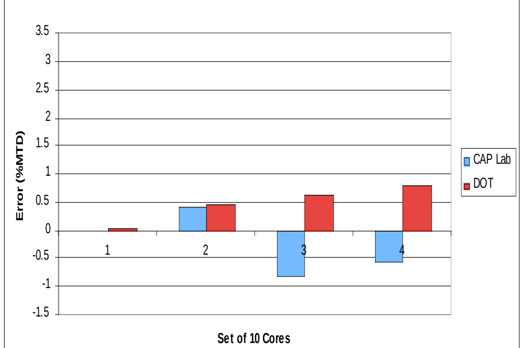
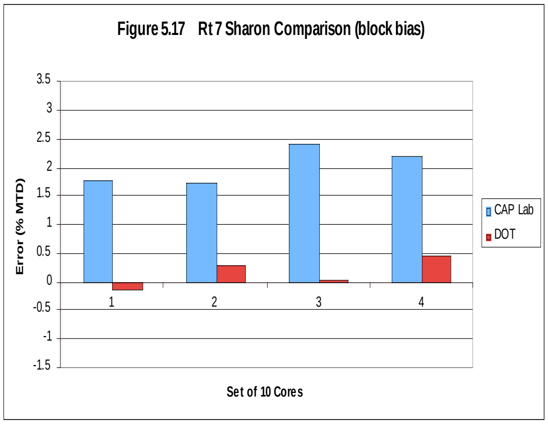
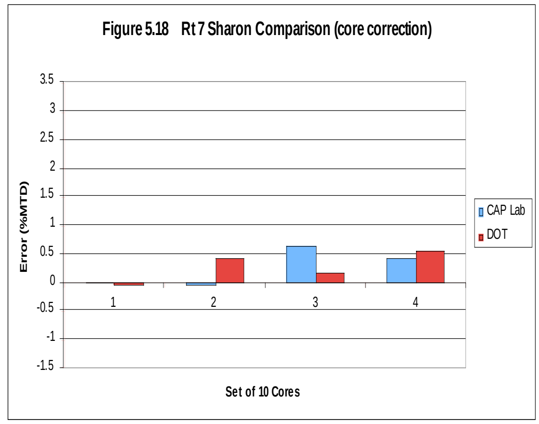


Figure 5.16 Rt 44 Comparison (core correction)




### *5.3 Comparison of Nuclear Gauge Bias's Determined Using the ConnDOT Blocks to the Correction Factor Calculated Using Cores*

Currently, all nuclear density gauges to be used on ConnDOT projects must have their bias determined annually using a set of blocks at the ConnDOT Research and Materials Lab in Rocky Hill, Connecticut. The density of these blocks is known and the bias for each gauge is determined by adjusting the densities reported by the nuclear density gauge to the known values for the blocks. This same value is then added to all readings made with the gauge throughout the year.

Table 5.2 contains a comparison of the nuclear density gauge bias determined using the blocks and the correction factor determined from cores for the paving projects used in this study. Note the bias values obtained using the blocks did not change during the year however the correction factors obtained using the cut cores are project specific. The numbers in Table 5.2 have been converted to percent compaction that is dependent on the maximum theoretical density that varies from project to project. Data in the table with a negative value would be added to the percent compaction reading of the nuclear density gauge and positive values would be subtracted from the nuclear density gauge percent compaction readings.

Table 5.2 – ConnDOT Block Bias and Coring Correction Factor

| Project | Town | Route | | Nuclear Gauge S/N | ConnDOT Block Bias, % Comp.* | Coring Correction Factor, % Comp.* |
|---|---|---|---|---|---|---|
| 172-345A | Bozra | 2 | CAP Lab | 574 | -2.5 | -1.7 |
| 172-345A | Bozra | 2 | Contractor | L540 | -1.2 | -1.6 |
| 172-349A | Eastford | 44 | CAP Lab | 574 | -2.6 | 0.2 |
| 172-349A | Eastford | 44 | ConnDOT | 17269 | -2.7 | -0.1 |
| 171-306A | Manchester | I-384 | CAP Lab | 574 | -2.7 | -1.7 |
| 171-306A | Manchester | I-384 | ConnDOT | 354 | -0.5 | 0.8 |
| 171-306A | Manchester | I-384 | Contractor | L540 | -1.1 | -0.6 |
| 79-219 | Meriden | I-691 | CAP Lab | 574 | -2.4 | -0.2 |
| 79-219 | Meriden | I-691 | ConnDOT | 990 | -0.4 | -0.4 |
| 79-219 | Meriden | I-691 | Contractor | L540 | -1.3 | 1.3 |
| 58-300 | Mystic | I-95 | CAP Lab | 574 | -2.5 | -1.6 |
| 58-300 | Mystic | I-95 | ConnDOT | 559 | 0 | -0.9 |
| 58-300 | Mystic | I-95 | Contractor | L540 | -1.4 | -0.6 |
| 174-319D | Sharon | 7 | CAP Lab | 574 | -2.7 | -0.9 |
| 174-319D | Sharon | 7 | ConnDOT | 990 | -0.4 | -0.5 |
| 172-346A | Stonington | I-95 | CAP Lab | 574 | -2.8 | -1.5 |
| 172-346A | Stonington | I-95 | ConnDOT | 559 | -0.8 | -2.3 |
| 172-346A | Stonington | I-95 | Contractor | L540 | -1.1 | -1.5 |

* Note: negative values indicate the nuclear density gauge readings are below the core density values and positive values indicate the nuclear density gauge readings are above the core density values.

The results observed in Table 5.2 indicate that the correction factor used for nuclear gauge readings vary greatly from project to project even when the same nuclear gauge is used on multiple projects. For example, the CAP Lab nuclear gauge core correction factor varied from -1.7% to 0.2% throughout the research project. Had the ConnDOT block bias been used with the CAP Lab nuclear density gauge, all the readings would have been adjusted by -2.4% to -2.8%. This suggests that the standard block is not accomplishing its purpose.

The results in Table 5.3 compare the effect of applying the block bias against the core correction for the average nuclear density gauge percent compaction difference throughout specific projects. These results indicate that in most instances the core correction factor improved the overall accuracy of the readings in Table 5.3 as values closer to zero are best. In two instances the use of the core correction factor made the overall average worse. In the instance of the contractor nuclear density gauge in Meriden, the data generated on that project with that gauge contained some anomalies that could not easily be explained. Based upon the data in Table 5.3 excluding the results from ConnDOT – Manchester and Contractor - Meriden, the largest errors observed using the core correction factor are less than 0.75% of MTD. This level of error may still be deemed unacceptable for contract payment.

Table 5.3 – Nuclear Gauge Percent Compaction Error Using Block Bias and Core Correction Factor

| | | CAP Lab | | ConnDOT | | Contractor | |
|---|---|---|---|---|---|---|---|
| Project | Avg. Core % Comp | Block Error | Core Error | Block Error | Core Error | Block Error | Core Error |
| Bozra | 92.3 | 0.68 | -0.12 | NA | NA | -0.62 | -0.23 |
| Eastford | 91.7 | 2.54 | -0.26 | 3.06 | 0.47 | NA | NA |
| Manchester | 91.4 | 1.17 | 0.17 | 0.02 | -1.27 | 1.19 | 0.69 |
| Meriden | 90.7 | 1.63 | -0.57 | 0.61 | 0.61 | 0.65 | -1.95 |
| Mystic | 91.6 | 0.89 | -0.01 | -0.80 | 0.10 | 0.78 | -0.02 |
| Sharon | 92.1 | 2.04 | 0.24 | 0.18 | 0.28 | NA | NA |
| Stonington | 92.0 | 0.86 | -0.43 | -0.81 | 0.69 | -0.26 | 0.14 |

Note: Negative Values denote the nuclear gauge readings with additions were lower than the core and positive values were above the average core readings.

### *5.4 Transferring a Core Correction Factor Between Nuclear Density Gauges*

Occasionally a nuclear density gauge needs to be replaced on a project. In the event the replacement gauge was not used in the determination of the correction factor, determining the correction factor appropriate for the replacement gauge would be very important. This transferred correction factor can not be expected to be as accurate as the original correction factor.

Each 2004 project where data was collected had a location where 4 one-minute readings were taken with each nuclear density gauge used on the project where everyday data was collected. The data collected on the first day for these locations on each 2004 project was used to calculate a core correction factor for a different nuclear density gauge. This was calculated by figuring the corrected percent compaction at the repeated test location by subtracting the core correction factor from the average of the nuclear density gauge readings. The average of four one-minute readings from a different nuclear density gauge was then determined as percent compaction. The core correction factor for the different nuclear density gauge was calculated by subtracting the percent compaction for "replacement" nuclear density gauge from the corrected percent compaction as determined with original nuclear density gauge. Figures 5.19–5.22 summarize the results obtained from transferring the core correction factor from nuclear density gauge to a different nuclear density gauge. Transferring the core correlation factor between nuclear density gauges potentially reduces the accuracy of the readings made with the nuclear density gauges and should only be used as a last resort.

**Figure 5.19 - Sharon Rt 7**
**Transfer From ConnDOT Gauge to CAP Lab Gauge**

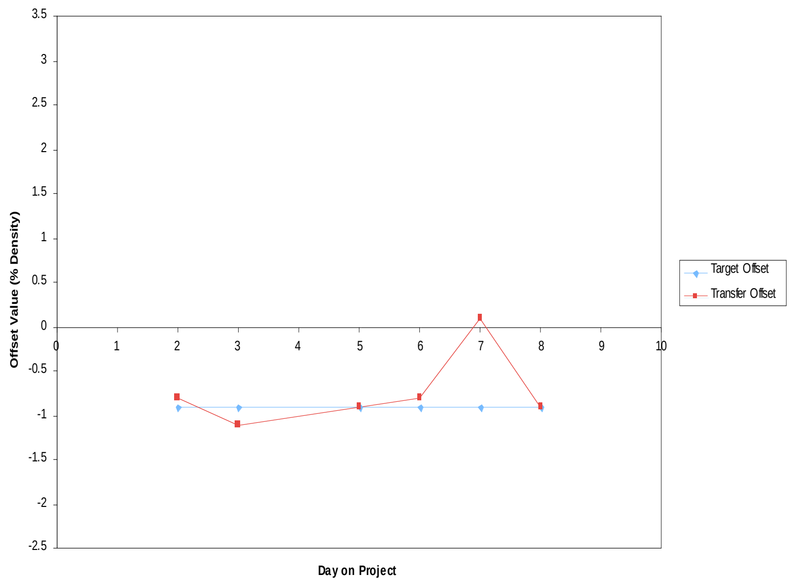
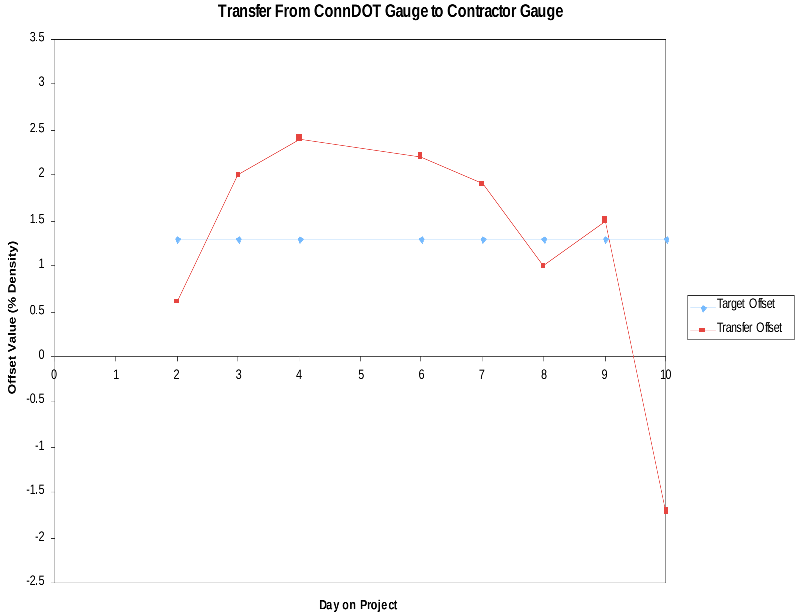
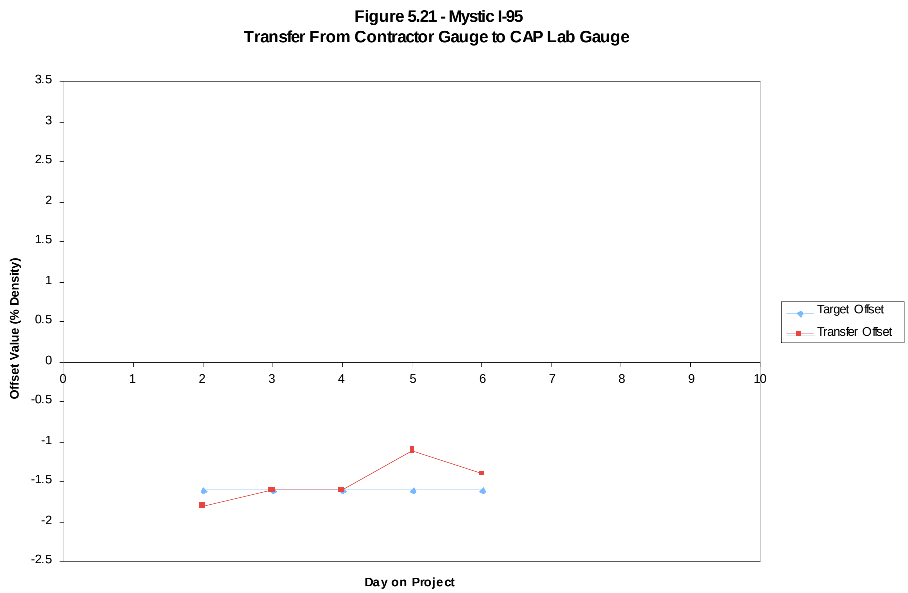
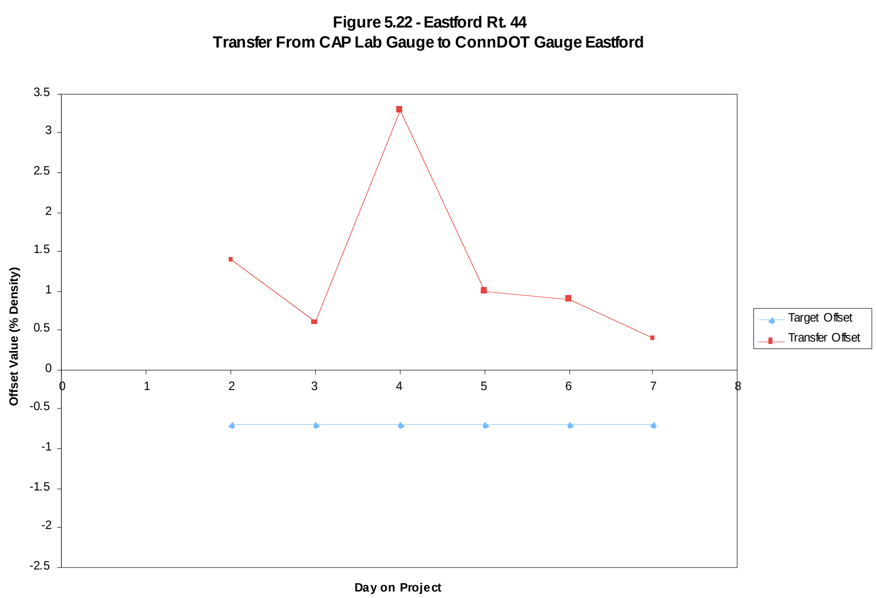



**Figure 5.20 - Meriden I-691**
**Transfer From ConnDOT Gauge to Contractor Gauge**






Figures 5.19 – 5.22 show the results of this investigation on 4 different projects. The differences between the replacement transfer offset and the actual offset for the gauge on

that specific project are plotted for each day on each project. As is seen in the figures this procedure is less reliable than correlating the gauge to the pavement using the ten cut cores. In the event a correlated nuclear density gauge needs to be replaced on a project, best practice would be to repeat the correlation procedure for the replacement gauge.

### *5.5 Summary of Procedures to Maximize Nuclear Density Gauge Accuracy*

A draft specification in Appendix A contains the procedural steps required to relate core density values with densities obtained from nuclear density gauges. The use of this procedure will maximize the accuracy of the nuclear density gauge readings but will not attain the 0.1% level of accuracy. The following is a brief summary of the procedures recommended to increase the accuracy of nuclear density gauges.

- Nuclear density gauges should be calibrated and serviced at least once per year in accordance with the manufacturer's procedure
- A correction factor based upon the in-place density measured from cores should be applied to all nuclear density gauge readings
    - These correction factors are project, mix and gauge specific and should be verified every six months or whenever in question
- A minimum of 10 cores should be used to establish the correction factor
- A density measured by a nuclear density gauge should consist of 4 readings
    - The gauge should be rotated as described in Appendix A after each reading
- Each reading should be at least one minute long
- All cores should be tested for density using AASHTO TP69
- A location should be selected on the paving project where each gauge can be used to take 4-one minute readings each day of paving. The readings at this location would be known as the repeated measurements and should be used to monitor the gauge and can be used as a last resort to transfer a correction factor to a replacement gauge.
- The practice of transferring correction factors from one gauge to another should be avoided if at all possible

# 6 CONCLUSIONS AND RECOMMENDATIONS

This chapter begins with a discussion of the general conclusions followed by the specific conclusions for the seven individual research questions addressed in this project. Section 6.2 of this chapter includes recommendations for continued use of the nuclear gauge on field projects while section 6.3 discusses further research needs.

Overall, the findings of this investigation indicate that the six nuclear gauge density instruments did not produce similar results and did not consistently correlate with the laboratory-based core densities. The variability of nuclear density results differed not only from gauge to gauge, but also from location to location with each gauge tested. Furthermore, this variability is also present for both nuclear gauge density testing modes (backscatter versus thin lift). The differences between the core density values obtained by each laboratory were significantly higher than 0.1% reported accuracy set by ConnDOT for nuclear gauge compaction reported accuracy limits suggesting a need to change this reported accuracy level. A project and gauge specific correction factor procedure that improves nuclear gauge accuracy was developed. However, even the corrected error exceeds the 0.1% reported accuracy level.

## *6.1 CONCLUSIONS FOR INDIVIDUAL RESEARCH QUESTIONS*

1. **The comparison of core densities from three different labs:** The results of core densities varied by the laboratory performing the test. The mean difference in core sample density between a pair of laboratories ranged from 0.06 to 0.29 as a percent of MTD. These values are well below the published values in AASHTO TP69 for between laboratory precision when they are converted to percent of MTD which would be approximately 1.46% of MTD assuming a maximum

specific gravity of 2.600. This indicates that the testing of cores for bulk density is much more repeatable between laboratories than the results obtained using different nuclear density gauges on the same location.

2. **The comparison of six different nuclear density gauges:** The nuclear gauge data showed little consistency between gauges. The mean difference between two nuclear gauge density values obtained at the same field location ranged from 0.30 to 1.36 as a percent of MTD. These differences were slightly larger than core density differences between labs. No two nuclear gauges produced statistically similar results.

3. **The comparison of average core density to nuclear gauge density:** When comparing the density values obtained with the nuclear gauges to the respective density values of the cores cut from those locations, the errors ranged from 0.3 % of MTD to 1.2 % of MTD depending on the gauge. The difference measurements were inconsistent, suggesting that the variability of density readings exists as a product of the gauge itself because the changes in the materials would be seen in the bulk density of the cores and accounted for in that manner. In half of the cases, the nuclear gauge densities had statistically significantly lower mat mean density values than the core mean values. These variations were originally assumed to be a product, to some extent, of external factors. Three factors were tested: thickness of the mat, temperature of HMA during nuclear gauge measurement, and location/aggregate source. Only thickness of the HMA mat was found to have any effect. As the thickness of the HMA mat increased, the error of the density measurement by nuclear gauges decreased. This decrease in

error may indicate that the nuclear density gauges are affected by the underlying pavement's density on thinner pavements. The increase in the size of the error when nuclear density gauges were used in conjunction with Montville aggregates was not able to be statistically validated as an effect of the aggregate due to the limited number of gauges/projects.

4. **The comparison of average transverse and longitudinal nuclear gauge density measurements:** The readings from the direction at which the gauge rests with respect to the new mat was statistically different but very small, the mean difference was 0.05% of MTD. The pavement density measurements with the nuclear gauge in longitudinal direction were slightly higher than those in the transverse direction. This variation was minimal and is considered to be insignificant. In the future, the orientation of the nuclear gauge on the new HMA should not be considered as a factor that affects the density measurement.
5. **Deviation of nuclear gauge density as a function of external variables:** Based on the repeated location measurements over the length of a typical paving project (day-to-day), there is not enough evidence to support that nuclear gauge density readings change or drift over time. The standard deviation and standard error of the densities varied from project to project suggesting variation may be a function of unmonitored external factors.
6. **The comparison of backscatter versus thin lift nuclear gauge mode:** The comparison of the test data obtained by using two nuclear gauge modes on a single model gauge indicated that the density measured in two modes is statistically different, but the data to determine if the thin lift mode was a more

accurate method of obtaining density was not collected. Furthermore, the variation of results could have been caused by relative changes of HMA thickness through out the project. The source of the coarse aggregate was analyzed to further explain the differences between the two modes. Out of four sites, only one stood out with a larger mean difference between the two modes when compared to the other three project sites. This could also be a result of factors not monitored such as fine aggregate source or construction conditions.

7. **The effect of recording time interval on nuclear gauge density accuracy:** The 1-min recording time interval produces slightly better results than the 30-sec recording time interval. This increase in recording time intervals is not enough to impede construction to take these longer measurements. When determining the optimum time interval for nuclear gauge density measurements only two factors were found to be statistically significant: ConnDOT as an agency grouping and nuclear gauge mode (thin lift and backscatter). The project location did not affect the coefficient of variance of the density values in the time interval dataset, but the location did affect the average density values. The agency grouping, with the exception of ConnDOT, also did not have an effect on the coefficient of variance of density results in the time interval dataset. Note that the findings in the statistical analyses for the time interval dataset differ from those found in the Stroup-Gardiner study (9). After comparison between the Stroup-Gardiner study and this study, the following differences were determined to be the most probable causes of the inconsistency in conclusion: Comparisons in the Stroup-Gardiner study were made between the 15 second counts and the 1 minute counts and then

the 1 minute counts and the 4 minute counts. There was no comparison made between the 15 second counts and the 4 minute counts. If a difference exists, the most clearly observed difference would be between the 15 second versus 4 minute count comparison as these time intervals represent the extremes of the three different counts. Another possible contribution to the difference between the Stroup-Gardiner and CAP Lab results is the wide variety of different surfaces and surface conditions that were tested on during the Stroup-Gardiner study. These pavements ranged from 2.0” to 3.5” thicknesses, limestone bases to gravel bases, unsealed surfaces to coal tar sealed surfaces, high traffic volume areas to untraveled areas and parking lots to Accelerated Loading Facility (ALF) mats. Each geographic location used in the Stroup-Gardiner study contained ten different test locations from which the results were used in the statistical analysis. These conditions represent a wide range of circumstances. The CAP Lab study differs in the sense that testing was limited to three parking lots in which each case the gauge was placed and all readings were taken without lifting the gauge from this location. The fact that all of the readings were taken without the gauge having been moved provides for one single set of conditions for each location and a more controlled experiment from which to draw conclusions from since all of the aforementioned variability in the Stroup-Gardiner study had been eliminated.

### *6.2 RECOMMENDATIONS*

There are several key steps that need be taken to ensure minimum differences when using the nuclear gauge as a means to obtain HMA density values for payment purposes. The nuclear gauges were inconsistent with the correlation to mean core samples suggesting that the variability of the density readings is a product of the gauge itself. The following changes are recommended to ensure field procedures maximize the correlation between the nuclear gauge and the core samples:

- The recording time interval used for nuclear gauge measurements on the mat should be increased from two 30-sec counts to four 1-min counts. The 1-min recording time interval produces slightly better results than 30-sec. It is also true that with even longer recording time intervals, the accuracy increases but perhaps delay construction for density measurement. A recording time interval of 60-sec was chosen to balance accuracy with practicality. The additional advantage of taking 4 measurements is that it allows the exclusion of an outlier at a test location where as only two measurements prohibits the exclusion of an outlier. In general, the nuclear gauge results should improve by 0.45% of MTD when using 60-sec instead of 30-sec.
- Based on this research result, the differences between the longitudinal and transverse direction measurements were minimal and insignificant, but note that all nuclear gauge manufacturers suggest multiple measurements at one location. Therefore, we recommend to continue taking four measurements per location. This will ensure, through taking a mean of these four measurements, an average nuclear gauge density reading for that location. This will allow for future study of other models of nuclear gauge and if similar conclusions can be made for different make and model of nuclear gauge.
- A correction factor can be developed for the nuclear density gauges. The correction factor is project and nuclear density gauge specific. Even with the proper implementation of the correction factor, nuclear gauge readings can only

be expected to be within 1% of the density as measured by cores. In order to compensate for the inherent variability with the nuclear density gauge readings, it is advisable for contractors to account for this when determining the point for cessation of rolling operations in the field.

- The overall average of all the cores tested in accordance with AASHTO TP69 throughout this research project was 91.6 % of the MTD. The average density when corrected using ConnDOT block biases was 92.4%, indicating that actual average density was 0.8% less than what was measured using current ConnDOT protocol. This also indicates that achieving and measuring density in the field remains a major concern.
- The reported compaction measurement accuracy limits should be revised from 0.1 % to a minimum of 1%. This is based on the comparison of gauge densities to core densities, consistency between gauges as well as the variation from external factors. The reported accuracy level of 1% is based on the 95% confidence level for the nuclear gauge data collected in this experiment.
- The current ConnDOT specification has a target value of 94.5% ± 2.5% of MTD for pavement compaction. It is recommended to increase the minimum acceptance value for density to 93% of MTD. This recommendation is supported by research work conducted which indicates that for each one percent increase in air voids above 7%, there is a reduction in pavement service life of approximately 10% [23]. The current ConnDOT specification with a lower specification limit of 92% of MTD would be reducing the pavement's service life by 10% assuming that the density is uniformly 92% of MTD. Assuming that the pavement density

has a normal distribution, a pavement whose overall average density is exactly 92.0% of the MTD would have 50% of it density below 92%. Therefore, the air voids in half of the pavement would exceed 8%, which begins to greatly reduce the service life of the pavement. Additional research has demonstrated in order to reduce problems with water permeability of HMA mixes, the air voids should not exceed 6%-7%. [24]

- Additional research work needs to be performed to determine if the core correction factor is applicable to longitudinal joint density readings.
- There are many non-destructive methodologies under development for the measurement of pavement density. Additional research should be undertaken as these technologies mature to determine if they are capable of measuring the in-place density of the pavement more accurately than the current generation of nuclear density gauges. The use of core drying systems is another area of improvement that could be made. A preliminary investigation by the CAP Lab using a system recently purchased by Tilcon Connecticut showed that the system worked and did not affect the bulk specific gravity of cores. Additional testing of the system should be performed as it may allow core density values to be obtained much faster than is currently possible, without risking the integrity of the cores.

## *6.3 LIMITATIONS OF STUDY AND FURTHER RESEARCH*

While six gauges were used in this study, it should be noted that the findings apply only to these gauges on the type of projects being constructed in Connecticut. There was some degree of variability among the gauges produced even by a single gauge manufacturer in this study suggesting that external variables beyond those tested here have a large impact on the device. The final regression model developed in this study accounted for only 62.8 % of the total variation in nuclear gauge accuracy. The nuclear density testing variability must be assessed further and the following variables should be considered: mix properties such as aggregate gradation, source, and mix design, ambient temperature or weather conditions in general, surface texture variations within a certain project, and the temperature of the pavement when compacted.

## REFERENCES:


1. Parker, F., Wu, Y., *Comparison of Asphalt Contents Measured with the Nuclear Gage and Extraction Methods.* Journal of Testing and Evaluation, 1994. **22**(6): p. 556-563.
2. Alexander, M.L., Doty, R. N., *California Study of Asphalt Concrete Density Measurement-Nuclear Versus Core Density.* American Society for Testing and Materials, 1984: p. 80-92.
3. Brown, R., *Density of Asphalt Concrete- How Much is Needed?* 1990, Transportation Research Board: Washington DC. p. 21.
4. Burati, J.L., Jr. ,Elzoghbi, G. B., *Correlation of Nuclear Density Results with Core Densities.* Transportation Research Record, 1987. **1126**: p. 53-67.
5. Chaubane, B., Upsaw, P.B., Sholar, G.A., Page, G.C. ,and Musselman, J.A., *Nuclear Density Readings and Core Densities.* Transportation Research Record. **1654**: p. 70-78.
6. Mahoney, J., *Correlation of Nuclear Gauge Density Readings with Cores Cut from Compacted Roadways*. 2004, Connecticut Advanced Pavement Laboratory. p. 14.
7. Henault, J.W., *Field Evaluation of non-nuclear Density Pavement Quality Indicator*. 2001, Connecticut Department of Transportation. p. 47.
8. Parker, F., Hossain M. S., *An Analysis of Hot Mix Asphalt Mat Density Measurement.* Journal of Testing and Evaluation, 1995. **23**(6): p. 415-423.
9. Stroup-Gardiner, M., Newcomb, D., *Statistical Evaluation of Nuclear Density Gauges Under Field Conditions.* Transportation Research Record, 2000(1178): p. 38-46.
10. Garber, N.J., and Hoel, L.A., *Design of Flexible Pavements*, in *Traffic and Highway Engineering*. 1995, West Publishing Company: St. Paul. p. 784-845.
11. Huang, Y.H., *Pavement Analysis and Design*. 1993, Englewood Cliffs: Prentice Hall. 1-805.
12. Muench, S.T., Mahoney, J.P., and Pierce, L.M., *Pavement Guide Interactive*. 2002.
13. *Hot Mix Asphalt Pavement Manual*. 2003, Lathem: New York Construction Materials Association, Inc. 42.
14. Garber, N.J., and Hoel, L.A., *Pavement Rehabilitation Management*, in *Traffic and Highway Engineering*. 1995, West Publishing Company: St. Paul. p. 896-929.
15. Hanna, A.S., Russell, J.S., Schmitt, R.L., *Nuclear Density Gauge Implementation*. 1996, Wisconsin Department of Transportation.
16. Kandhal, P.S., Koehler, W. C., *Pennsylvania's Experience in the Compaction of Asphalt Pavements.* American Society for Testing and Materials, 1984: p. 93-106.
17. Sanders, S.R., Rath, D., and Parker, F, *Comparison of Nuclear and Core Pavement Density Measurement.* Journal of Testing and Evaluation, 1994. **120**(6): p. 953-966.
18. Stephens, J. *Evaluation of Nuclear and other Device Methods for Obtaining Bituminous Paving Densities*. in *6th Annual Paving Conference*. 1964. Chicago, IL: Connecticut Bituminous Concrete Producers Association.

19. Mitchell, T.D., *Density Monitoring on Asphalt pavement.* Better Roads, 1984. **54**(12): p. 22-25.
20. Zha, J., *Revisions of California Test Method 11 for Nuclear Gage Calibration*. 2000, California Department of Transportation: Sacramento. p. 1-18.
21. Regimand, A., *A Nuclear Density Gauge for Thin Overlays of Asphalt Concrete.* Transportation Research Record, (1126): p. 68-75.
22. American Association of State Highway and Transportation Officials Organization, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 24th Edition, and AASHTO Provisional Standards, 2004.
23. Linden, R. N., Mahoney, J. P. and Jackson, N. C., *Effect of Compaction on Asphalt Concrete Performance,* Transportation Research Record, (1217): p. 20-28.
24. Brown, E. R., Hainin, M. R., Cooley, A. and Hurley, G., *Relationship of Air Voids, Lift Thickness and Permeability in Hot Mix Asphalt Pavements,* NCHRP Report 531.
25. Miller, John S, Bellinger, William Y. *Distress Identification Manual for the Long-Term Pavement Performance Program.* SHRP-P-338. FHWA –RD-03-031. June, 2003.
26. Stephens, Jack E, Joint Highway Research Advisory Committee. Association of Asphalt Paving Technologists. 1964.
27. Hot Mix Asphalt Plant Technician Manual. NETTCP, Copyright January, 2005.

# Appendix A

## Draft Protocol for the Determination a Project Specific Nuclear Gauge Correction Factor

## Procedure for Determining a Correction Factor between Nuclear Density Readings and Cores

This procedure is intended to determine a correction factor that relates nuclear density readings to cores cut from compacted roadways. It is intended for nuclear density readings taken from the mat. Its applicability to joint density measurements is unknown.

Currently, this procedure is intended to produce a correction factor that is specific only to the project in question and the nuclear density gauge(s) to be used throughout the project. Further data collection will provide the information to determine if the correction factor is applicable for similar mixes produced with similar aggregates placed on different projects.

1.0 Scope

1.1 This method covers the determination of density of Hot Mix Asphalt (HMA) pavements in accordance with Connecticut Department of Transportation Form 816 section 4.06.03-5. This method requires the correlation of Nuclear Density Gauge readings with core densities determined in accordance with AASHTO TP69.

1.2 All Nuclear Density Gauges to be used on a project must be correlated to the HMA and field conditions present at a project by the use of cores.

1.3 This correction procedure must be performed for all HMA mixes to be used as binder course and wearing surface. Leveling courses are exempt from this requirement.

1.4 The use of leveling sand is prohibited when testing in accordance with this procedure.

2.0 Apparatus

2.1 Nuclear Density Gauge with the factory matched standard reference block including manufacturer’s Operator’s Manual for the specific gauge, factory calibration, Standard Count Log Book and proper transport case.

2.2 A rolling measuring device that will measure from 1 to 10,000 linear feet.

2.3 Coring machine capable of sawing cores with a minimum 6 inch (150 mm) diameter and with minimal distortion of the specimen.

2.4 Diamond blade wet saw.

2.5 Forced draft oven capable of maintaining 125 ± 5 degrees Fahrenheit.

2.6 Equipment conforming to AASHTO TP69 for determining the Bulk Specific Gravity of cores.

3.0 <u>Calibration</u>

3.1 The Nuclear Density Gauge shall be calibrated in accordance with ASTM D2950 every 12 months or sooner if the readings from the gauge become suspect.

3.1.1 Calibration shall be performed by the gauge manufacturer or by other methods acceptable to the Engineer.

3.2 Copies of gauge calibration certificates will be submitted to the Engineer.

4.0 <u>Standardization</u>

4.1 Standardization of the Nuclear Density Gauge shall be performed at the start of each day's work. The gauge shall be turned on and allowed to stabilize for 10-20 minutes or per manufacturer's recommendation prior to performing Standardization.

4.2 Follow the manufacturer's procedure for performing the Standardization.

4.3 Record the Standard Count in the Standard Count Log Book. If the Standard Count exceeds the reported accuracy established by the manufacturer, repeat the Standardization procedure. If the second Standard Count is within the manufacturer's tolerance, the gauge may then be used. If the second Standard Count remains outside of the manufacturer's tolerances, then the Nuclear Density Gauge must be adjusted or repaired as recommended by the manufacturer before use.

4.4 After completing Standardization, the Nuclear Density Gauge power should remain on for the rest of the day.

5.0 <u>Field Testing to Establish a Nuclear Density Correction Factor</u>

5.1 A correction factor between Nuclear Density Readings and cores tested in accordance with AASHTO TP69 shall be established for each HMA mixture used on a project. A new correlation factor will also be established when the job mix formula changes sufficiently to require a new mix design to be submitted. Also, a new correlation factor will be required when the target compacted thickness is changed more than 0.5 inch. A new correlation factor should be established whenever the test results from the Nuclear Density Gauge become suspect. If a different Nuclear

Density Gauge is used than was during the determination of the correction factor for the project, then a new correction factor must be established for that Nuclear Density Gauge.

5.2 The correction factor will be established during the first day's production for the project. All locations used for establishing the correction factor shall occur in the travel lanes of the roadway.

5.3 10 test locations will be chosen by dividing the first day's paving occurring in the travel lanes into 10 subsections of equal length. One test location will occur within each of the subsections. Its location will be determined randomly in accordance with ASTM D3665 or other method acceptable to the Engineer.

5.3.1 For purposes of establishing the correction factor, no testing shall occur within 50 feet of the starting transverse joint and no testing will occur within 2 feet of either longitudinal edge. Any random transverse location falling within 2 feet of a longitudinal edge shall be eliminated and a new random transverse location determined. Unless otherwise noted, transverse offsets are referenced from the left edge when facing the direction of paving.

5.3.2 All measurements used for random locations shall be rounded to the nearest foot.

5.4 Locate points determined randomly as described in section 5.3.

5.5 At each test location, 4 nuclear density readings shall be taken. The bias in the gauge should be set to zero. For each reading, the operator must ensure the Nuclear Density Gauge is seated on a flat surface. This may be accomplished by ensuring the Nuclear Density Gauge does not rock when downward force is applied at each corner of the Gauge. It is critical to maintain maximum contact area between the Nuclear Density Gauge and the pavement surface. At no time shall any gap exceed 0.25 inches or 6 mm as per ASTM D-2950. The Nuclear Density Gauge testing mode used for determining correlation factor must be recorded on Connecticut Department of Transportation testing report form YYY and used throughout the entire project.

5.5.1 Place the Nuclear Density Gauge parallel with the direction of paving such that the center of the Nuclear Density Gauge is over the random location. Mark the footprint of the Nuclear Density Gauge with a crayon. Take a reading using a minimum 60 second count. Record this value in $lb/ft^3$.

5.5.2 Rotate the Nuclear Density Gauge 180 degrees placing the Nuclear Density Gauge back on the pavement within the crayon footprint outline previously made in 5.5.1. Take a reading using a minimum 60 second count. Record this value in $lb/ft^3$.

5.5.3 Rotate the Nuclear Density Gauge 90 degrees placing the center of the Nuclear Density Gauge in the center of the crayon footprint established in 5.5.1. The Nuclear Density Gauge should now be perpendicular to the direction of paving. Mark the footprint of the Nuclear Density Gauge with a crayon. Take a reading using a minimum 60 second count. Record this value in $lb/ft^3$.

5.5.4 Rotate the Nuclear Density Gauge 180 degrees placing the Nuclear Density Gauge back on the pavement within the crayon footprint outline previously made in 5.5.3. Take a reading using a minimum 60 second count. Record this value in $lb/ft^3$.

5.5.5 The Nuclear Density Value in $lb/ft^3$ for this location will be represented by the average of the 4 readings.

5.5.6 This process shall be repeated for all Nuclear Density Gauges to be used on the project.

5.6 A core shall be cut at the Contractor's expense from the center of the crayon footprint outlines created in section 5.5. The coring apparatus must be able to cut a core with minimal disturbance to the specimen.

5.6.1 The temperature of the mat shall be sufficiently cool to allow the core to be cut without distorting it. This may be aided by applying ice or dry ice to the surface prior to cutting. It is recommended that the maximum surface temperature of the pavement be 100-120°F prior to cutting the core.

5.6.2 The minimum diameter of the core shall be 6 inches.

5.6.3 The core bit must cut completely through the layer being tested. If the core delaminates after penetrating the full depth of the layer of interest, then coring may stop. If the core does not delaminate, then the coring must extend on until the core is free.

5.6.4 After removing the core, the core should be inspected to ensure it is not damaged or distorted.

5.6.5 Each core shall be labeled using a lumber crayon with: Project Number, Core Number matching subsection number and date.

5.6.6 Any core that appears to be damaged or distorted shall be rejected. A new test location will be established moving in the direction of paving at least 1 foot to the closest dry location, while maintaining the same transverse offset.

5.6.7 Each core location shall be patched by the Contractor at the contractor's expense.

5.6.7.1 Excess water shall be removed from core hole using a sponge.

5.6.7.2 The sides of the hole shall be tacked.

5.6.7.3 HMA from the project will be used to fill the hole. Compaction of the core hole shall be accomplished by using a circular tamper.

5.6.7.4 At the contractor's discretion, an alternate core may be cut to allow testing at the contractor's lab. This core should be located approximately one foot away from the original core in the longitudinal direction of paving.

5.7 This process will be repeated until all 10 test locations have been completed.

5.8 The cores will be transported to the Connecticut Department of Transportation Materials Laboratory in Rocky Hill within 24 hours of cutting the cores. Care must be exercised in storing the cores for transport to the Materials Lab to avoid distorting and damaging the cores.

5.9 Cores extending beyond the layer of measurement shall be sawn using a wet-diamond blade saw to remove the extraneous material.

5.10 The cores shall be dried to a constant mass in accordance with AASHTO TP69, Note 2.

5.11 The density of the cores shall be determined in accordance with AASHTO TP69.

5.12 The core thicknesses shall also be measured and recorded.

6.0 <u>Calculation of the Correction Factor</u>

6.1 Nuclear Density Computations

6.1.1 The average of the four nuclear densities obtained for each cored location shall be determined.

6.1.2 The percent compaction shall be computed for the average nuclear density obtained for each cored location. The average maximum theoretical density for the day's production shall be used in the computation of percent compaction.

$\% \text{ Comp}_{nuclear} = \{(\text{Average Nuclear Density})/(\text{Maximum Theoretical Density})\}*100$

6.2 Core Density Computations

6.2.1 The percent compaction for the core shall be computed. The average maximum theoretical density for the day's production shall be used in the computation of the percent compaction.

$\% \text{ Comp}_{core} = \{(\text{Core Density})/(\text{Average Maximum Theoretical Density})\}*100$

6.3 Compute the difference between the percent compaction of the nuclear density gauge and core for each cored location.

$\% \text{ Difference} = \% \text{ Comp}_{nuclear} - \% \text{ Comp}_{core}$

6.4 Discard any results where the % Difference, as calculated in section 6.3, is greater than +2%. (Values greater than +2% typically indicate the core is damaged and should not be used) Values less than -2% are acceptable and should be used.

6.5 Compute the correction factor for the nuclear density gauge by averaging the remaining % differences.

6.6 The correction factor shall be subtracted from all subsequent measurements of percent compaction made with the nuclear density gauge. This value is nuclear density gauge and project specific. (Subtraction of negative number is the same as adding the absolute value of the number.)

7.0 <u>Daily Validation</u>

7.1 A location shall be selected on the first day of paving where measurements shall be taken each day for each nuclear density gauge on the project. This location must be selected to allow safe access each paving day. This would typically be located on a shoulder or ramp. It should also be on material that is representative of the material being placed. Care should be taken to avoid areas exhibiting visible defects.

7.2 Each day of the project, the nuclear density gauges used shall make 4 one-minute measurements similar to the procedure outlined in section 5.5 on this location. The position of the nuclear density gauge should be marked out using temporary marking paint on the first day's measurements.

7.3 The average of the four density measurements should be computed for each day. This value shall be compared to the average obtained on the first day's testing. Average values obtained after the first day should not differ from the first day's average by more than 4 pcf.

8.0 <u>Nuclear Density Gauge Replacement</u>

8.1 In the event that a nuclear gauge used in the original determination of the correction factor must be replaced, the following procedure should be followed. This situation should be avoided whenever possible as the confidence in the accuracy of the correction factor is decreased.

8.2 The correction factor for the replacement gauge shall be determined using the location marked out for the Daily Validation. Note: the maximum theoretical specific gravity ($G_{mm}$) used in this section is the $G_{mm}$ from the first day's paving when the Daily Validation location was placed.

8.2.1 The replacement gauge shall make a series of 4 one-minute readings in a similar fashion as was used in the Daily Validation measurements. The bias in the nuclear density gauge shall be set to zero for these measurements.

8.2.2 The average of these four density measurements shall be determined.

8.2.3 The corrected density shall be determined for this location using data collected by a nuclear density gauge utilized on the first day of paving. This will utilize the average density for the Daily Validation location obtained on the first day's paving and the correction factor for that gauge obtained in section 6.6.

$Density_{corrected}$ = (first day's Daily Validation average) + (correction factor/100)*$G_{mm}$*62.4

8.2.4 The correction factor in pcf for the replacement gauge shall be computed by subtracting the average of the four density measurements obtained from the corrected density at Daily Validation location.

Replacement Correction Factor, pcf = $Density_{corrected}$ – average obtained in section 8.2.2

8.2.5 To convert the replacement correction factor determined in section 8.2.4 to percent compaction, divide the replacement correction factor by the $G_{mm}$ and 62.4.

Replacement Correction Factor,% =(Replacement Correction Factor, pcf)/($G_{mm}$*62.4)*100

9.0 Mat Nuclear Density Measurements After Determining Correction Factor

9.1 After determining the correction factor, all subsequent measurements on the project shall be adjusted by subtracting the correction factor from the percent compaction determined by the nuclear density gauge. (Subtraction of negative number is the same as adding the absolute value of the number.)

9.2 A measurement at a randomly determined location shall consist of the average for 4 one-minute readings. The nuclear density gauge shall be oriented in the same manner as is outlined in sections 5.5.1 through section 5.5.5 for the 4 one-minute readings.

9.3 When testing the mat density for a day's production where testing has occurred at least 10 different mat locations, the highest and lowest density values obtained from the nuclear density gauge shall be dropped from the computation of the day's average percent compaction. All nuclear gauge measurements of the percent compaction shall be corrected using the average $G_{mm}$ for that day's production.