# STATE OF FLORIDA

# PRECISION OF LOCKED WHEEL TESTERS FOR MEASUREMENT OF ROADWAY SURFACE FRICTION CHARACTERISTICS

Research Report
FL/DOT/SMO/03-464

Bouzid Choubane
Charles R. Holzschuher
Salil Gokhale

July 2003

## STATE MATERIALS OFFICE

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# 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 test tire ($FN_{40R}$). The results were then used as a basis for an evaluation of the repeatability and reproducibility of the friction units. In addition, the effects of pavement surface texture on friction measurements were assessed.

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 since the late 1950s. It initially used the vehicle stopping distance method, which consisted of a sudden application of brakes to cause the vehicle to skid at a known initial speed and measuring the distance required for the vehicle to come to a full stop. This method, although the most natural and straightforward, was inherently dangerous, particularly at high speeds. The stopping distance method was subsequently modified to include a decelerometer, known as a Tapley Decelerometer, mounted on a vehicle dashboard. This worked on the principle of a damped pendulum, which swings forward from its normally level position proportionally to the rate of the vehicle deceleration. The main advantage of this method was that complete stops were not necessary.

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 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 their pavement management and safety programs, survey and monitor the friction characteristics of its roadway system in accordance with the ASTM E-274 requirements. This also provides a tool to ensure that all travel surfaces are constructed and maintained with desirable friction properties and that sections with questionable performance are identified and corrected.

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 an ASTM E 501 standard ribbed tire ($FN_{40R}$) *(5)*. The results were then used as a basis for an evaluation of the repeatability and reproducibility of the friction units. In addition, the effects of pavement surface texture on friction measurements were assessed.

## OBJECTIVE

The primary objective of this study was to assess the precision of locked-wheel testers for determining the friction characteristics of roadway surfaces in Florida in accordance with ASTM

E-274, *StandardTest Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. The precision of these units was addressed in terms of testing repeatability and reproducibility.

## TESTING PROGRAM AND DATA COLLECTION

### Locked Wheel Measuring Devices

The present study focused on devices that collect friction data using an instrumented trailer with a locked wheel system. These are commonly referred to as "locked-wheel testers". A photographic illustration of a locked wheel tester is shown in Figure 1. 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**

During the course of this investigation, test data was acquired on a number of asphalt pavement sections using four locked wheel friction units with the standard ribbed test tire. These pavement sections were randomly selected to include different 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 2-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. Therefore, within each pavement section, 80 tests were conducted representing an overall total of 400 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 intrinsical to the friction unit testing/measurements.

## DATA ANALYSIS

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 and reproducibility.

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:

$$FN_{40} = (F/W) * 100 \quad (1)$$

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)*.

Theoretically, the friction that develops between a rubber tire and a traveled surface consists of two components, namely (1) adhesion (FA) and (2) hysteresis (FH), as shown in Figure 2. The adhesion accounts for the actual contact area (Ai) between the tire and the traveled surface as well as the shear strength (S) of the interface *(6)*. Therefore, adhesion is an indication of the shear force between the tire-traveled surface interface as the tire conforms to the shape of the surface contact area. Typically, the adhesion friction is dominant until critical slip occurs. As the test tire is in skid mode, the adhesion friction term generally decreases while the hysteresis component increases *(6)*. The hysteresis relates to the energy stored (Ec) and dissipated (Ee) during tire-surface interaction for a known velocity (V). It reflects, then, energy losses that occur as the rubber is alternately compressed and expanded.

**Data 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 results, summarized in Table 1, indicate a high level of repeatability and reproducibility of FN measurements. The maximum absolute difference in friction data, based on 4 individual runs each, was found to be 4.7 FN (within unit) and 5.4 FN (between units). The methodology used to calculate the variances and standard deviations in Table 1 are discussed further on. 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 2. The results of this analysis showed that the units 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. However, the standard deviations between friction unit measurements were found to be 1.24 and 1.47 FN respectively, on both of these two projects (incidentally, the mixtures on both of these sections are open-graded). The current ASTM E-274, while addressing only the repeatability of friction units, recommends a standard deviation of 2 FN units. Thus, it suggests that a maximum difference of 5.6 FN is appropriate for repeatability (within unit) of friction measurements (*3*). 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. Furthermore, as shown in Table 3, the maximum absolute difference in friction data between the friction units was 5.4 FN, also well below the recommended ASTM within unit precision value.

**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 Table 1, also show that the friction measurements exhibited a comparable level of variability on all of the pavement sections considered in this study. For instance, the pooled standard deviation values for open and dense-graded friction courses are 1.35 FN and 1.63 FN respectively, for between-unit variation, which are still 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 *(7)*. 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 (8),* 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.

***Repeatability (Within-Unit Precision)***

The pooled standard deviation for repeatability (within unit) was found to be 1.38 FN. 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 3.9 FN at a 95 percent confidence level.

***Reproducibility (Between-Unit Precision)***

The pooled standard deviation between-units was calculated to be 1.47 FN. 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 4.16 FN, 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 were 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 testers precision were considered. Within the test range, the findings indicated the following:

- A comparison consisting of 400 data points (or spot measurements) showed a good correlation between all friction units. A high level of repeatability and reproducibility of the friction measurements was obtained regardless of the surface texture type or level of serviceability. Friction data from the five pavement sections showed a pooled standard deviation for repeatability, for instance, well below the standard deviation described by ASTM-274.

- A comparison of the respective pooled-statistics indicated that the effect of the surface textures on the friction testers repeatability and reproducibility was negligible.
- The respective friction number results ($FN_{40}$) of two properly conducted tests under similar conditions using the same friction unit on the same test section should not differ by more than 3.90 FN 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 under similar conditions using two friction units on the same test section should not differ by more than 4.16 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. The possibility always remains, though, 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.

## ACKNOWLEDGEMENTS

The work reported herein was the result of a team effort. The authors would like to acknowledge Larry Hewett, Albert Schaub, Ray Sheese, Jimmy Jones, and Bob Daniels of the

Florida Department of Transportation Friction Group for their efforts in operating the locked wheel friction devices, conducting all the required testing, collecting and processing the raw friction data. The authors are grateful for their diligent efforts and contributing knowledge.

**DISCLAIMER**

The content of this paper reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Florida Department of Transportation. This report does not constitute a standard, specification, or regulation. In addition, the above listed agency assumes no liability for its contents or use thereof.

## REFERENCES


1. ASTM E 274-65T. *Tentative Method of Test for Skid Resistance of Pavements Using A Two-Wheel Trailer.* (Revised 1970, as E 274-70 with name change). American Society For Testing And Materials.
2. Smith, L. L., and S. L. Fuller. *Florida Skid Correlation Study of 1967 – Skid Testing with Trailers.* ASTM STP-456. American Society For Testing And Materials, 1969.
3. ASTM E-274. *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire.* American Society For Testing And Materials, 1999.
4. Henry, J. J. . *Evaluation of Pavement Friction Characteristics.* National Cooperative Highway Research Program Synthesis 291. Transportation Research Board, 2000.
5. ASTM 501. *Standard specification for Standard Rib Tire for Pavement Skid-Resistance Tests.* American Society For Testing And Materials, 1994.
6. Zimmer, R. A., B. Choubane, and C. R. Holzschuher. *A Friction Testing Method for Open Grated Steel Bridge Decks.* Transportation Research Record, Journal of The Transportation Research Board, (In Press).
7. ASTM C-802 – 96 (Reapproved 2002). *Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials.* American Society For Testing And Materials, 2002.
8. ASTM C-670. *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials.* American Society For Testing And Materials, 1999.

**TABLE 1 Summary of Statistics Pooled by Test Section and Mixture Type**

| Pavement Section | | Average $FN_{40R}$ | Maximum Difference (Range) | | Variance | | Standard Deviation | | Coefficient of Variation (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | W/U | B/U | W/U | B/U | W/U | B/U | W/U | B/U |
| Open Graded Mixtures | Section-1 | 36.14 | 3.8 | 3.9 | 1.12 | 1.53 | 1.06 | 1.24 | 2.92 | 3.43 |
| | Section-2 | 35.15 | 4.4 | 4.4 | 1.73 | 1.73 | 1.31 | 1.31 | 3.74 | 3.74 |
| | Section-3 | 45.08 | 4.0 | 5.4 | 1.45 | 2.17 | 1.20 | 1.47 | 2.67 | 3.27 |
| Pooled Statistics | | | | | 1.43 | 1.81 | 1.20 | 1.35 | -- | -- |
| Dense Graded Mixtures | Section-4 | 35.56 | 4.3 | 4.7 | 2.20 | 2.27 | 1.48 | 1.51 | 4.17 | 4.23 |
| | Section-5 | 49 | 4.7 | 4.7 | 3.03 | 3.03 | 1.74 | 1.74 | 3.55 | 3.55 |
| Pooled Statistics | | | | | 2.62 | 2.65 | 1.62 | 1.63 | -- | -- |
| Overall Pooled Statistics | | | | | 1.91 | 2.15 | 1.38 | 1.47 | -- | -- |

Note: W/U = within unit (repeatability)
B/U = between units (reproducibility)

**TABLE 2 Summary of the Results of the Analysis of Variance**

| Source of Variation | Deg. Of Freedom | Sum of Squares | Mean Squares | F-value | *P-value* |
|---|---|---|---|---|---|
| | Pavement Section 1 (Open Graded Mixture) | | | | |
| Unit | 3 | 22.59 | 7.53 | 5.97 | 0.001 |
| Test Site | 4 | 12.00 | 3.00 | 2.38 | 0.062 |
| Interaction | 12 | 4.33 | 0.36 | 0.29 | 0.989 |
| Error | 60 | 75.72 | 1.26 | -- | -- |
| Total | 79 | 114.63 | -- | -- | -- |
| | Pavement Section-2 (Open Graded Mixture) | | | | |
| Unit | 3 | 3.76 | 1.25 | 0.70 | 0.556 |
| Test Site | 4 | 31.75 | 7.94 | 4.44 | 0.003 |
| Interaction | 12 | 10.06 | 0.84 | 0.47 | 0.925 |
| Error | 60 | 107.27 | 1.79 | -- | -- |
| Total | 79 | 152.84 | -- | -- | -- |
| | Pavement Section-3 (Open Graded Mixture) | | | | |
| Unit | 3 | 51.66 | 17.22 | 12.52 | 0.000 |
| Test Site | 4 | 24.10 | 6.03 | 4.38 | 0.004 |
| Interaction | 12 | 9.34 | 0.78 | 0.57 | 0.861 |
| Error | 60 | 82.53 | 1.38 | -- | -- |
| Total | 79 | 167.64 | -- | -- | -- |
| | Pavement Section-4 (Dense Graded Mixture) | | | | |
| Unit | 3 | 10.53 | 3.51 | 2.75 | 0.052 |
| Test Site | 4 | 73.17 | 18.29 | 14.36 | 0.000 |
| Interaction | 12 | 17.77 | 1.48 | 1.16 | 0.330 |
| Error | 60 | 76.44 | 1.27 | -- | -- |
| Total | 79 | 177.92 | -- | -- | -- |
| | Pavement Section-5 (Dense Graded Mixture) | | | | |
| Unit | 3 | 7.57 | 2.52 | 1.00 | 0.400 |
| Test Site | 4 | 90.21 | 22.55 | 8.91 | 0.000 |
| Interaction | 12 | 6.22 | 0.52 | 0.20 | 0.998 |
| Error | 60 | 151.79 | 2.53 | -- | -- |
| Total | 79 | 255.79 | -- | -- | -- |

**TABLE 3 Maximum Differences in Measured Friction Numbers ($FN_{40R}$) Between any Two Units**

| Respective Units | Open Graded Mixtures | | | Dense Graded Mixtures | |
|---|---|---|---|---|---|
| | Section-1 | Section-2 | Section-3 | Section-4 | Section-5 |
| 1 and 2 | 3.9 | 4.4 | 4.3 | 4.5 | 4.7 |
| 1 and 3 | 3.9 | 4.0 | 4.0 | 4.5 | 4.5 |
| 1 and 4 | 3.1 | 4.3 | 5.2 | 3.6 | 4.5 |
| 2 and 3 | 3.8 | 4.4 | 5.0 | 4.7 | 4.7 |
| 2 and 4 | 3.8 | 4.4 | 3.5 | 4.3 | 4.7 |
| 3 and 4 | 3.9 | 4.1 | 5.4 | 4.3 | 3.5 |

**FIGURE 1  A Photographic Illustration of a FDOT Friction Unit.**

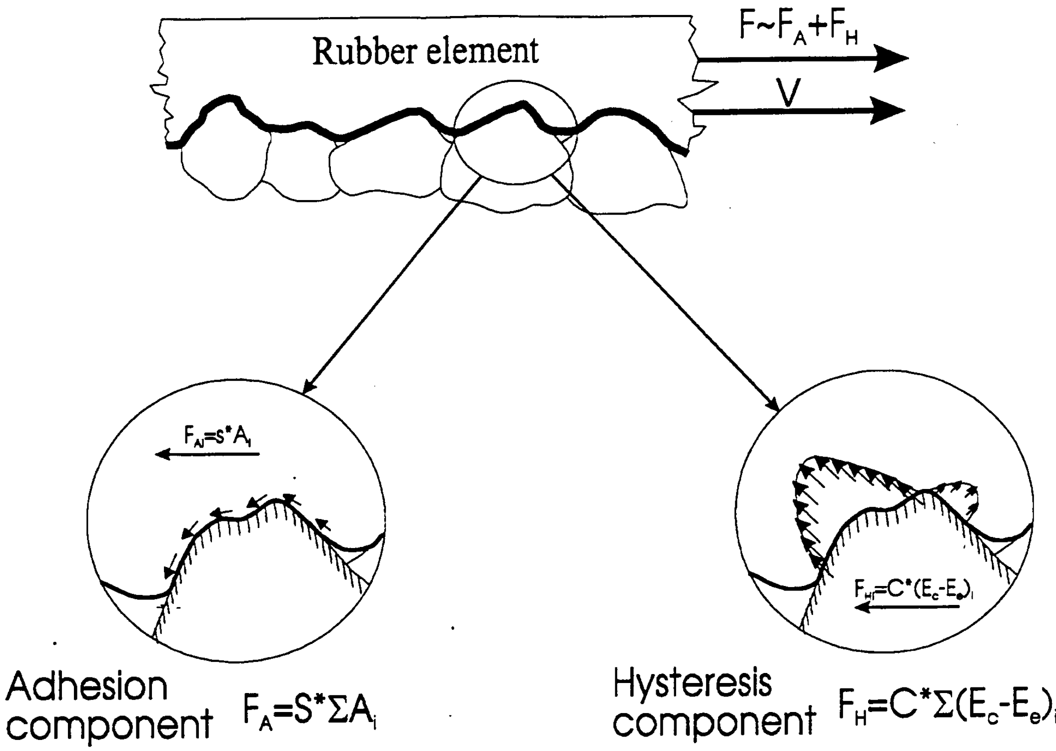


**FIGURE 2 A Schematic Illustration of the Principal Components of Rubber-Tire Friction (*7*).**

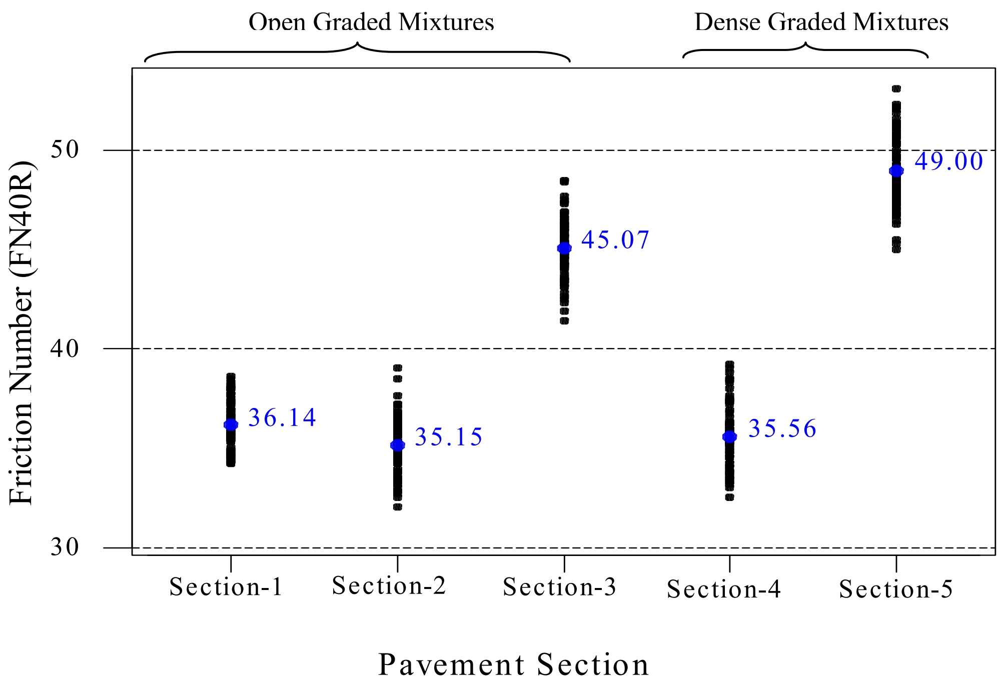


**FIGURE 3 Range of Measured Friction Data ($FN_{40R}$).**

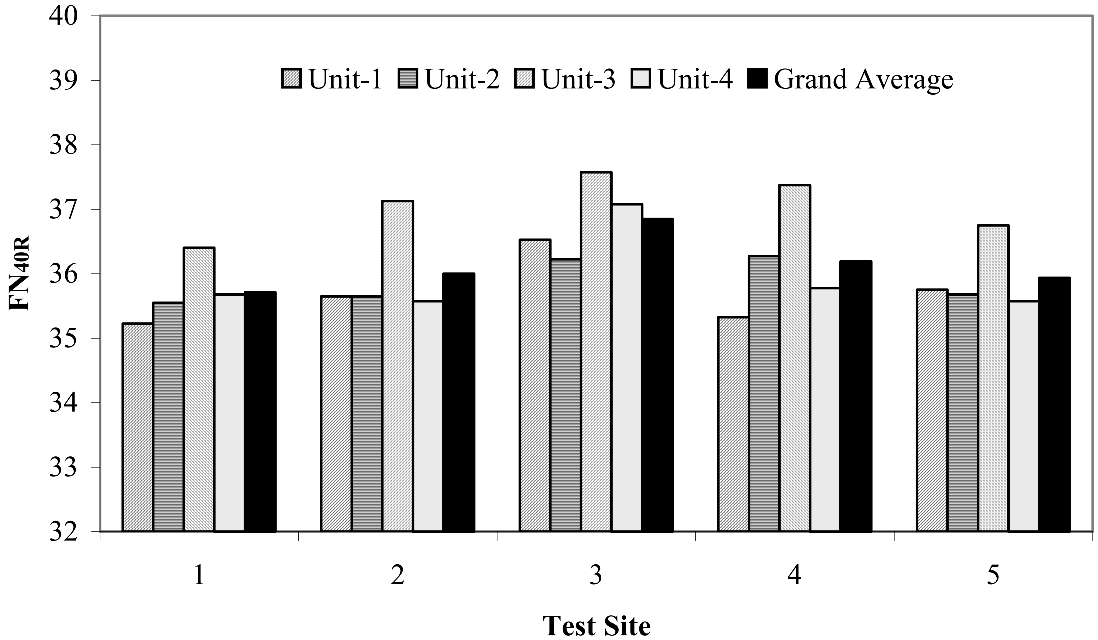


**FIGURE 4 Average Friction Numbers as Measured on Pavement Section-1.**

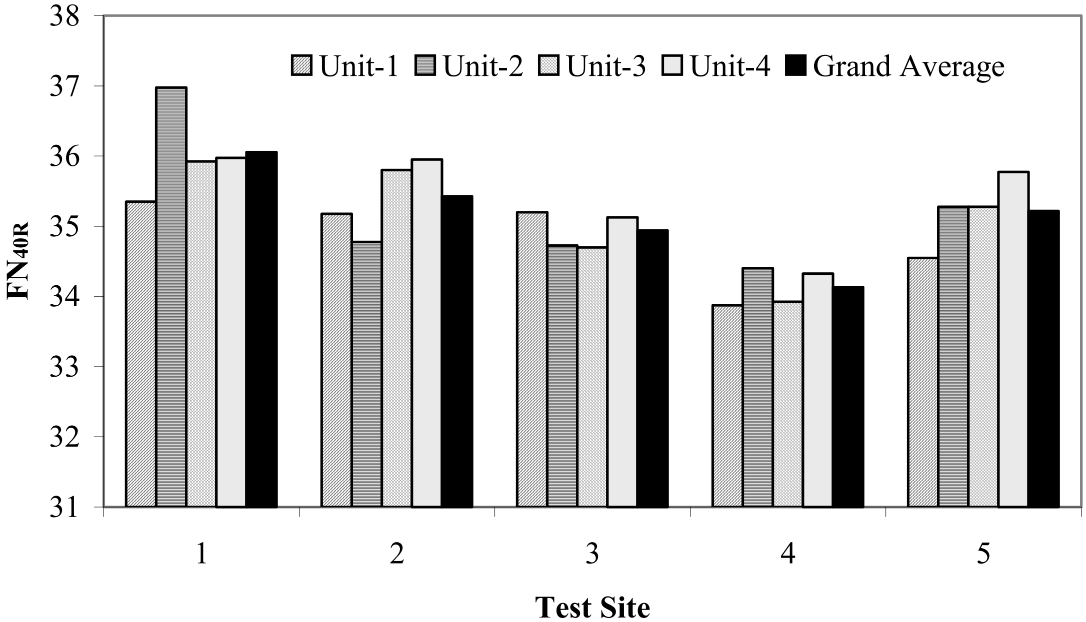


**FIGURE 5 Average Friction Numbers as Measured on Pavement Section-2.**

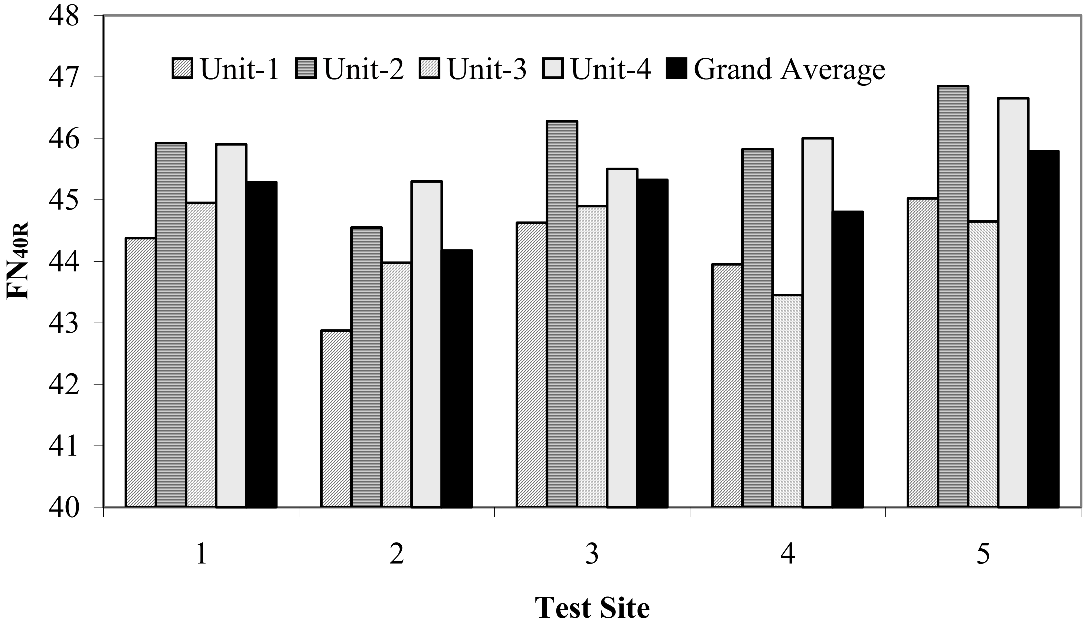


**FIGURE 6 Average Friction Numbers as Measured on Pavement Section-3.**

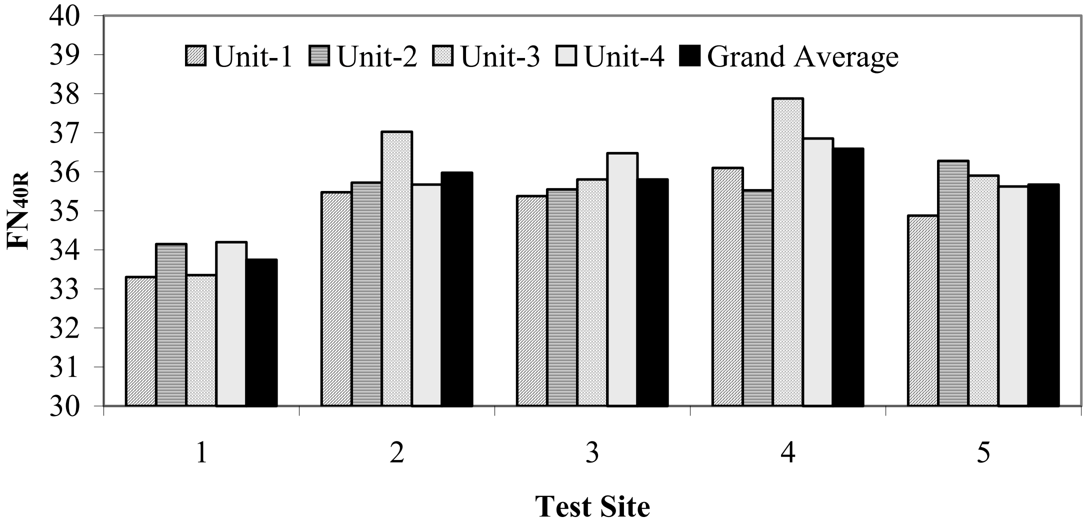


**FIGURE 7 Average Friction Numbers as Measured on Pavement Section-4.**

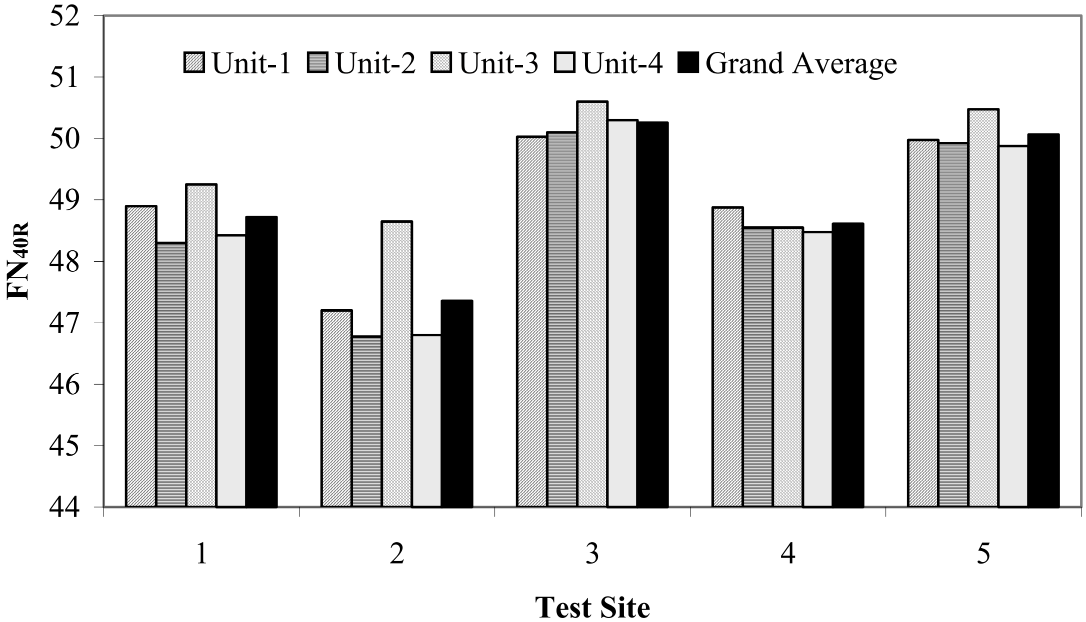


**FIGURE 8 Average Friction Numbers as Measured on Pavement Section-5.**