STATE OF FLORIDA

PRECISION OF SMOOTH AND RIBBED TIRE LOCKED WHEEL TESTERS FOR MEASUREMENT OF ROADWAY SURFACE FRICTION CHARACTERISTICS

Research Report

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Executive Summary

The present state-of-the-art locked wheel testers for roadway surface friction evaluation are fully automated. As with any testing using subject-driven, instrumented devices, the major concerns of the end usefulness of the resulting data are accuracy and precision. Although a level of uncertainty is always inherent to any measurement process, it must also be appropriately quantified or assessed. Therefore, the Florida Department of Transportation (FDOT) initiated the present field study to assess the level of precision of its own locked-wheel testers for field measurements. Friction measurements were acquired using four friction locked-wheel testers concurrently on a number of asphalt section sites. These test sections were randomly selected to include both open and dense graded surface mixtures. The collected friction data was first analyzed to determine the friction characteristics at each test location, in terms of a friction number at 40 mph using a standard ribbed (FN_{40R}) and smooth tire (FN_{40S}). The results were then used as a basis for an evaluation of the repeatability (within-unit precision) and reproducibility (between-unit precision) of the friction units.

This report presents a description of the testing program, the data collection effort and the subsequent analyses and findings.

Background

As travel safety and efficiency are of increasing importance to state agencies, friction measurements have become an important tool in the management of pavement surfaces. They are being used to identify potential hazardous conditions, determine/monitor friction characteristics of the various in-service pavement surfaces, and assess the need for rehabilitation and maintenance. As such, the Florida Department of Transportation (FDOT) has been conducting friction tests on pavement surfaces for over forty years.

The concept of a skid trailer was introduced in the mid-1960s to improve the safety and efficiency of skid testing operations. Working under this concept, FDOT constructed its first friction trailer in compliance with ASTM E-274-65T, *Tentative Method of Test for Skid Resistance of Pavements Using a Two-Wheel Trailer* (*1*). Design, fabrication and construction of this unit were completed in 1966. The unit was then utilized for routine friction testing (*2*). In the mid-1960s, ASTM also adopted Committee E17's proposed test method E-274 for Skid Resistance of Paved Surfaces Using a Full-Scale Tire (*3*). The ASTM E-274 test method is designed for locked wheel friction measurements where the relative velocity of the tire contact over the pavement surface is equal to the test vehicle speed (*4*). The pavement surface friction coefficient measured this way is a sliding (locked-wheel) coefficient termed friction number (FN). It is usually measured at 40 mph and the value thus obtained is designated as FN_{40}.

Currently, most jurisdictions, as part of its pavement management and safety programs, surveys and monitors the friction characteristics of its roadway system in accordance with the ASTM method E-274 which allows the use of several different types of tires for friction evaluations including the most frequently used ASTM E-501 *Standard Rib Tire for Pavement Skid-Resistance Test* and ASTM E-524 *Standard Smooth Tire for Pavement Skid-Resistance*. Florida has historically used both the ribbed tire for Pavement Management Inventory purposes, and the smooth tire for pavement special request and research testing applications. In 1984, FDOT began collecting smooth tire skid data at wet weather accident sites, in addition to ribbed tire data. It has been documented that the ribbed tire test is predominantly influenced by micro-texture, whereas the smooth tire test is influenced to a greater extent by macro-texture (*4*).

Historical analysis of smooth-tire friction test data collected by FDOT at wet-weather accident sites has been documented to correlate better than ribbed tire data. As a result, additional smooth tire testing has been included in this study. A photographic illustration of the smooth and ribbed tires is shown in Figure 1.

Figure 1 Photographic illustration of a E-501 (ribbed) and E-524 (Smooth) test tire.

The present state-of-the-art locked wheel testers are fully automated. As with any testing using subject-driven, instrumented devices, the major concerns of the end usefulness of the resulting data are accuracy and precision. Although a level of uncertainty is always inherent to any measurement process, and, thus, must be accepted, it must also be appropriately quantified or assessed. Therefore, FDOT initiated this study to assess the precision of its own locked-wheel testers for field measurements. Friction data were acquired using four friction locked-wheel testers concurrently on a number of asphalt section sites. These test sections were randomly selected to include both open and dense graded surface mixtures. The collected friction data was first analyzed to determine the friction characteristics at each test location, in terms of a friction number at 40 mph using both a ribbed and smooth tire and data was reported as FN40R and FN40S, respectively. The results were then used as a basis for an evaluation of the repeatability and reproducibility of the friction units. An illustration of one of FDOT's friction testers is shown in Figure 2.

Figure 2 Photographic illustration of a FDOT friction unit.

The main objective of this study was to assess the precision of locked-wheel testers for determining the frictional characteristics of roadway surfaces in Florida in accordance with ASTM E-274, *Standard test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. The precision of these units were addressed in terms of testing repeatability and reproducibility for both of the Ribbed and Smooth Test Tires.

Testing Program and Data Collection

LOCKED WHEEL FRICTION MEASURING DEVICES

The present study focused on devices that collect friction data using an instrumented trailer with a locked wheel system, commonly referred to as "locked-wheel testers". During testing, the data is recorded in terms of friction force on a locked wheel as it is dragged over a pavement surface under constant speed. A quintessential component of the locked wheel friction unit consists of a 2-axis force transducer that measures both the horizontal locked wheel friction force and the dynamic vertical load of the friction trailer. These respective outputs are then processed to estimate a pavement surface friction number.

In the present investigation, friction data were acquired using four FDOT-owned locked-wheel testers. Each of the four units consisted of a full-sized pick-up truck and an instrumented two-wheel trailer with a locked wheel system. The tow vehicles supply all the mechanical and electrical power required to perform testing. Additionally, the tow vehicles house all support systems, including a control panel and a data acquisition system to collect and store information from the traveled surface. A distance-measuring instrument (DMI) is provided to determine the position along the road. The longitudinal distance measurement is needed to associate a precise location with each "wheel lock-up". The locked-wheel testers are also fitted with a controlled watering system for wet pavement testing. Prior to initiating the subject study, the friction testers were calibrated at the Central/Western Field Test Center and correlated with one of the Area Reference Friction Measurement Systems. All these measuring instruments comply with the ASTM E-274 standard, as certified by the equipment manufacturer.

DATA COLLECTION

In this study, pavement sections were randomly selected to include diverse surface textures and levels of serviceability in an effort to achieve unbiased test site distribution. Also, the testing was conducted in a randomized sequence to minimize potential environmental effects on the test results. The pavement sections included two types of dense graded mixtures and three types of open graded mixtures. Thus, each pavement section was associated with a particular mixture type/friction course type. The testing was conducted in accordance with ASTM E-274, *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*.

Within each pavement section, friction data was collected at five predefined test sites with the locked wheel tire aligned to the center of the left wheel path. Each test site was identified with a 4-in by 4-ft thermoplastic strip centered on the left wheel path to ensure a uniform and accurate point of testing reference between all friction test units. Furthermore, at each test site, four replicate measurements were taken using each of the friction units along the predetermined paths using both ribbed and smooth test tires. In addition, an approximate five-minute 'rest period' was also allowed before any replicate measurements were made on any given test site. This was done to ensure that spray water from a previous test was drained away from the pavement surface, and therefore would not affect subsequent friction measurements. It should be noted that the smooth tire is relatively sensitive to water film thickness and varying the water film thickness due to water accumulation on the surface during testing will affect its repeatability. During testing, it was ensured, by visual inspection, that no water accumulation/ponding took place on the pavement surface.

In summary, within each pavement section, 160 tests were conducted representing an overall total of 800 friction data points. The results were then analyzed and used for the purpose of this study. One has to note that, for practicality, each of the friction units was randomly assigned one operator for the duration of this investigation. Therefore, any potential operator effects become intrinsic to the friction unit testing/measurements.

Data Interpretation

Two of the most important criteria of the usefulness of any testing device are accuracy and precision. Since the present study is concerned only with friction measurements on in-service pavement systems, providing references with which the measured results could be compared to determine the bias in the measurements is not realistic and/or practical. According to ASTM E-274, the relationship of observed friction numbers to a true value is an elusive goal (*3*). Therefore, without such a measurement, the accuracy of the friction-measuring units considered in this study could not be appropriately assessed. In addition, pavement surface characteristics are affected by many variables such as environmental conditions, testing time, site condition, etc., and measured values are only valid until one of these conditions significantly changes. The precision, however, was addressed in term of the level of testing repeatability (within-unit precision) and reproducibility (between-units precision).

The pavement surface friction coefficient required to transmit all the forces associated with a given maneuver under a given set of condition is termed friction number (FN). When measured at 40 mph, the friction number is designated as FN_{40}, and is obtained as follows:

$$FN_{40} = (\frac{F}{W}) \times 100 \quad \text{..(1)}$$

Where:

- F is the sum of all horizontal forces acting on the test tire at the tire-pavement contact area, and
- W is the dynamic vertical load applied to the test wheel (*3*).

Statistical Analysis

Statistical analyses were performed to assess the data repeatability and reproducibility. The first assessment was in terms of range, averages, standard deviations and coefficient of variations. The standard deviation and coefficient of variation (COV) respectively serve as a convenient measure of deviation around the average and a normalized way of measuring data variability. In general, the ribbed and smooth tire results, summarized in Tables 1 and 2 respectively, indicate a high level of repeatability and reproducibility of their respective FN measurements. The methodology used to calculate the variances and standard deviations in Table 1 are discussed further on.

TABLE 1 Summary of Ribbed Tire Test Statistics

Pavement Section		Ribbed Tire (E-501)						
		Average FN_{40R}	Variance		Standard Deviation		Coefficient of Variation (%)	
			W/U	B/U	W/U	B/U	W/U	B/U
Open Graded Mixtures	Section-1	36	1.1	1.5	1.1	1.2	2.9	3.4
	Section-2	35	1.7	1.7	1.3	1.3	3.7	3.7
	Section-3	45	1.5	2.2	1.2	1.5	2.7	3.3
Pooled Statistics			1.4	1.8	1.2	1.4	--	--
Dense Graded Mixtures	Section-4	36	2.2	2.3	1.5	1.5	4.2	4.2
	Section-5	46	1.7	2.6	1.3	1.6	3.5	3.5
Pooled Statistics			1.9	2.4	1.4	1.6	--	--
Overall Pooled Statistics			1.6	2.0	1.3	1.4	--	--

TABLE 2 Summary of Smooth Tire Test Statistics

Pavement Section		Smooth Tire (E-524)						
		Average FN_{40R}	Variance		Standard Deviation		Coefficient of Variation (%)	
			W/U	B/U	W/U	B/U	W/U	B/U
Open Graded Mixtures	Section-1	35	2.5	3.6	1.6	1.9	4.5	5.5
	Section-2	34	2.4	2.4	1.5	1.5	4.5	4.5
	Section-3	42	1.7	2.4	1.3	1.6	3.1	3.7
Pooled Statistics			2.2	2.8	1.5	1.7	--	--
Dense Graded Mixtures	Section-4	19	3.6	4.1	1.9	2.0	10.0	10.6
	Section-5	23	2.0	2.8	1.4	1.7	6.3	7.4
Pooled Statistics			2.9	3.6	1.7	1.9	--	--
Overall Pooled Statistics			2.5	3.1	1.6	1.8	--	--

Figure 3 shows the range in collected data on each of the five pavement sections. This figure also illustrates the range of serviceability levels considered in this investigation in an effort to achieve unbiased test site distribution. The average friction measurements for each of the pavement sections as collected using each of the friction units are presented in Figures 4 through 8. It should be noted that the primary objective of this study was not to determine the significance and/or differences in friction measurements between different surface types, but only to assess the precision levels of the locked-wheel testers in the measurement of friction data. The resulting friction numbers within each pavement section were further analyzed as a factorial experiment with 4 locked-wheel tester units and 5 testing sites using a two-way analysis of variance (ANOVA). The purpose of such an analysis was to evaluate, within each pavement section, any evidence of real differences between and within the respective friction values as determined using the four units at each test site. An important result of ANOVA is the P-value corresponding to the factor(s) considered (friction testing units and test sites in this case). The P-value for a particular factor indicates the probability of error of the hypothesis that the factor has a significant effect on the measured parameters. The results of ANOVA are presented in Table 3.

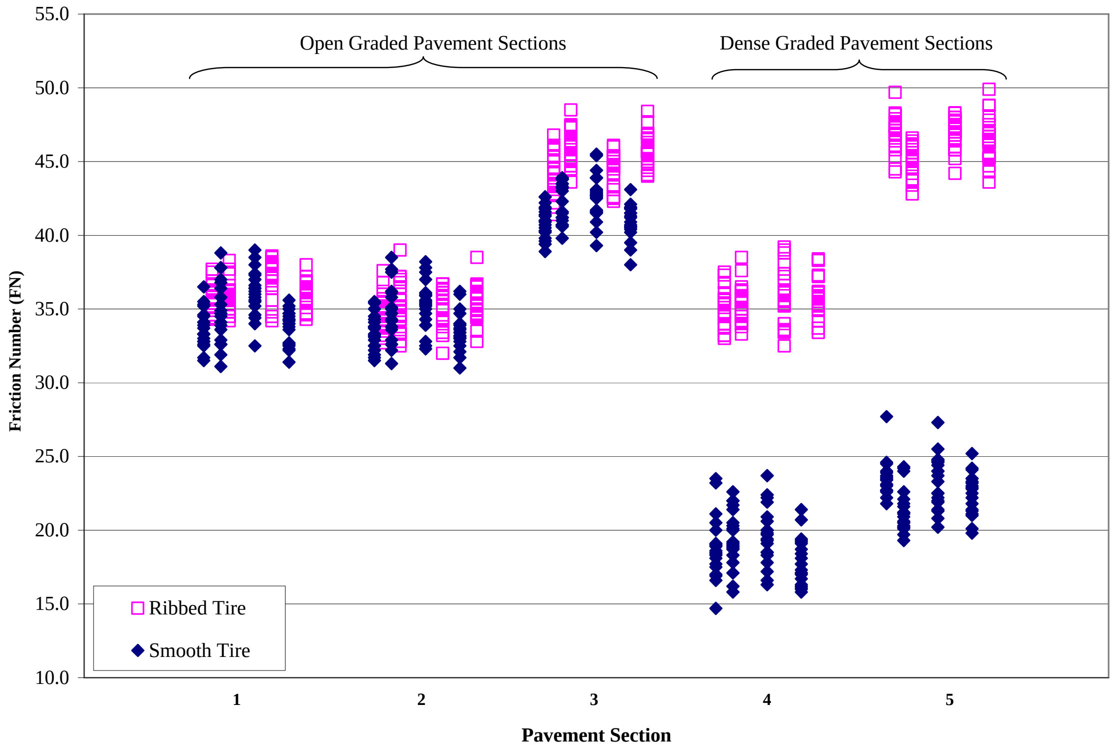
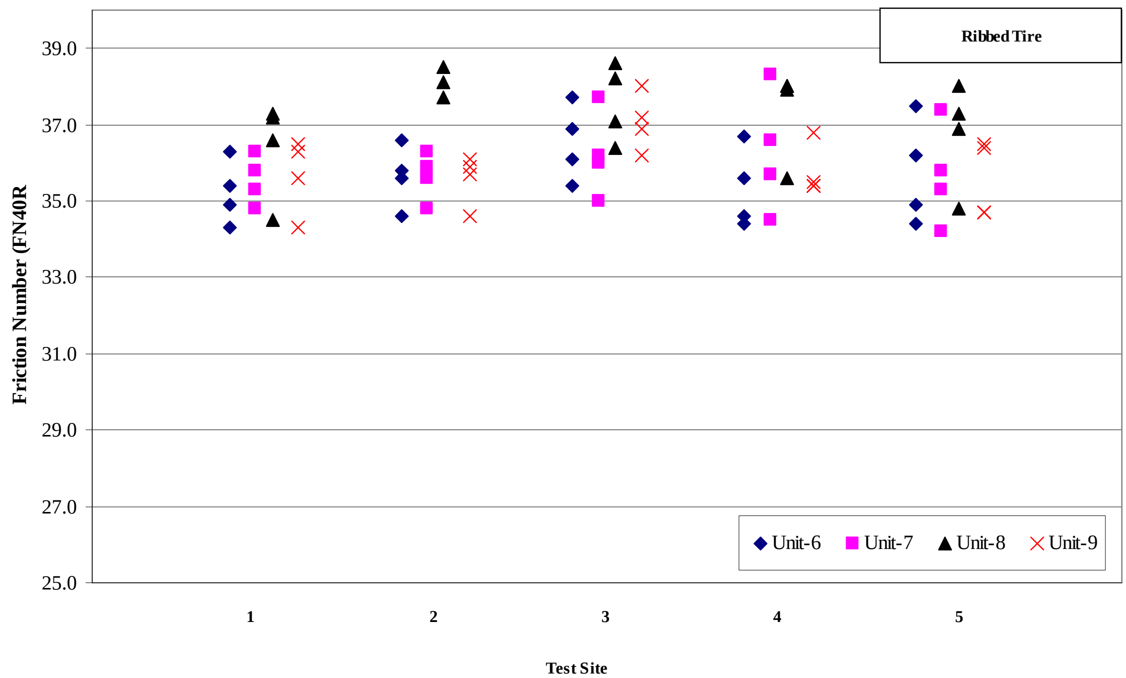


FIGURE 3 Comparison of ribbed and smooth tire friction data.



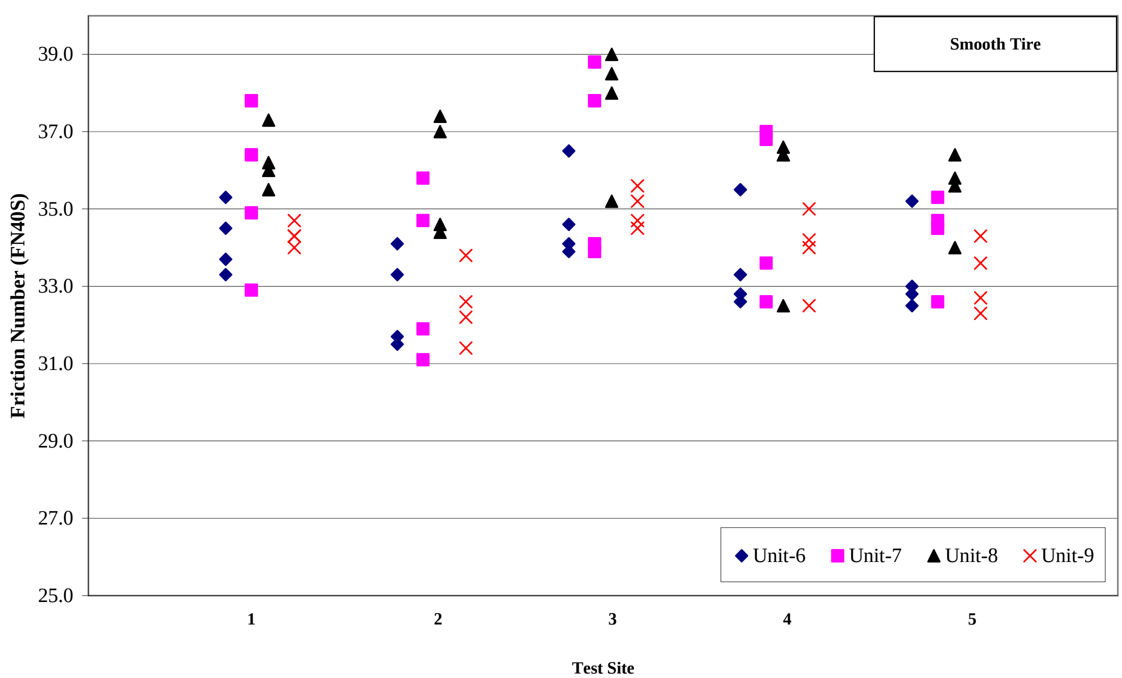
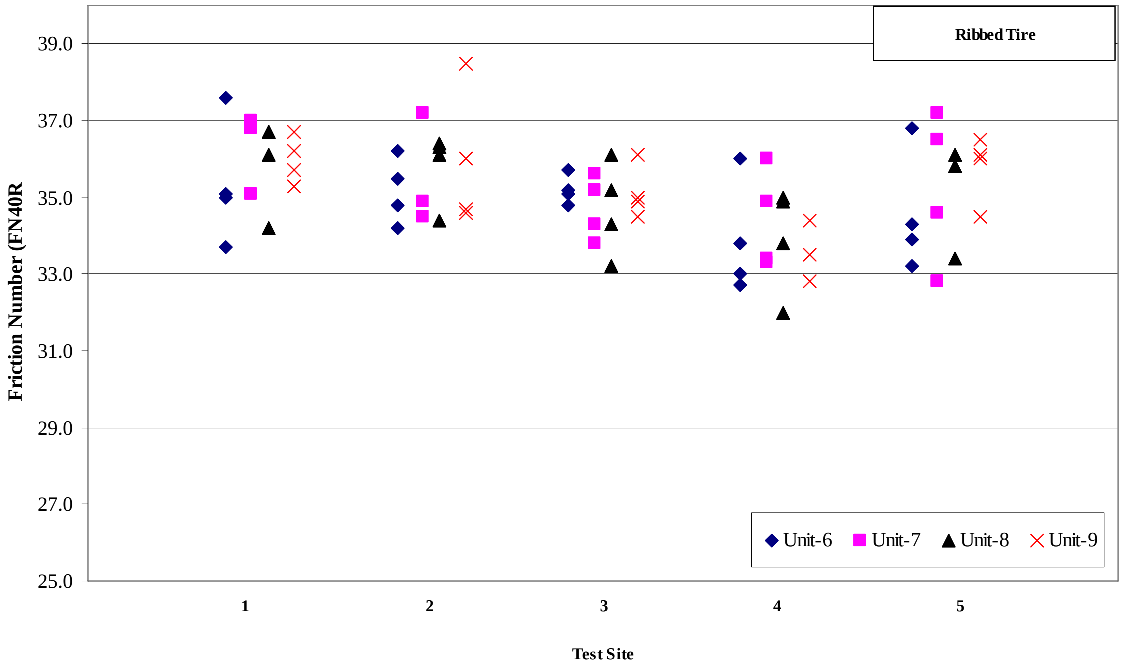


FIGURE 4 Friction data measured on pavement section 1.



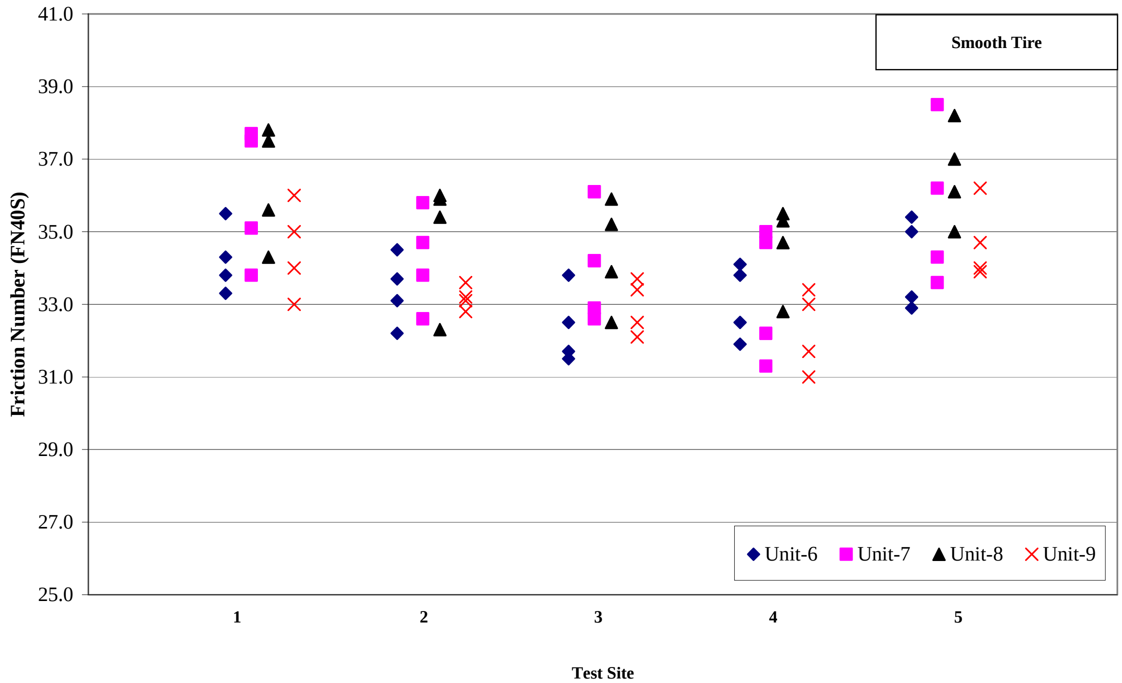
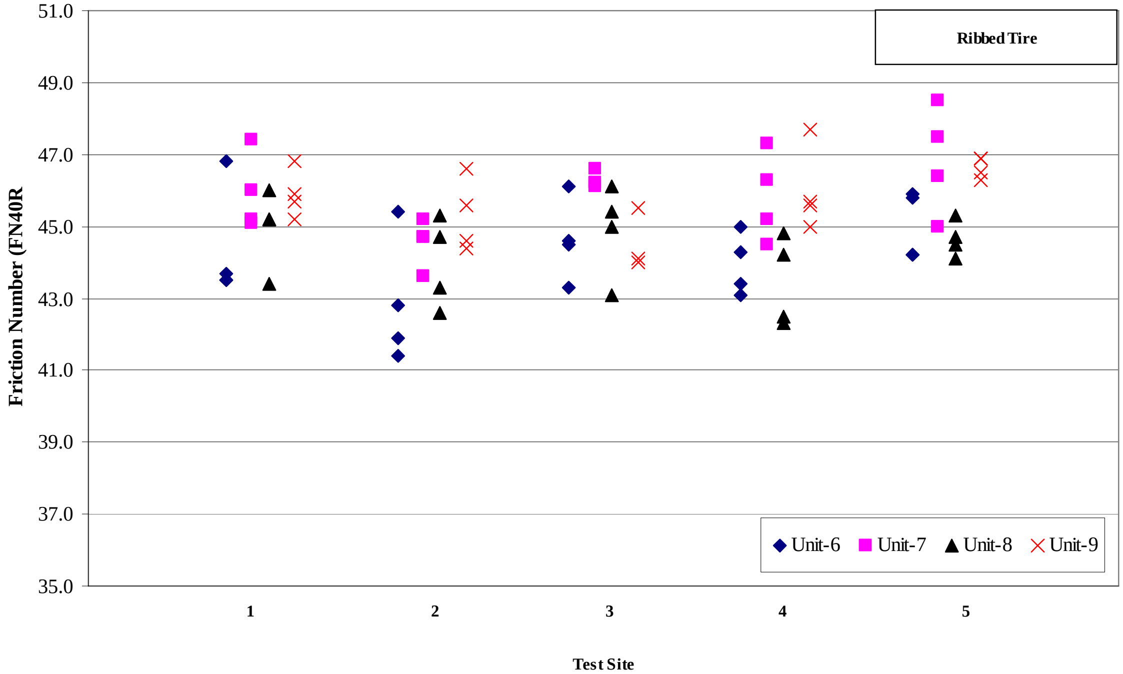


FIGURE 5 Friction data measured on pavement section 2.



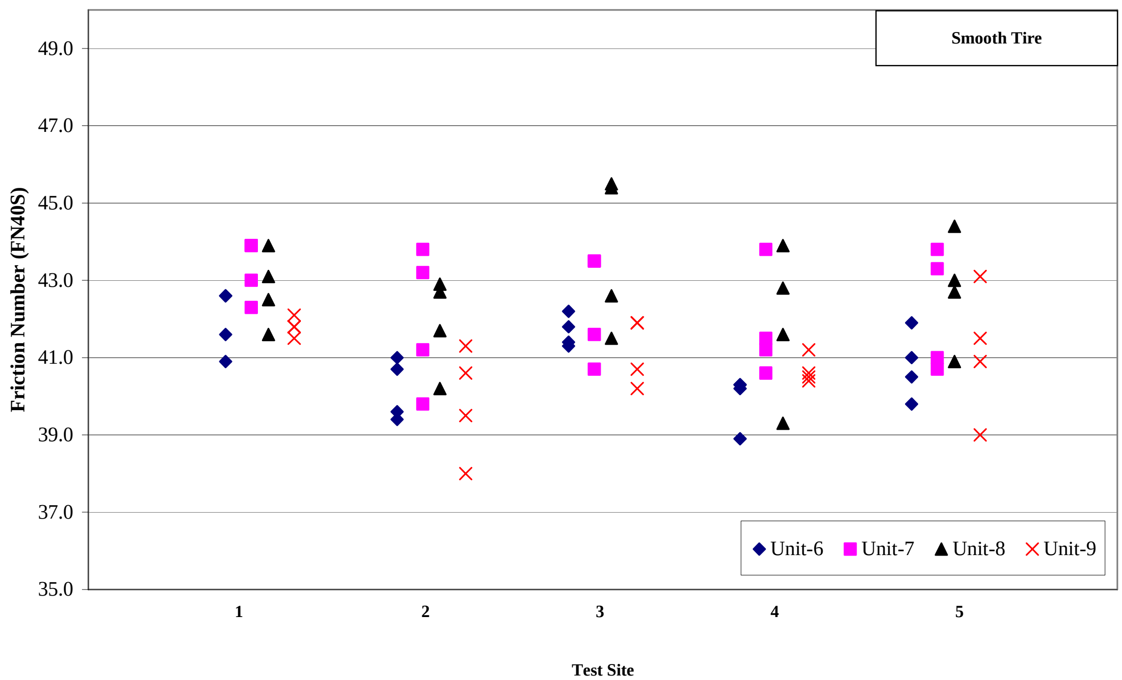


FIGURE 6 Friction data measured on pavement section 3.

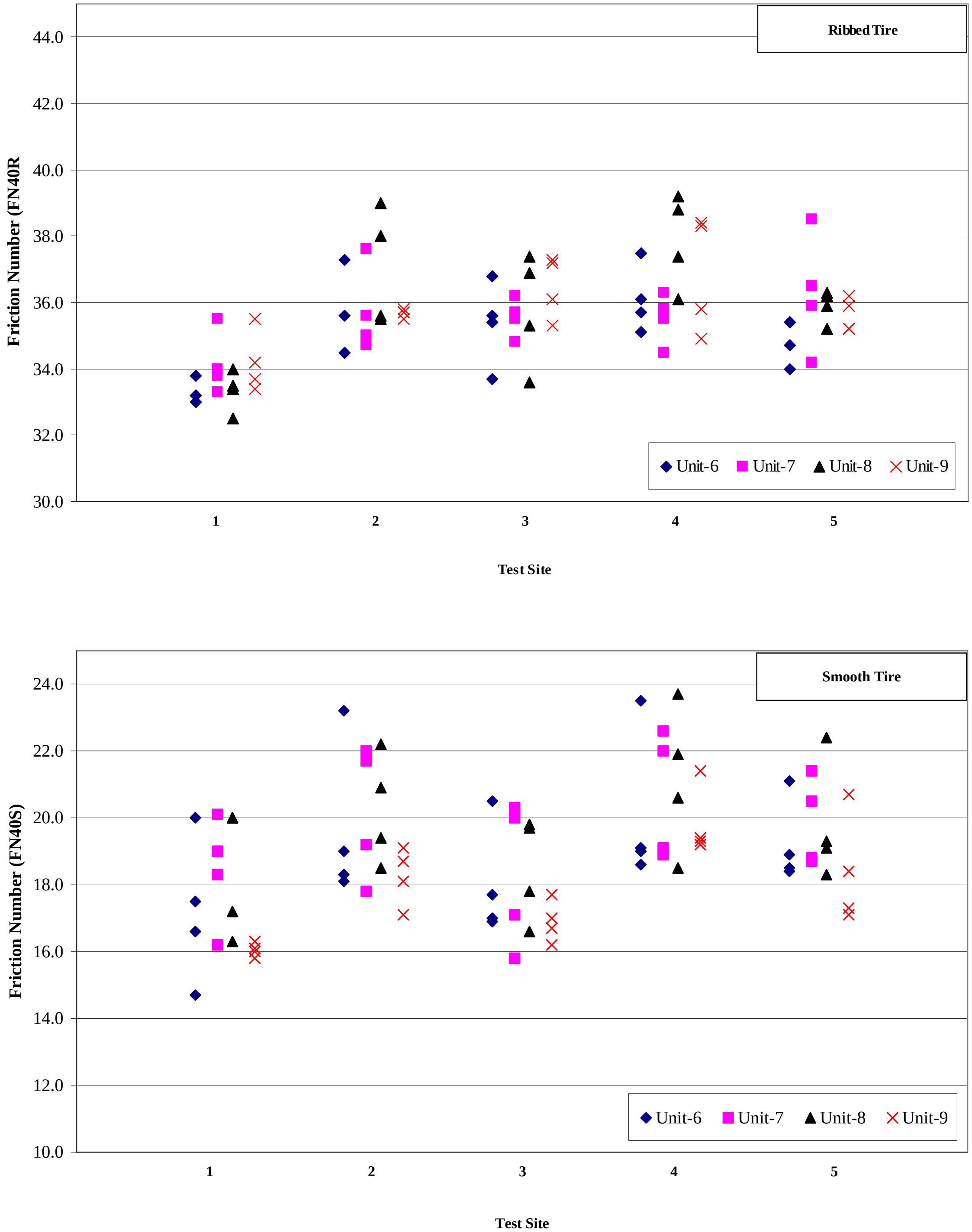


FIGURE 7 Friction data measured on pavement section 4.

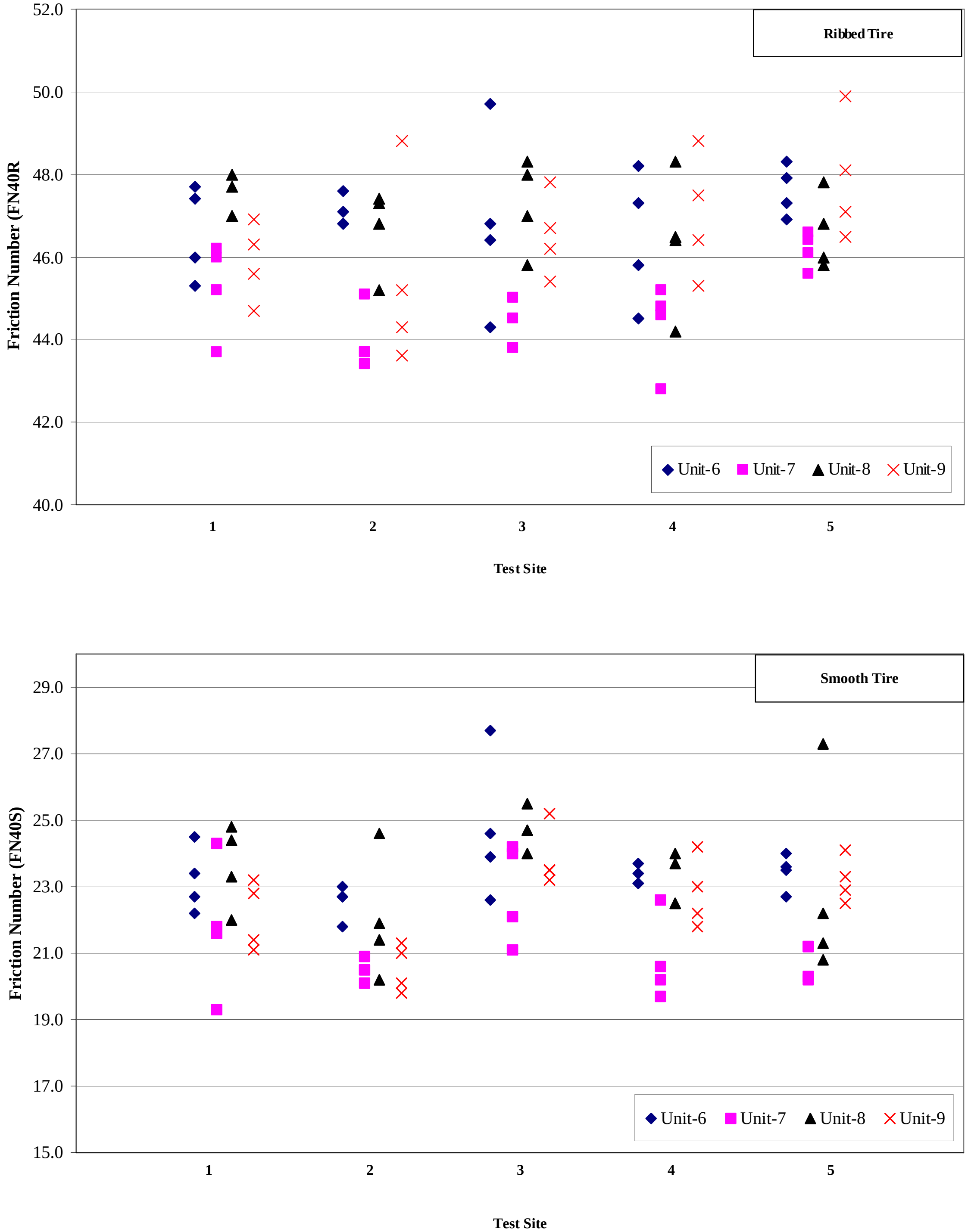


FIGURE 8 Friction data measured on pavement section 5.

TABLE 3 Summary of the Results of the Analysis of Variance (Ribbed and Smooth Tire)

	Ribbed Test Tire					Smooth Test Tire				
Variation of Source	Deg. Of Freedom	Sum of Squares	Mean Squares	F-value	*P-value*	Deg. Of Freedom	Sum of Squares	Mean Squares	F-value	*P-value*
Pavement Section 1 (Open Graded Mixture)										
Friction Unit	3	22.59	7.53	5.97	0.001	3	77.53	25.84	11.93	0
Test Site	4	12	3	2.38	0.062	4	51.21	12.8	5.91	0
Interaction	12	4.33	0.36	0.29	0.989	12	6.39	0.53	0.25	0.995
Error	60	75.72	1.26	--	--	60	129.95	2.17	--	--
Total	79	114.63	--	--	--	79	265.07	--	--	--
Pavement Section-2 (Open Graded Mixture)										
Friction Unit	3	3.76	1.25	0.7	0.556	3	50.93	16.98	8.97	0
Test Site	4	31.75	7.94	4.44	0.003	4	60.17	15.04	7.95	0
Interaction	12	10.06	0.84	0.47	0.925	12	4.91	0.41	0.22	0.997
Error	60	107.27	1.79	--	--	60	113.6	1.89	--	--
Total	79	152.84	--	--	--	79	229.61	--	--	--
Pavement Section-3 (Open Graded Mixture)										
Friction Unit	3	51.66	17.22	12.52	0	3	48.93	16.31	10.35	0
Test Site	4	24.1	6.03	4.38	0.004	4	28.14	7.04	4.47	0.003
Interaction	12	9.34	0.78	0.57	0.861	12	7.62	0.63	0.4	0.957
Error	60	82.53	1.38	--	--	60	94.5	1.57	--	--
Total	79	167.64	--	--	--	79	179.19	--	--	--
Pavement Section-4 (Dense Graded Mixture)										
Friction Unit	3	10.53	3.51	2.75	0.052	3	37.41	12.27	4.21	0.009
Test Site	4	73.17	18.29	14.36	0	4	93.38	23.34	7.87	0
Interaction	12	17.77	1.48	1.16	0.33	12	4	0.33	0.11	1
Error	60	76.44	1.27	--	--	60	177.88	2.96	--	--
Total	79	177.92	--	--	--	79	312.66	--	--	--
Pavement Section-5 (Dense Graded Mixture)										
Friction Unit	3	59.39	19.79	12.82	0	3	56.62	18.87	11.19	0
Test Site	4	14.64	3.66	2.37	0.062	4	55.66	13.91	8.25	0
Interaction	12	19.71	1.64	1.06	0.406	12	10.67	0.89	0.53	0.889
Error	60	92.67	1.55	--	--	60	101.24	1.69	--	--
Total	79	186.41	--	--	--	79	224.19	--	--	--

The results of this analysis showed that the units for the ribbed test tires measured statistically similar data in three of the pavement sections. For the remaining two sections, the P-values corresponding to the 'unit' factor were much lower than 0.05, which indicated that the four units did not measure statistically comparable data. Smooth tire testing also indicated the four units did not measure statistically comparable data with all five sections. However, for the individual open and dense grade mixtures with both ribbed and smooth tire data produced pooled standard deviations less than 2. The current ASTM E-274, while addressing only the repeatability of friction units, recommends a standard deviation of 2 FN units. Therefore, although the friction data was found to be statistically different, the significance level of these differences may not be of any considerable importance for all practical purposes.

EFFECT OF SURFACE TEXTURE

All the above findings indicate that, within this test range, the surface mixture type/textures and serviceability levels did not significantly or differently affect the precision of the friction testers for all practical purposes. In addition, the resulting variances, standard deviations and coefficients of variations, as summarized in Tables 1 and 2, also show that the friction measurements exhibited a comparable level of variability on all pavement sections considered in this study. For instance, the ribbed tire resulting standard deviation values for open and dense-graded friction courses are 1.4 FN and 1.6 FN respectively, and smooth tires exhibited slightly higher results with 1.7 FN and 1.9 FN respectively for between unit variations. All reported standard deviations are well below the 2 FN standard deviation (within-unit) limit suggested by ASTM E-274.

Precision estimates

In order to determine precision estimates, pooled standard deviations and coefficients of variations were calculated according to the methodology described in ASTM C-802 (*6*). The resulting variances, standard deviations and coefficients of variations are presented in Table 1. These pooled-statistics were obtained considering all the measurements collected in accordance with ASTM E-274 on the 5 pavement sections using 4 friction units.

ASTM C-670, *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials* (*7*), states that an acceptable difference between two tests results or the 'difference two sigma (d2s)' can be selected as an appropriate index of precision in most precision statements. This index indicates the maximum acceptable difference between two test results obtained on test portions of the same material under the same test conditions. The (d2s) index can be calculated by multiplying the appropriate standard deviation by the factor $2\sqrt{2}$ (equal to 2.83). Therefore, within this test range, the following precision statements are developed respectively for the repeatability and reproducibility of the friction number determination when conducted in accordance with ASTM E-274.

Ribbed and Smooth Tire Repeatability (Within-Unit Precision)

Friction data from the five pavement sections showed a pooled standard deviation for repeatability well below the standard deviation described by ASTM-274. The overall pooled standard deviation for ribbed and smooth tires was found to be 1.3 FN and 1.6 respectively, and therefore, the results of two properly conducted friction tests using the same friction unit on the same pavement test section should not differ by more than 3.7 FN for ribbed and 4.5 FN for smooth at a 95 percent confidence level.

Ribbed and Smooth Tire Reproducibility (Between-Unit Precision)

The pooled standard deviation between-units were calculated to be 1.4 FN for ribbed and 1.8 FN for smooth. Thus, the results of two properly conducted friction tests using two locked-wheel tester units on the same pavement test section should not differ by more than 4.0 FN ribbed and 5.1 FN smooth, at a 95 percent confidence level.

Conclusions

The present study was conducted primarily to assess the precision levels of locked-wheel testers for determining the friction characteristics, in terms of friction numbers, of asphalt pavements in Florida. The friction data as collected in accordance with ASTM E-274 during the course of this investigation was first analyzed to determine the friction numbers at each test site. The results were then used as a basis for an evaluation of repeatability and reproducibility of the friction units. Also, the effects of different surface textures on the tester's precision were considered. Within the test range, the findings indicated the following:

- A comparison consisting of 800 data points (or spot measurements) showed a good correlation between all friction units. For all practical purposes, a high level of repeatability and reproducibility of the friction measurements was obtained regardless of the test tire, surface texture type, or level of serviceability.

- A comparison of the respective pooled-statistics indicated that the effect of the surface textures on the friction tester's repeatability and reproducibility was negligible. When comparing the repeatability and reproducibility of the ribbed and smooth tires, an important point to note is that the ribbed tire is relatively insensitive to water film thickness. On the other hand, the smooth tire is sensitive to water film thickness. Varying water film thickness due to water accumulation on the pavement surface during testing will affect the repeatability for the smooth tire. Sufficient time should be allowed to pass between successive data collection runs to ensure that spray water from previous runs is drained away from the pavement surface.

- The respective friction number results (FN_{40}) of two properly conducted tests using the same friction unit on the same test section should not differ by more than 3.7 FN (ribbed) and 4.5 FN (smooth) at a 95 percent confidence level. This shows a higher level of repeatability than that indicated by ASTM E-274.

- The friction number results (FN_{40}) of two properly conducted tests using two friction units on the same test section should not differ by more than 4.0 (ribbed) and 5.1 (smooth) at a 95 percent confidence level.

One has to note that the above analysis assumed that, since the test sections were randomly selected, the potential for sampling error or bias is minimized. A biased selection (or sampling error) of test sites affects the representativeness of the test results. In addition, the variability of the friction numbers from a particular test section was assumed to be randomly distributed around a correct mean value. It is also always possible that the variability will distribute randomly around an incorrect mean value. The difference between the two means represents an error in the mean itself, or a bias error. However, although the bias can change the mean value, it will not affect the evaluation of the relative testing variability as conducted in this study.

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Disclaimer

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