Variability Evaluation of Density Profiling Systems' Test Protocol

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ABSTRACT

The work conducted under this study was designed to establish achievable tolerances for DPS-related measurements, break the measurement errors down into their components, and estimate the error propagation impact on the final DPS evaluated in-place pavement density. To determine the repeatability and reproducibility precision in the field, six sensors were used to comply with the minimum number of participants as required in ASTM E691. Pavement sections built at the NCAT Test Track in 2021 were used in this study and included: fine-graded mixes and open-graded mixes; three underlying materials: new asphalt layer, milled asphalt surface, and granular base; thicknesses ranging from 3.8 to 13.9 cm; and two testing locations: within the mat and along the joint. Computed precision statements for the within laboratory and between laboratory in terms of dielectric values were 0.083 and 0.125, respectively. In terms of density the statements were 27.4 kg/m^3 and 36.4 kg/m^3, respectively.

INTRODUCTION

ASTM E691, "Standard Practice for Conducting an Inter-laboratory Study to Determine the Precision of a Test Method" provides a standard procedure for determining the precision of a test method. Precision, when evaluating test methods, is expressed in terms of two measurement concepts, repeatability and reproducibility. Under repeatability conditions, the factors such as the operator, equipment used, calibration of the equipment, and environment (temperature, humidity, air pollution, etc.) should remain reasonably constant and usually contributes only minimally to the variability. Under reproducibility conditions, the factors are generally different (i.e., they change from laboratory to laboratory) and usually contribute appreciably to the variability of test results. Thus, repeatability and reproducibility are two practical extremes of precision (ASTM E691).

To obtain reasonable estimates of repeatability and reproducibility precision, it is necessary in an interlaboratory study to be aware of excessively "clean" data in the sense that only the uniquely best operators are involved or that a laboratory takes unusual steps to get "good" results. In this study, graduate students, technicians, and researchers with relatively little to abundant experience participated. It is also important to recognize and consider how to treat "poor" results that may have unacceptable assignable causes, as the inclusion of such results in the final precision estimates might be questioned. In this case, it has been determined that samples compacted at low density (high air void) levels tend to add significant error in the prediction of air voids in the laboratory and potentially in the field (Mickey et al, 2004).

An essential aspect of collecting useful consistent data is careful planning and conduct of the study. Questions concerning the number of laboratories required as well as the number of test results per laboratory affect the confidence in the precision statements resulting from the study. According to ASTM E691, at least six laboratories should be part of an interlaboratory study. Other issues involve the number, range, and types of materials to be selected for the study, and the need for a well-written test method and detailed instructions to the participating laboratories. In this case, each individual sensor or antenna was considered an independent laboratory. Thus, 12 total sensors were used in the laboratory dielectric (velocity-based) to air voids conversion subtask with two different materials compacted at four density levels. For the field dielectric (surface reflection-based) subtask, six sensors were used with the eight different asphalt pavement sections.

To evaluate the consistency of the data obtained in an interlaboratory study, two statistics are used in ASTM E691: the “k-value”, used to examine the consistency of the within-laboratory precision from laboratory to laboratory, and the “h-value”, used to examine the consistency of the test results from laboratory to laboratory. These test statistics are particularly useful for interlaboratory studies. By studying the collated data deviations and accuracy, the performance of a laboratory in terms of its reliability and errors can be established. A laboratory with poor performance can then do its own in-house investigation and make corrective actions for such deficiencies (ASTM E177, ASTM E456).

Most standard practices will not report k- and h-values. Instead, the repeatability standard deviation Sr (single operator) and reproducibility standard deviation SR (multi-laboratory) are typically reported. Table 1 shows standard deviation and precision statement values of tests used to measure field density of asphalt pavements. ASTM standard practices also include repeatability and reproducibility limits or statements (r and R), which are defined as 2.8 times the respective repeatability and reproducibility standard deviations.

Table 1. Density Single and Multi-Laboratory Standard Deviations and Statements

Parameter	Nuclear Gauge ASTM D2950	Electromagnetic Surface Contact ASTM D7113
Single Operator - S_r	25.1 kg/m^3 (1.57 pcf)	20.4 kg/m^3 (1.28 pcf)
Multi-Laboratory - S_R	28.0 kg/m^3 (1.75 pcf)	23.5 kg/m^3 (1.47 pcf)
Single Operator - r	70.4 kg/m^3 (4.40 pcf)	57.3 kg/m^3 (3.58 pcf)
Multi-Laboratory - R	78.4 kg/m^3 (4.90 pcf)	65.8 kg/m^3 (4.11 pcf)

The repeatability limit is defined in ASTM E691 as “the value below which the absolute difference between two individual test results obtained under repeatability conditions may be expected to occur with a probability of approximately 0.95 (95%)”. The reproducibility limit is defined in ASTM E691 as “the value below which the absolute difference between two test results obtained under reproducibility conditions may be expected to occur with a probability of approximately 0.95 (95%)”.

As part of the evaluation of the potential use of the international friction index as the standard for the reporting of friction measurements, the Florida Department of Transportation (FDOT) assessed the precision of the dynamic friction tester (DFT) and circular track meter (CTM) test methods. The FDOT CTM equipment and DFT equipment were compared with similar portable equipment owned and operated by NCAT in an attempt to quantify both the repeatability and the reproducibility of the test data obtained. The FDOT portable equipment was shipped to Auburn, Alabama, for side-by-side testing with the NCAT equipment (Jackson et al, 2009).

Compared to what is indicated in ASTM E691, only two laboratories were used to establish precision statements. In this study, the repeatability and reproducibility of the data were analyzed statistically according to the range, standard deviation, and coefficient of variance (COV). Here, the range served as a convenient measure of data dispersion, whereas the standard deviation is a measure of the deviation around the mean. COV is commonly used as a normalized measure of how much variability exists in the data. It is the ratio of the standard deviation to the mean for the data set, expressed in a percentage. In addition to these statistical methods, paired t-tests were performed to compare the difference between the means of the paired data sets. In this case, the acceptance of the null hypothesis was used and an indication that the means of the data sets were not statistically different between laboratories (Jackson et al, 2009).

The assessment of the precision of the DFT and CTM equipment was conducted on 10 different test surfaces at the NCAT Test Track. Tests with the DFT and CTM were performed at five different locations within each of the 10 different test sections by using both the NCAT and FDOT equipment. Based on the results of this comparison testing, proposed precision statements were presented for both the repeatability and the reproducibility of the data for the respective pieces of equipment. Correlation relationships were also developed for the portable equipment and the full-scale equipment currently used by FDOT and others (Jackson et al, 2009). Although this approach deviated slightly from ASTM E691, it has proven to be an effective method when there are limited laboratories available to determine preliminary precision statements or verify existing ones.

Based on the information obtained from ASTM E691 and the friction study conducted by FDOT, the experimental plans for both laboratory and field testing were adjusted according to the conditions and limitations found in this study. The experimental plan included a total 6 sensors to conduct the inter-laboratory study with one operator, eight different asphalt pavement sections, two different locations within the sections, and three replicates per location.

DPS TEST PROTOCOL

After several years of work, the pooled fund named “Continuous Asphalt Mixture Compaction Assessment Using Density Profiling System (DPS) [TPF-5(443)]” has developed and refined the various processes for using DPS to properly collect data, as well as a range of supporting documents and training videos that detail and demonstrate the steps involved. The efforts have provided hundreds of miles of DPS data that pooled fund members, consultants, vendors and other industry stakeholders have shared and discussed at DPS pooled fund project updates, peer exchanges, trainings, vendor updates, technical working group meetings and an in-person training. The experiences contributed to the development of a draft specifications, delivered to AASHTO in 2019 and one more in 2023. This drafts marks a major milestone by adding a standard procedure to accurately convert dielectric data to density measurements without cutting any field cores.

The first AASHTO Designation: PP 98-19: “Standard Practice for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar,” specifies the equipment and software requirements for a dielectric profiling system (DPS). Calibration and verification procedures are also detailed. Several operating requirements were included in this draft standard practice; however, these criteria were developed based on limited experience. Thus, the need for conducting a study that can complete the draft standard practice with precision statements for refinement of those criteria.

FIELD DIELECTRIC TEST RESULTS AND PRECISION STATEMENTS

To determine the repeatability and reproducibility precision in the field, six sensors were used to comply with the minimum number of participants as required in ASTM E691. Tested pavement sections included:

- Fine-graded mixes and open-graded mixes
- Underlying surface: new asphalt layer, milled asphalt surface, granular base
- Thickness: ranged from 3.8 cm (1.5 in) to 13.9 cm (5.5 in)
- Testing location: within the mat and along the joint

Table 2 shows more details of some of the tested sections in terms of thickness, base material and in some cases compaction level from quality control data. Not all the construction information was available during the development of this report.

Table 2. NCAT Test Section Properties

Section	**E9**	**E10**	**N8**	**N6**	**N9**	**N1, N2, N7**
Thickness, cm (in)	3.8 (1.5)	3.8 (1.5)	5.7 (2.25)	5.9 (2.33)	8.1 (3.18)	13.9 (5.5)
Base material	Old AC	Old AC	New AC	Old AC	Old AC	Granular Base
%G_{mm} (cores)	Not Available	94.0%	95.3%	94.4%	94.5%	94.5 to 96.1%

Before testing, equipment consistency verification (standard HDPE and line) was performed to check the adequacy of each sensor to be used. The length of each section was measured and a metal plate was positioned at the beginning and at the end of each test section (Figure 1) as reference points for each measured profile. One of the sensors was placed approximately 15.2 cm (6 in) from the longitudinal joint and another sensor was placed on the other end of the transverse bar of the cart (this should be close to the center of the lane) as shown in Figure 51. The operator proceeded to collect dielectric values in distance mode starting about 60.9 cm (2-ft) from the metal plate and kept track of the sensor placed near the longitudinal joint to be about 15.2 cm (6 in) from it through the entire length of the section. This process was repeated three times for each pair of sensors at both positions (center and joint). Some variability was expected from one profile to another because there was no marked line to follow with the laser in the sensor. However, this exercise was conducted to reproduce a typical dielectric profile test performed at any location within a pavement section and near the joint.

Figure 2 shows the average dielectric values measured along the joint (six inches away from the joint) and within the mat near the center of the lane for eight different sections. For six out of eight sections, no significant differences were noted in average dielectric values between the joint and the within mat test locations. In addition, average dielectric values obtained from all six sensors were not significantly different.

Figure 3 shows standard deviations of dielectric values measured along the joint and within the mat near the center of the lane for eight different sections. It was determined that sensor 207 tended to have higher variabilities (7 out of 16 cases) than other sensors and showed the highest overall standard deviation. However, higher variabilities obtained with sensor 207 did not affect the consistency of the repeatability and reproducibility (h- and k-values) and the results were considered acceptable.

An evaluation of each sensor's height, captured from the bottom of the sensor to the pavement surface, was conducted to identify if there was anything unique about sensor 207. Table 3 shows average, standard deviations, and maximum and minimum recorded heights when sensors were positioned near the center of the pavement section and near the joint. These results do not show any significant difference of the height of sensor 207 with respect to the other sensors. However, it is important to mention that on average, all the sensors were slightly below the target height of 22.8 cm (9.0 in). Therefore, this may be an indication that the device may need to be adjusted to correct for any sagging.

Figure 1. Test Configuration

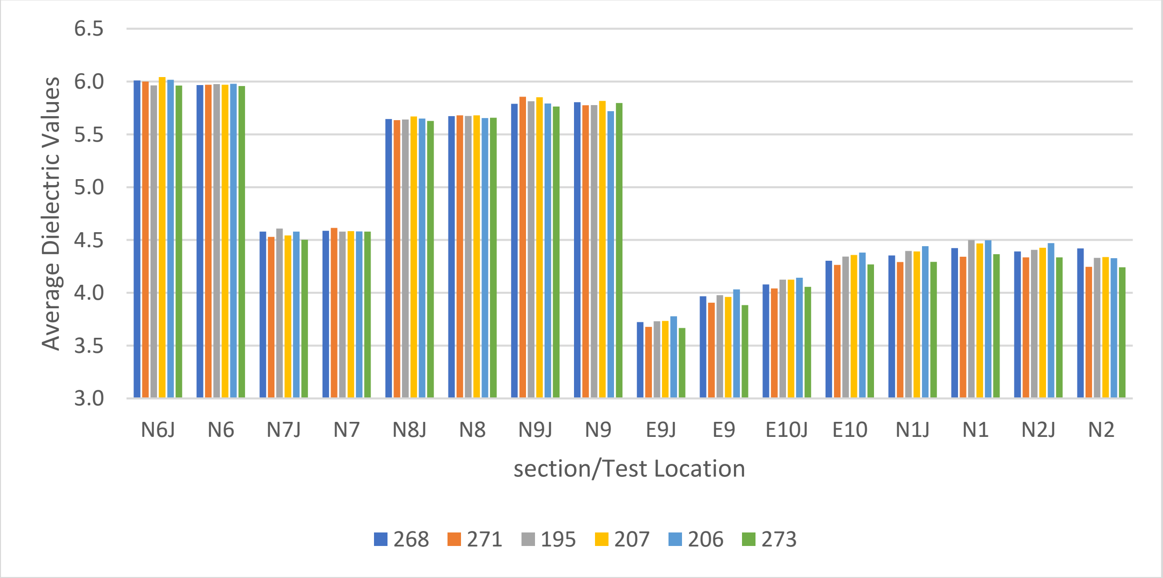


Figure 2. Average of Field Dielectric Values

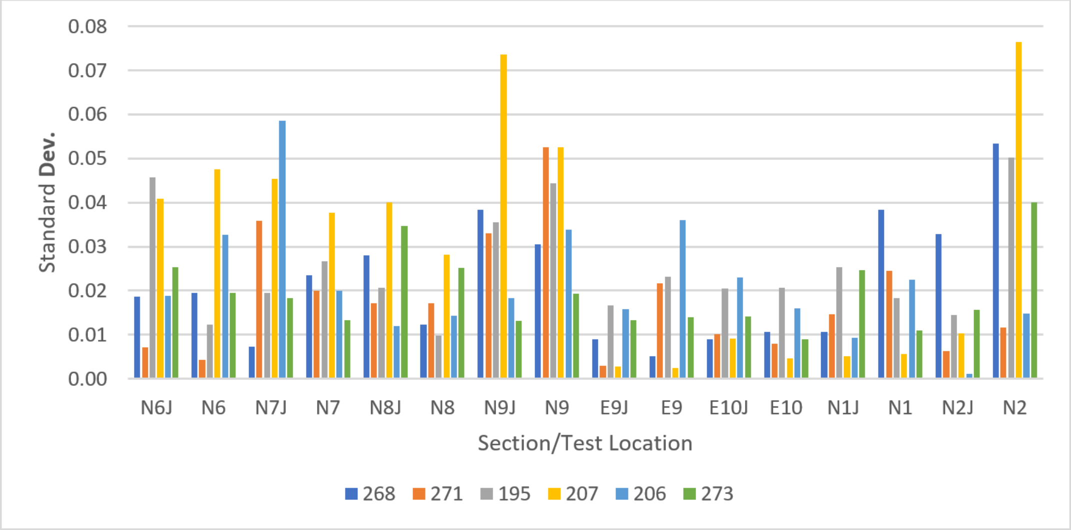


Figure 3. Standard Deviation of Field Dielectric Values

Table 3. Evaluation of Sensor Height During Testing

Location	**Sensor**	**268**	**271**	**195**	**207**	**206**	**273**
Center	Average Ht., cm	22.0	22.0	22.1	22.0	22.2	22.0
	Stand. Dev.	0.25	0.28	0.25	0.28	0.25	0.28
	Max	23.1	23.5	23.1	23.8	23.6	23.3
	Min	21.1	20.8	21.1	20.8	21.2	21.0
Joint	Average Ht., cm	22.3	21.8	22.4	21.8	22.4	21.8
	Stand. Dev.	0.28	0.23	0.28	0.23	0.25	0.23
	Max	24.1	22.9	23.9	23.0	23.7	22.9
	Min	21.2	20.7	21.1	20.9	21.3	20.7

Figures 4 and 5 show field dielectric consistency h- and k-values, respectively. Critical h- and k-values were obtained from Table 5 of ASTM E691. Selection of these critical values depends on the number of laboratories or in this case, number of sensors (six) and number or replicates (three). h-critical for nine sensors is 1.92 and k-critical is 1.98. For all sensors, levels of air voids, and mixtures, h- and k-values did not exceed the respective critical values. Therefore, it can be concluded that the mean dielectric results can be considered accurate and acceptable.

Evaluation of the potential effect of dielectric testing near the joint was conducted with two-sample t-tests of S_r and S_R values. Figure 6 shows bar plots of S_r and S_R values computed for the joint and the other location within the mat. Significant differences between S_r and S_R values can be observed within the same section but in some cases, these values were higher at the joint location and in other cases lower. A two sample paired t-test was conducted for each parameter (S_r and S_R) and at a confidence level of 0.05 and no statistical differences were identified (S_r: p-value = 0.292, S_R: p-value = 0.486). Therefore, separate precision statements are not required for joint and mat testing at this time. Figure 6 also shows the relationship between standard deviations and the average of dielectric values. No trends were observed, and the use of standard deviation is considered a valid approach to determine precision statements.

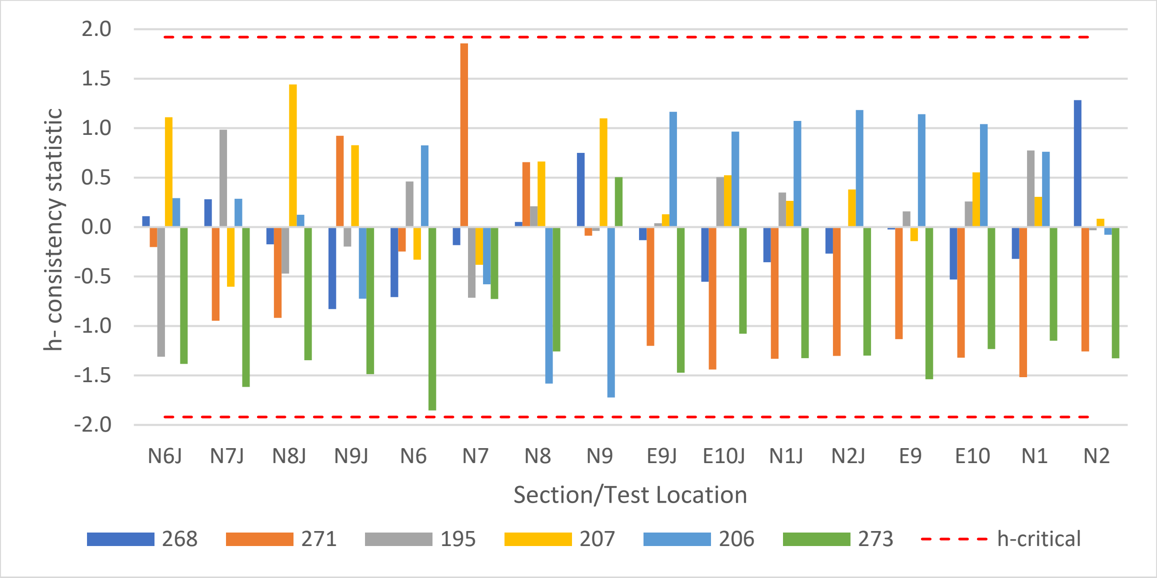


Figure 4. Field Dielectric h-Values

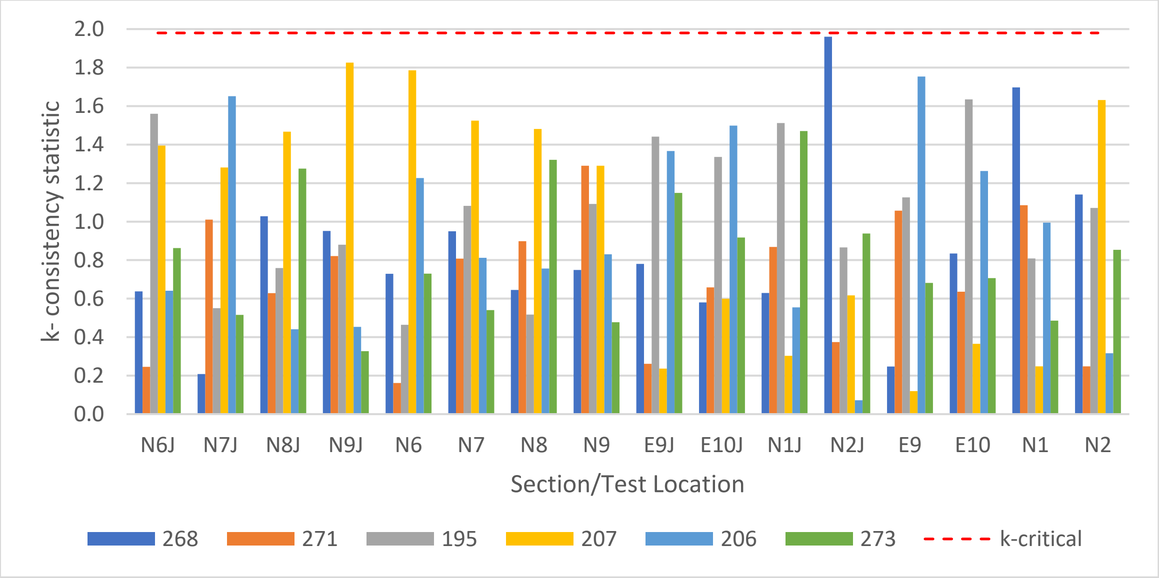
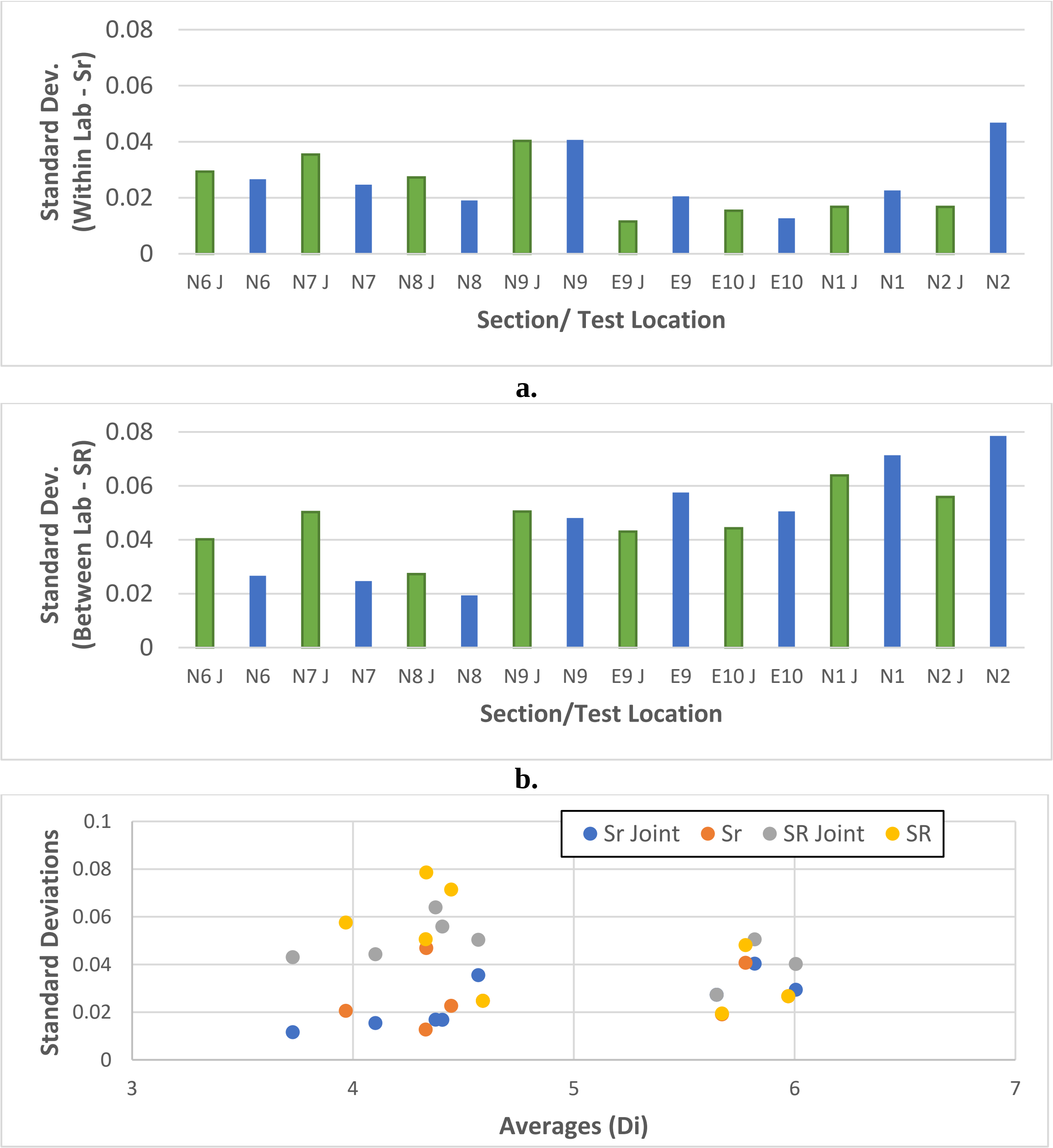


Figure 5. Field Dielectric k-Values

Table 4 shows computed field repeatability and reproducibility statements for measured dielectric values and estimated density. These limits indicate that the maximum expected difference in the average dielectric values in the same pavement profile/location by the same operator should be 0.071. In addition, the maximum expected difference in the average dielectric values for identical test locations performed with different sensors should be 0.129. In this case, statements for estimated density were 22.8 kg/m^3 (1.42 pcf) for single laboratory and 36.8 kg/m^3

(2.30 pcf) for multiple laboratories. These are significantly lower statements compared to the ones shown in ASTM D2950 (Nuclear Gauge) and ASTM D7113 (Electromagnetic Surface Contact). However, the statements for ASTM D2950 and ASTM D7113 were obtained over single locations and these dielectric-density statements were obtained over continuous locations.



a.

b.

c.

Figure 6. Field Dielectric Standard Deviations, a. Within Lab, b. Between Lab, c. S_r and S_R vs Average Values

All the evaluated sections at the NCAT Test Track had different lengths ranging from 30.5 m (100 ft) to about 67 m (220 ft). It was decided to standardize the process to account for 30.5 m (100 ft) sections. Therefore, all these and future evaluations of precision statements will be performed on the same length (30.5 m). In addition, each 30.5 m (100 ft) section was subdivided into subsections of 15.2, 6.1, 3.0, 1.5 and 0.9 meters to compute precision statements for each of these subsections.

Table 4. Field Precision Statements

Variable		Within Lab (r)	Between Lab (R)
Dielectric	Average	0.071	0.129
	Max	0.131	0.215
	Min	0.032	0.054
Density kg/m^3 (pcf)*	Average	22.8 (1.42)	36.8 (2.30)
	Max	39.8 (2.49)	60.6 (3.79)
	Min	13.5 (0.845)	16.6 (0.853)

* Estimated from dielectric-density equations

Tables 5 and 6 show field dielectric standard deviations and precision statements for all scenarios, respectively. These tables indicate that averaging dielectrics over a greater distance tends to reduce variability and provides lower precision statements. It is important to point out that when performing these tests, there were no lines marked on the pavement sections for operators to follow. This was conducted with the idea to reproduce field tests on a brand new pavement where an operator would simply test near the joint and follow a swerve or a line pattern without marks or specific references to test over. As expected, due to the location variability of the sensor along the joint, chances of matching profiles over a short distance were very low and negatively affected repeatability of the results.

Table 5. Field Dielectric Standard Deviations for all Scenarios

Section Size	Within Lab - Sr			Between Labs - SR		
	Average	Maximum	Minimum	Average	Maximum	Minimum
30.5 to 67 m	0.025	0.047	0.012	0.046	0.077	0.019
30.5 m	0.030	0.059	0.013	0.044	0.082	0.021
15.2 m	0.032	0.072	0.010	0.048	0.080	0.021
6.1 m	0.035	0.076	0.012	0.052	0.097	0.022
3.0 m	0.041	0.090	0.012	0.065	0.118	0.033
1.5 m	0.045	0.099	0.014	0.069	0.142	0.032
0.9 m	0.050	0.119	0.014	0.074	0.170	0.032

Table 6. Field Dielectric Precision Statements of all Scenarios

Section Size	Within Lab - r			Between Labs - R		
	Average	Maximum	Minimum	Average	Maximum	Minimum
30.5 to 67 m	0.071	0.131	0.032	0.129	0.215	0.054
30.5 m	0.083	0.165	0.035	0.125	0.228	0.058
15.2 m	0.089	0.201	0.028	0.133	0.224	0.058
6.1 m	0.098	0.212	0.034	0.146	0.273	0.061
3.0 m	0.114	0.253	0.033	0.182	0.330	0.092
1.5 m	0.125	0.278	0.040	0.192	0.398	0.088
0.9 m	0.141	0.334	0.040	0.208	0.475	0.088

Table 7 shows field repeatability and reproducibility statements for estimated density considering subsections of 30.5 m and below. As expected from the results shown in Table 6, lower precision statements were obtained as the length of the section was decreased. As previously mentioned, this is most likely explained by the low chance of obtaining profiles at the exact same location. These short length profiles can have lateral and longitudinal offsets. In order to better evaluate variability on short distances (less than 6.1 meters), it is recommended to mark a line on the pavement and obtain at least three profiles per sensor.

Table 7. Field Estimated Density Precision Statements of all Scenarios

Section Size	**Within Lab – r,** kg/m^3			**Between Labs – R,** kg/m^3		
	Average	**Maximum**	**Minimum**	**Average**	**Maximum**	**Minimum**
30.5 m	27.4	46.8	14.7	36.4	65.5	14.7
15.2 m	28.0	54.5	14.7	37.7	66.4	14.7
6.1 m	27.5	57.4	15.4	41.9	78.2	17.6
3.0 m	31.7	68.3	15.0	52.2	94.5	26.3
1.5 m	34.9	71.8	16.0	57.2	106.6	27.5
0.9 m	37.3	126.9	20.2	63.2	136.2	30.1

Given that 30.5 m sections are now considered the standard size, the maximum expected difference in the average dielectric values in the same pavement profile/location by the same operator should be 0.165. In addition, the maximum expected difference in the average dielectric values for identical test locations performed with different sensors should be 0.228. In this case, statements for estimated density had to be updated to 46.8 kg/m^3 (2.922 pcf) for single laboratory and 65.5 kg/m^3 (4.089 pcf) for multiple laboratories.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been derived from the results of this task:

- After conducting field testing, it was determined that for all sensors and field variables, h- and k-values did not exceed the respective critical values. Therefore, the mean dielectric results can be considered accurate and acceptable.
- Preliminary field test precision statements indicated that the maximum expected difference in the measured dielectric values in the same pavement location by the same operator should be 0.083. In addition, the maximum expected difference in the measured dielectric values for identical test locations performed with different sensors should be 0.125.
- On both cases (within and between laboratory precision), estimated density precision statements were significantly lower than the laboratory and field test methods reported for nuclear and electromagnetic density gauges.
- Further evaluation and verification of the proposed precision statements is highly recommended with new mixtures containing different materials and gradations. This is especially important for the evaluation and determination of precision statements of shorter distances where, under this experiment, it was not guaranteed that the sensor were reading exactly over the same line.

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