1038

DETERMINATION AND IMPROVEMENT OF RELEVANT PAVEMENT SKID COEFFICIENTS

MICHIGAN DEPARTMENT OF TRANSPORTATION

TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

DETERMINATION AND IMPROVEMENT OF RELEVANT PAVEMENT SKID COEFFICIENTS

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INTRODUCTION

Background

This five-year Highway Planning and Research study, begun on July 1, 1970, was intended to help provide skid testing information which is more relevant to highway safety. The Research Laboratory has been involved in pavement skid testing for about 30 years. In 1947, a 140 mile length of US 2 between St. Ignace and Escanaba was tested using the stopping distance method. Such a method involves locking the brakes on a vehicle which is moving over a wetted pavement and then measuring its stopping distance.

As a result of the 1947 study, manufactured limestone sand was prohibited from use in pavement surfaces and the roadway under investigation was resurfaced. In 1954, concurrently with the General Motors Corp., development of a skid trailer began. The basic trailer, constructed from a salvaged 1949 Buick chassis, still serves effectively as a "workhorse" tester. Because of high priority operational demands, the workhorse unit was seldom available for pure research work. Therefore, in 1971 a K. J. Law Engineers, Model 965 Surface Dynamics Pavement Friction Tester, initially developed by General Motors Corp., was purchased.

During our many years of skid testing, questions have been generated which should be answered to make skid testing a more reliable tool for improving highway safety. Among questions that have arisen during the years are:

1) How reliable is the skid test equipment? If the same pavement surface is retested how closely will results compare?

2) What causes wet friction coefficients to change when measurements are made at different times of the year? Can such changes be predicted and quantified?

3) Can a reliable and accurate correlation be developed between the Department's two trailer test units? How accurate is such a correlation?

4) Why do some surface textures reduce wet weather accidents even though little benefit is apparent when wet friction coefficients are measured by the ASTM method?

5) How do wet friction values on Michigan pavements compare when measured with smooth rather than treaded tires?

6) Non-locking vehicle brake systems are becoming more popular; how does this type system affect wet pavement friction.

The purpose of this study is to answer the preceding questions. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Research Procedures

Data in this report were taken from friction measurements made on state trunkline pavements throughout central Michigan. Both the workhorse unit, built by the Research Laboratory, and the K. J. Law pavement friction tester unit were used for testing. There are significant differences in measurements made by the two units but since the same tester was used at any given site data measurements are given just as they were taken, i.e., measurements were not converted to a common standard.

Also, since the relationships between variables at each site were being investigated, it was unnecessary to equate data taken by one tester with that taken by the other.

For certain phases of the investigation, it was desirable to eliminate the effects of traffic on pavement surfaces. Therefore, an unused strip of concrete pavement constructed in 1962 and located at a truck weighing station on westbound I 94 near Grass Lake was barricaded from traffic and used in the study. In 1971, a bituminous concrete mat was constructed over about a 200-ft length of the barricaded section. Thus, both a concrete and a bituminous surface without traffic wear were used in the study. For comparison, the I 94 bituminous pavement adjacent to the weigh station was included in the study. Interstate 94 is a heavily traveled route connecting Detroit and Chicago, and the bituminous pavement consists of materials identical to those used in the overlay on the weigh station pavement.

Pavement friction tests were made periodically throughout every season during the five years of the study. However, because water must be used for making wet sliding friction tests, the field program was interrupted during freezing weather.

Pavements for friction testing were selected to include a wide range of textures of both concrete and bituminous surfaces. Grooved pavements, open-graded friction courses, and polished surfaces were among the surfaces tested.

CORRELATION AND REPEATABILITY OF INSTRUMENTS

The workhorse skid test unit was developed by the Research Laboratory during the middle 1950's. Although it is still an efficient and reliable instrument, it did not have the versatility needed for a broad research program. Because of this lack of versatility and because the workhorse skid device was kept so busy with routine testing, in 1971, a K. J. Law Engineers, Model 965 Surface Dynamics Pavement Friction Tester was procured.

Correlation

After using the Law unit sufficiently to be sure that any minor defects had been corrected, a correlation between the new and old test units was undertaken. An experiment was designed to determine the precision of each instrument as well as to correlate the two. The experimental design, a randomized block, is illustrated in Figure 1. Sites having low, medium, and high skid coefficients were selected for both bituminous and concrete pavements. Three different bituminous pavement sites were used and four concrete pavement sites; a total of seven different test sites. Although Figure 1 shows only three concrete test areas, a fourth was selected and used. When the three original concrete sections were tested with the workhorse unit at 40 mph, there were no surfaces with coefficients of friction between about 0.45 and 0.80. Therefore, a fourth concrete section with friction coefficients varying about 0.60 was used to fill the gap. Order of testing was randomized in the same manner as for the original sections.

At each site, three areas were tested; a total of 21 different areas. Tests were made at both 20 and 40 mph and were replicated three times; a grand total of 126 tests for each skid measuring instrument.

Figure 2, scatter diagrams of the test data, shows excellent correlation between the two instruments. Coefficients of determinations[1] of 0.98 for both 20 and 40 mph indicate that only 2 percent of the variance in the experiment cannot be accounted for in the correlation. Therefore, all data can be transformed to a common reference for reporting. Since there is a significant difference in the skid values measured on any pavement by the two units, it would be confusing if data were reported without being transformed to a common reference. To provide continuity with the older skid

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[1] Coefficient of determination is a measure of the intensity of association between two variables. It is the square of the correlation coefficient and indicates the proportion of variation of variable Y which is determined by variable X.

RANDOMIZED BLOCK DESIGN

Skid Coefficient Level	Type of Surface	Both Old and New Vehicles	
		Vehicle Speed	
		40 mph	20 mph
High	Bituminous	2 4 6	1 3 5
	Concrete	1 2 3	4 5 6
Medium	Bituminous	2 5 6	1 3 4
	Concrete	1 2 4	3 5 6
Low	Bituminous	1 5 6	2 3 4
	Concrete	2 3 4	1 5 6

Note: Numbers indicate order of testing for each pavement site.

For each cell both instruments were tested in random order.

Figure 1. Experimental design for correlating Michigan workhorse and K. J. Law pavement friction testers.

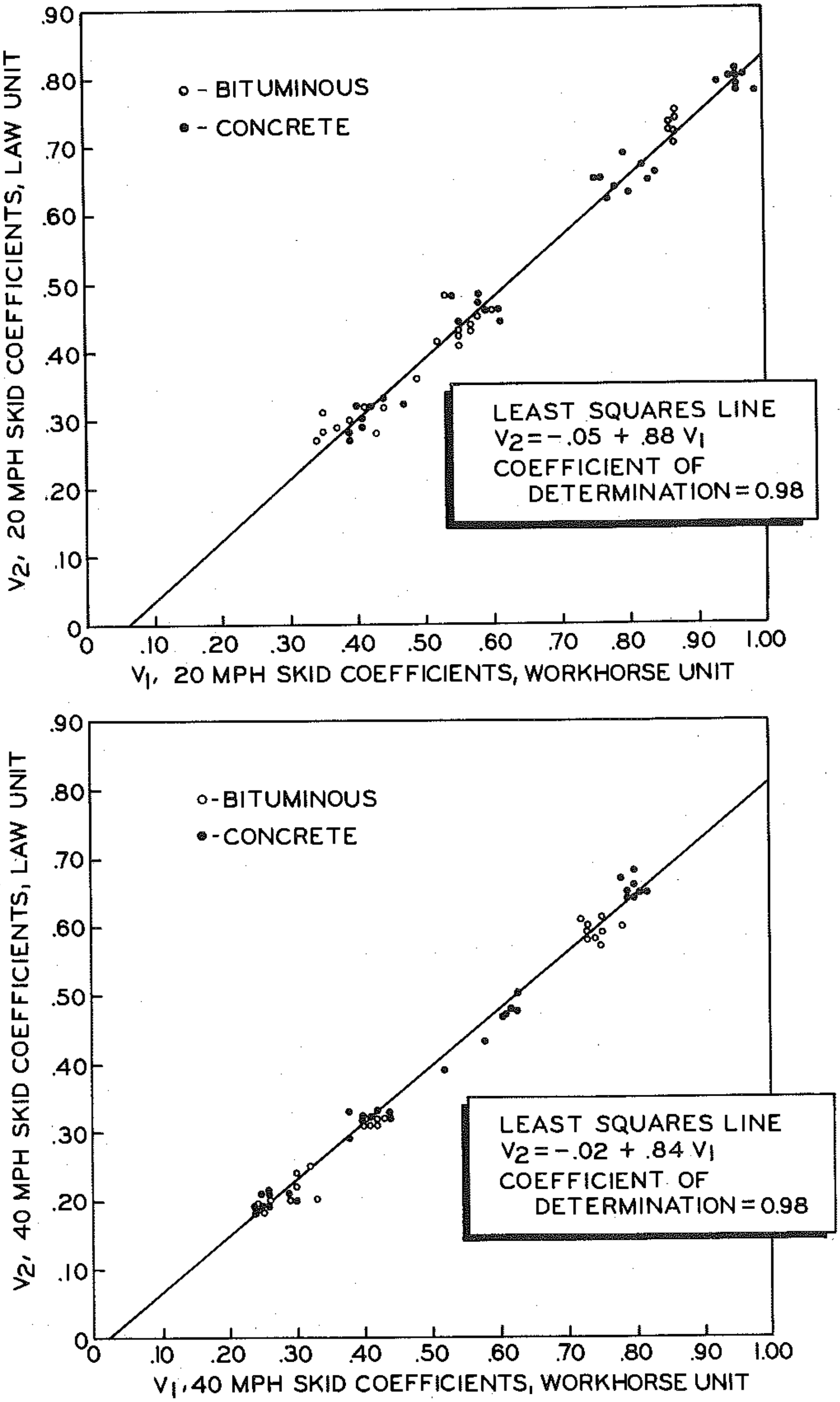


Figure 2. Correlation of Michigan workhorse and K. J. Law pavement friction testers.

TABLE 1
AVERAGE VARIANCES AND STANDARD DEVIATIONS FOR REPEATED TESTS WITH MICHIGAN PAVEMENT FRICTION TESTERS

Average Variances and Standard Deviations	20 mph		40 mph	
	Workhorse Skid Test Unit	Law Skid Test Unit	Workhorse Skid Test Unit	Law Skid Test Unit
average variance (all cond)	0.000480	0.000209	0.000373	0.000178
standard deviation	0.0219	0.0145	0.0193	0.0133
average variance (bit)	0.000650	0.000177	0.000288	0.000094
standard deviation	0.0255	0.0133	0.0170	0.0097
average variance (conc)	0.000354	0.000233	0.000437	0.000241
standard deviation	0.0188	0.0153	0.0209	0.0155
average variance (high)	0.000200	0.000066	0.000191	0.000166
standard deviation	0.0141	0.0081	0.0138	0.0129
average variance (med)	0.000583	0.000225	0.000250	0.000108
standard deviation	0.0241	0.0150	0.0158	0.0104
average variance (low)	0.000700	0.000183	0.000491	0.000066
standard deviation	0.0265	0.0135	0.0222	0.0981
average variance (extra)	0.000333	0.000483	0.000733	0.000566
standard deviation	0.0182	0.0220	0.0271	0.0238

program within the Department, data are transformed to units as measured by the workhorse skid device. Statistical models for computing regression equations and confidence intervals are described in the Appendix.

Repeatability

Using data from the correlation study, a measure of each instrument's ability to repeat skid values from tests on the same surface was estimated. Markings were placed at the beginning of each test area and three replicates were made so rapidly that water from the preceding test had not completely dried. In this manner, it was possible to replicate tests on the same pavement surface and obtain data to estimate instrument repeatability. Repeatability, expressed in terms of statistical variance, proved to be good for each instrument. Statistical models used for computing variances are described in the Appendix. Table 1 lists average variances and standard deviations for each skid test instrument. Equations expressing 95 percent confidence intervals for transforming skid measurements from unit to unit are also described in the Appendix.

RESEARCH FINDINGS

Smooth Tires

It has been widely recognized that, on most wet surfaces, stopping distances for vehicles with smooth tires are greater than for vehicles with treaded tires. Since the mid-1950's, Michigan has had a program for measuring and improving pavement skid resistance. Consequently, there are now very few state trunklines that are found to have low skid resistance as measured by the ASTM trailer test method. However, little is known about the wet sliding friction values of Michigan roads as measured with a smooth tire.

To determine differences in the reaction of pavement surfaces between smooth and treaded tires, 18 roadways were selected for testing, nine bituminous concrete, one sealcoat, and eight concrete surfaces. Tests were made at 20, 40, and 70 mph in wheelpaths of the roads using the ASTM E-249 treaded tire (14-in. diameter rim) on the right wheel of the trailer and a smooth tread test tire on the left. Multiple tests were made in each area giving 52 pairs of data, or points, at each speed. Each data point consisted of an average of two or more tests with a treaded tire paired with an equal number of tests with a smooth tire. To compare each pair of data, a ratio was calculated by dividing the skid coefficient with the treaded tire by the skid coefficient with the smooth tire. These ratios indicated how much better, proportionally, the friction of a treaded tire was than a smooth tire. Distributions of these ratios are shown in Figure 3 and are summarized as follows:

At 20 mph, mean average $\frac{\mu_T}{\mu_S} = 1.26$

range: 1.01 to 1.69

At 40 mph, mean average $\frac{\mu_T}{\mu_S} = 1.50$

range: 1.10 to 2.26

At 70 mph, mean average $\frac{\mu_T}{\mu_S} = 1.56$

range: 1.10 to 2.60

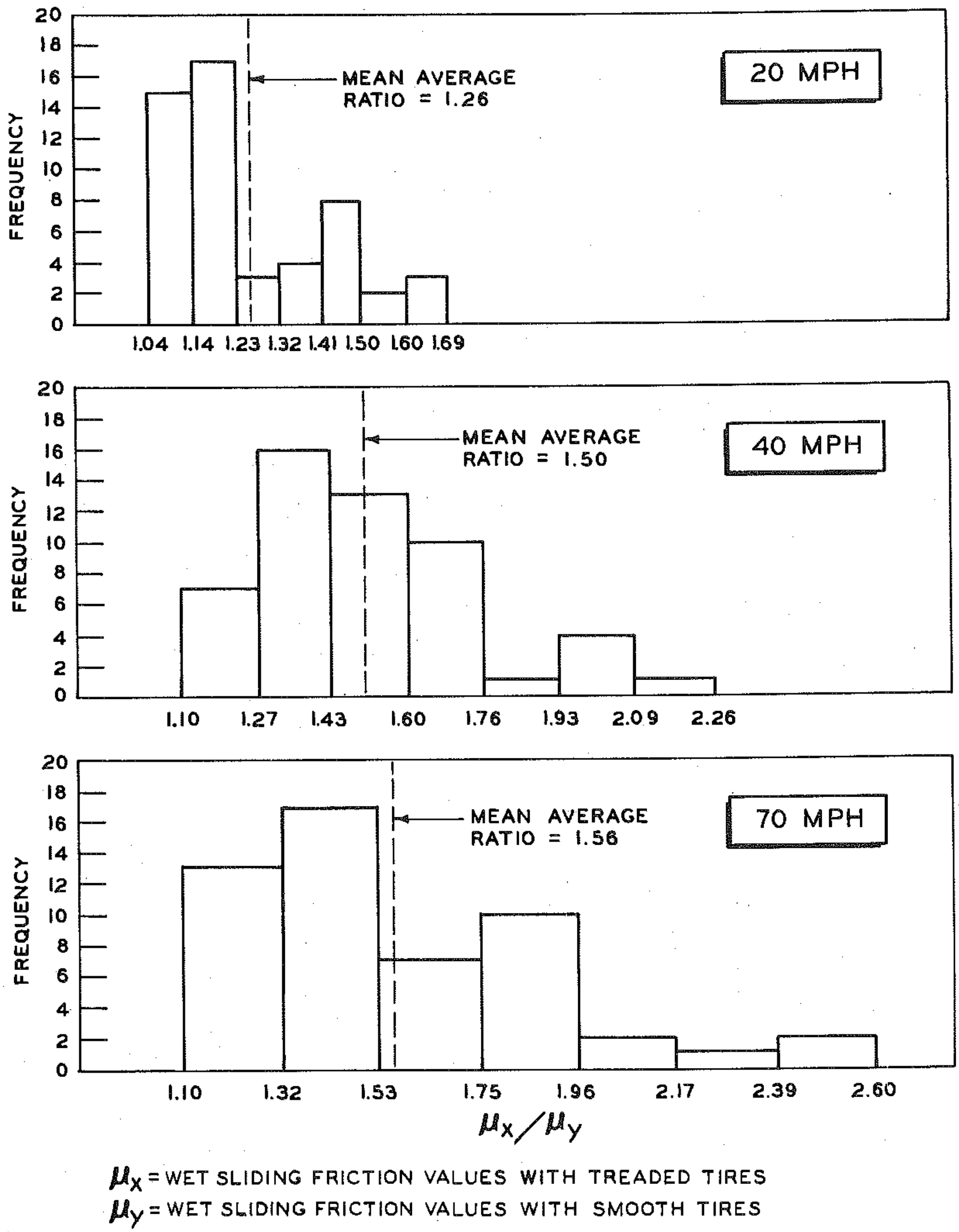


Figure 3. Frequency distribution showing wet friction advantages of treaded tires over smooth tires.

where μ_T = coefficient of wet sliding friction measured with a treaded tire.

μ_s = coefficient of wet sliding friction measured with a smooth tire.

Using velocity and coefficient of sliding friction, the stopping distance of a vehicle can be computed by the formula: $S = \frac{v^2}{30\mu}$, where S = stopping distance in feet, v = initial velocity of vehicle in mph, and μ = friction coefficient. This formula, in combination with the preceding test data, indicates that the average stopping distance on wet roads for smooth tires is about 50 percent longer at 40 or 70 mph than for treaded tires; the data also show that, in some cases, smooth tires take over 1.5 times more distance to stop than treaded tires.

There are a number of reasons why vehicles should not travel on smooth tires which can contribute to causing accidents in at least four ways. 1) Sudden tire disablement, such as a blowout, affects control of the vehicle; 2) a hazard is created when a disabled vehicle is parked alongside a road to change a tire; 3) as shown in the preceding discussion, worn tires provide much less traction on wet pavement than do treaded tires; and 4) if smooth tires are on one side of a vehicle and treaded tires are on the other, braking on wet surfaces will cause differential friction forces. Such differential forces will create a torque and the vehicle may spin.

A 1970 report by the United States Department of Commerce (1) has shown that a tire with 2/32 in. or less of tread is about 10 times as likely to become disabled as a new tire. Consequently, these greater chances of disablement increase the probability of the types of accidents described in 1) and 2) above.

In 1958, William Zuk (2) reported a mathematical analysis of vehicle deviation caused by different coefficients of friction between the right and left wheelpaths. Such deviations could cause a braking vehicle to spin out of control. Emperical evidence of the potential danger of differential friction between two wheelpaths was provided by John C. Burns (3) in 1976. A difference of only nine skid numbers (coefficient of friction x 100) measured at 40 mph caused a car making a locked wheel stop from 50 mph to rotate 129 degrees. Several tests reported on by Burns showed that the degree of rotation of a vehicle making a locked wheel stop on a wet pavement is a function of both speed and difference in friction between wheelpaths.

Although the preceding work by Zuk and Burns has been used to show vehicle response to differential pavement friction, their work could also apply to differential friction experienced by vehicles with smooth tires on one side and treaded tires on the other.

During the past several years, considerable attention to vehicle safety has been given by both national and state agencies. Large amounts of money are spent on mandatory vehicle safety equipment and there is now considerable controversy over whether to mandate the expensive air-bag passive restraint system in vehicles. In view of all the attention given to vehicle safety, it would appear that laws requiring a minimum depth of vehicle tire tread are warranted.

Annual statewide surveys made during the past few years by the Research Laboratory have shown that about 541,000 Michigan automobiles have at least one smooth tire and over 62,000 have all four tires smooth. Surveys were made during winter when studded tire use was being investigated. Vehicles in that condition are a threat not only to themselves but to others on the highway.

Smooth Tires for Measuring Pavement Friction

Pavement Grooving - Although they are dangerous for vehicles traveling on wet pavements, smooth tires can be a valuable tool for highway engineers. In this investigation, they were used for measuring the effectiveness of coarse texture in providing drainage channels under tires and also in estimating high speed skid resistance from low speed tests. For example, although pavement grooving is widely accepted as an effective means of reducing wet skidding accidents under many conditions, little if any improvements in skid coefficient have been measured in grooved areas. Reasons for the effectiveness of pavement grooves in reducing accidents have been explained by saying either that grooves reduced hydroplaning or else they provided a "railroad" effect and steered vehicles around curves.

Figure 4 suggests what may be a more likely explanation of the mechanics of grooving effectiveness. Skid measurements were made on M 21 east of Flint in a high wet accident area, before and after longitudinal grooving. Both smooth and treaded tires were used on the skid test units and measurements were made at speeds from 40 to 70 mph. Although skid coefficients measured with treaded tires were improved about 20 percent, coefficients with smooth tires were approximately doubled. Wet skidding accidents have decreased dramatically in the grooved areas with only the slight increase in skid resistance as measured with a treaded tire. Other

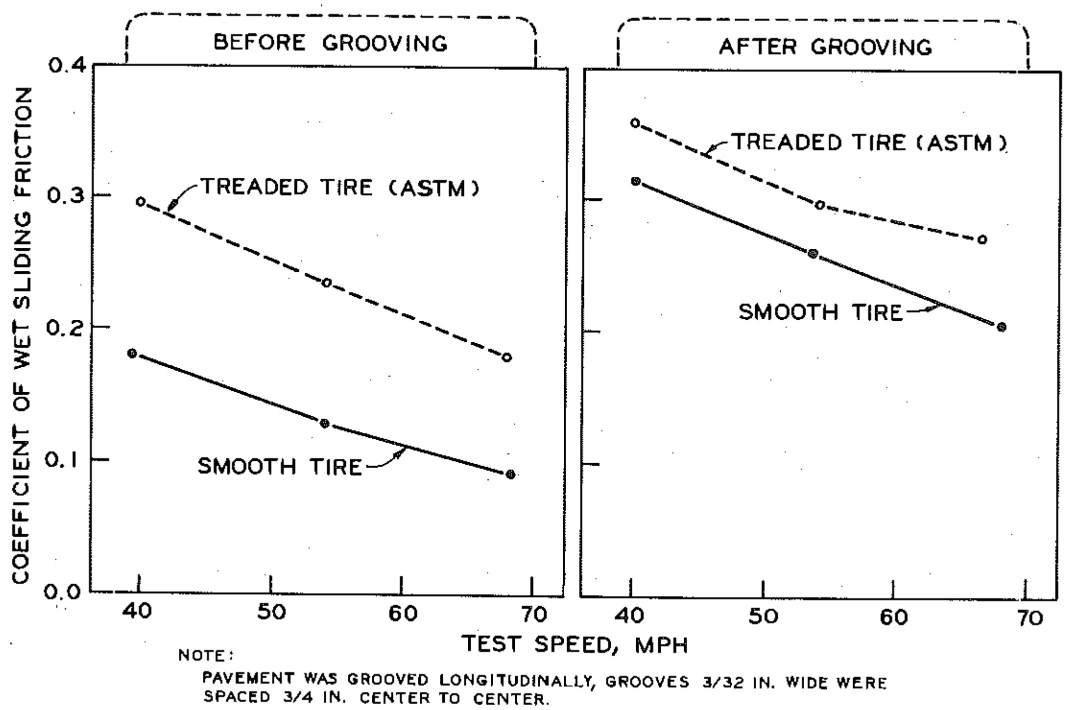


Figure 4. Improvement of wet friction by pavement grooving.

grooved pavements showed similar skid test results; a slight increase in skid resistance measured with treaded tires, a large increase with smooth tires. It seems plausible that pavement grooves are effective in reducing accidents simply because they are serving as tread for smooth tires.

Open-Graded Asphalt Mix - Conventional friction tests showed no advantage for open-graded friction course compared to bituminous concrete. Figure 5 shows skid test results from M 46 in Saginaw where an open-graded friction course and a conventional bituminous concrete mat were constructed on adjacent lengths of road and at the same time. When wet friction values were measured with the ASTM test tire, almost no differences could be seen between the two types of surfaces. However, tests made using smooth tires showed the open-graded friction course to be far superior to bituminous concrete.

Pavement Texturing - During the summer of 1976, a number of intersections on M 58 in Saginaw were textured using a CMI Rotomill. The Rotomill is a cold-planer that makes a cut 9 ft - 2 in. wide and can be used for both surface texturing and planing. The manufacturer claims the machine can cut to surface tolerances of ± 1/8 in. with the grade reference taken from a ski or stringline. Since the machine has a relatively high rate of production (about 2,000 sq yd/hr) it will probably prove very valuable in

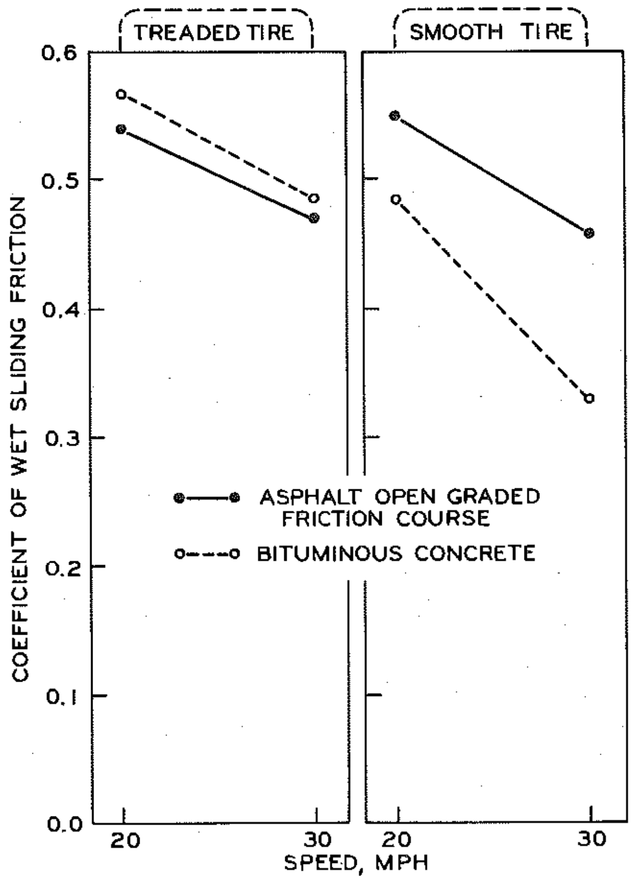


Figure 5. Friction of an open-graded asphalt friction course compared to a conventional bituminous concrete.

pavement skid proofing techniques. Figure 6 shows the coarse texture provided by the machine. Texture can be altered by regulating the speeds of the cutting drum and the rate of travel of the machine.

Prior to texturing, the bituminous surfaces on M 58 had satisfactory wet friction values while those of the concrete were marginal. Figure 7 shows skid test values for both textured and non-textured M 58 surfaces. While the textured surfaces improved skid resistance significantly for treaded tires, the improvement for smooth tires was remarkable--more than double for both bituminous and concrete. This means that the wet surface stopping distances for vehicles with smooth tires, on both concrete and asphalt pavements, are cut approximately in half by texturing.

From the foregoing discussion, it appears that the ASTM skid test procedure using a treaded tire does not provide enough information to properly evaluate a pavement surface. Textures providing great improvements in wet friction for smooth tires may not be detected when tested with a treaded tire. Since large numbers of vehicles travel on smooth tires, it is important that road surfaces be designed with that factor in mind. With limited

Figure 6. Two views of pavement texture as provided by the CMI Rotomill.

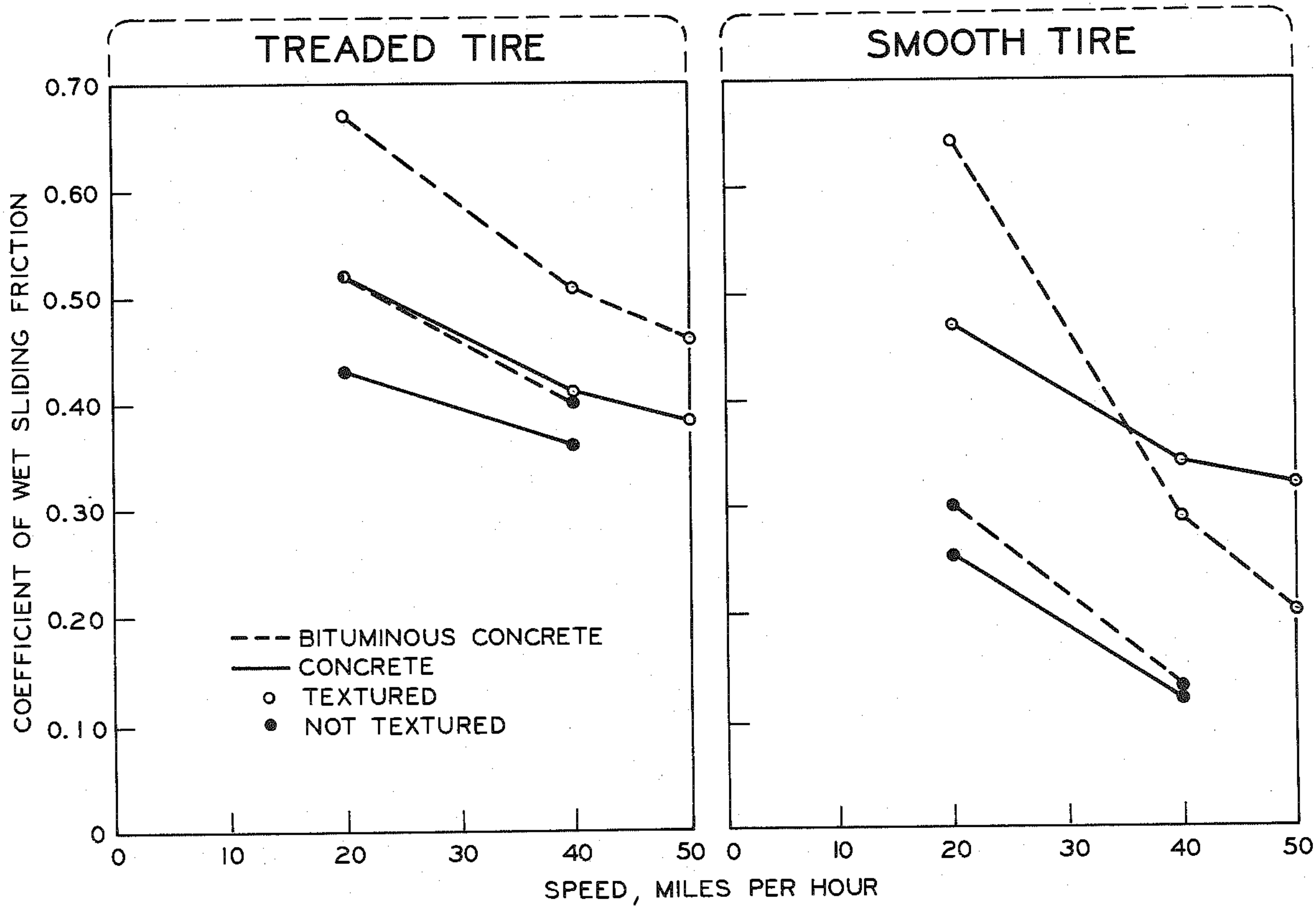


Figure 7. CMI Rotomill texturing effects on wet sliding friction.

resources, it would be impossible to maintain all road surfaces at a high wet friction level for smooth tired vehicles. In critical areas, however, minimum wet friction levels for smooth tired vehicles should be considered. Also, coarse texture providing high, smooth tire, wet friction should be constructed whenever economically feasible.

Estimation of High Speed Skid Coefficients

Situations frequently occur where skid coefficients cannot be measured at a desired high speed because of traffic congestion or other obstacles in the roadway. In such cases, it is important that high speed skid coefficients be accurately estimated using low speed test results.

A method used in the past by the Department involved estimating 40 mph coefficients from 10, 20, 30, or 50 mph coefficients by merely using correlation between the two which was established using data from a large number of previous tests. Table 2 is a set of conversion factors previously used for transforming skid tests to 40 mph value in Michigan. A further investigation to improve estimating high speed skid test values from low speed tests was carried out in this study. Tests were made at speeds of 20, 40, and 70 mph using both smooth and treaded tires. Multiple tests, with a smooth tire on the left wheel and an ASTM treaded tire on the right, were made over each of 17 different pavement sites. Both asphalt and concrete pavements having a wide range of wet sliding friction values were tested.

It is well known that wet pavement skid coefficients usually decrease with increasing speed while dry skid coefficients do not (4). The reduction in skid coefficient with respect to speed has been found related to the coarse texture of the pavement surface, because such texture, in combination with tire tread grooves, provides escape routes for surface water. As surface water is drained from between tire and pavement, intimate contact of rubber and road surface provides friction. If drainage is not complete, a layer of water separates tire and pavement causing reduced friction. At low speeds, there is ample time for surface water to flow into tire tread grooves and therefore coarse pavement texture is not as important, at least for treaded tires. At high speeds, however, there is so little escape time for water under the rolling tire, that both tire tread grooves and pavement texture become important in providing drainage paths. At low speeds, coarse pavement texture is important primarily for drainage from under smooth tires. Thus, while important for treaded tires at high speeds, it appears that coarse pavement texture is necessary in providing drainage and thereby increased friction for smooth tires at all speeds. It might be possible,

TABLE 2
CHART FOR CONVERTING MEASURED
COEFFICIENTS OF FRICTION (μ) TO
HIGHER SPEED FRICTION COEFFICIENTS

μ Value	Bituminous 10 to 40	Bituminous 20 to 40	Bituminous 30 to 40	Bituminous 50 to 40	Concrete 10 to 40	Concrete 20 to 40	Concrete 30 to 40	Concrete 50 to 40
.01	.01	.01	.01	.01	.01	.01	.01	.01
.02	.01	.02	.02	.02	.01	.01	.02	.03
.03	.02	.02	.03	.04	.02	.02	.03	.04
.04	.03	.03	.03	.05	.03	.03	.03	.05
.05	.03	.04	.04	.06	.03	.04	.04	.06
.06	.04	.05	.05	.08	.04	.04	.05	.08
.07	.05	.05	.06	.09	.05	.05	.06	.09
.08	.05	.06	.07	.10	.05	.06	.07	.10
.09	.06	.07	.08	.11	.06	.07	.08	.11
.10	.07	.08	.09	.13	.06	.07	.09	.13
.11	.07	.09	.10	.14	.07	.08	.09	.14
.12	.08	.09	.10	.15	.08	.09	.10	.15
.13	.09	.10	.11	.16	.08	.10	.11	.17
.14	.10	.11	.12	.18	.09	.10	.12	.18
.15	.10	.12	.13	.19	.10	.11	.13	.19
.16	.11	.12	.14	.20	.10	.12	.14	.20
.17	.12	.13	.15	.21	.11	.13	.15	.22
.18	.12	.14	.16	.23	.12	.13	.15	.23
.19	.13	.15	.17	.24	.12	.14	.16	.24
.20	.14	.16	.17	.25	.13	.15	.17	.25
.21	.14	.16	.18	.26	.14	.16	.18	.27
.22	.15	.17	.19	.28	.14	.16	.19	.28
.23	.16	.18	.20	.29	.15	.17	.20	.29
.24	.16	.19	.21	.30	.16	.18	.21	.30
.25	.17	.20	.22	.31	.16	.18	.22	.32
.26	.18	.20	.23	.33	.17	.19	.22	.33
.27	.18	.21	.23	.34	.18	.20	.23	.34
.28	.19	.22	.24	.35	.18	.21	.24	.36
.29	.19	.23	.25	.36	.19	.21	.25	.37
.30	.20	.23	.26	.38	.20	.22	.26	.38
.31	.21	.24	.27	.39	.20	.23	.27	.39
.32	.22	.25	.28	.40	.21	.24	.28	.41
.33	.22	.26	.29	.41	.21	.24	.29	.42
.34	.23	.27	.30	.43	.22	.25	.29	.43
.35	.24	.27	.30	.44	.23	.26	.30	.44
.36	.24	.28	.31	.45	.23	.27	.31	.46
.37	.25	.29	.32	.46	.24	.27	.32	.47
.38	.26	.30	.33	.48	.25	.28	.33	.48
.39	.27	.30	.34	.49	.25	.29	.34	.50
.40	.27	.31	.35	.50	.26	.30	.34	.51
.41	.28	.32	.36	.51	.27	.30	.35	.52
.42	.29	.33	.37	.53	.27	.31	.36	.53
.43	.29	.34	.37	.54	.28	.32	.37	.55
.44	.30	.34	.38	.55	.29	.33	.38	.56
.45	.31	.35	.39	.56	.29	.33	.39	.57
.46	.31	.36	.40	.58	.30	.34	.40	.58
.47	.32	.37	.41	.59	.31	.35	.40	.60
.48	.33	.37	.42	.60	.31	.36	.41	.61
.49	.33	.38	.43	.61	.32	.36	.42	.62
.50	.34	.39	.44	.63	.32	.37	.43	.64

μ Value	Bituminous 10 to 40	Bituminous 20 to 40	Bituminous 30 to 40	Bituminous 50 to 40	Concrete 10 to 40	Concrete 20 to 40	Concrete 30 to 40	Concrete 50 to 40
.51	.35	.40	.44	.64	.33	.38	.44	.65
.52	.35	.41	.45	.65	.34	.38	.45	.66
.53	.36	.41	.46	.66	.34	.39	.46	.67
.54	.37	.42	.47	.68	.35	.40	.46	.69
.55	.37	.43	.48	.69	.36	.41	.47	.70
.56	.38	.44	.49	.70	.36	.41	.48	.71
.57	.39	.44	.50	.71	.37	.42	.49	.72
.58	.39	.45	.50	.73	.38	.43	.50	.74
.59	.40	.46	.51	.74	.38	.44	.51	.75
.60	.41	.47	.52	.75	.39	.44	.52	.76
.61	.41	.48	.53	.76	.40	.45	.52	.77
.62	.42	.48	.54	.78	.40	.46	.53	.79
.63	.43	.49	.55	.79	.41	.47	.54	.80
.64	.44	.50	.56	.80	.42	.47	.55	.81
.65	.44	.51	.57	.81	.42	.48	.56	.83
.66	.45	.51	.57	.83	.43	.49	.57	.84
.67	.46	.52	.58	.84	.44	.50	.58	.85
.68	.46	.53	.59	.85	.44	.50	.58	.86
.69	.47	.54	.60	.86	.45	.51	.59	.88
.70	.48	.55	.61	.88	.46	.52	.60	.89
.71	.48	.55	.62	.89	.46	.53	.61	.90
.72	.49	.56	.63	.90	.47	.53	.62	.91
.73	.50	.57	.64	.91	.47	.54	.63	.93
.74	.50	.58	.64	.93	.48	.55	.64	.94
.75	.51	.59	.65	.94	.49	.56	.64	.95
.76	.52	.59	.66	.95	.49	.56	.65	.97
.77	.52	.60	.67	.96	.50	.57	.66	.98
.78	.53	.61	.68	.98	.51	.58	.67	.99
.79	.54	.62	.69	.99	.51	.58	.68	1.00
.80	.54	.62	.70	1.00	.52	.59	.69	
.81	.55	.63	.70		.53	.60	.70	
.82	.56	.64	.71		.53	.61	.71	
.83	.56	.65	.72		.54	.61	.71	
.84	.57	.66	.73		.55	.62	.72	
.85	.58	.66	.74		.55	.63	.73	
.86	.58	.67	.75		.56	.64	.74	
.87	.59	.68	.76		.57	.64	.75	
.88	.60	.69	.77		.57	.65	.76	
.89	.61	.69	.77		.58	.66	.77	
.90	.61	.70	.78		.58	.67	.77	
.91	.62	.71	.79		.59	.67	.78	
.92	.63	.72	.80		.60	.68	.79	
.93	.63	.73	.81		.60	.69	.80	
.94	.64	.73	.82		.61	.70	.81	
.95	.65	.74	.83		.62	.70	.82	
.96	.65	.75	.84		.62	.71	.83	
.97	.66	.76	.84		.63	.72	.83	
.98	.67	.76	.85		.64	.73	.84	
.99	.67	.77	.86		.64	.73	.85	
1.00	.68	.78	.87		.65	.74	.86	

then, to use a smooth tire at slow speed to predict the behavior of a treaded tire traveling at high speed over a wet pavement.

Low speed wet skid tests with both smooth and treaded test tires were combined using the following emperical expression which was developed for this study:

$$Z_{ij} = \sin \left[\frac{\pi}{2} \cdot \frac{\mu y_{ij}}{\mu x_{ij}} \right] \mu x_{ij}$$

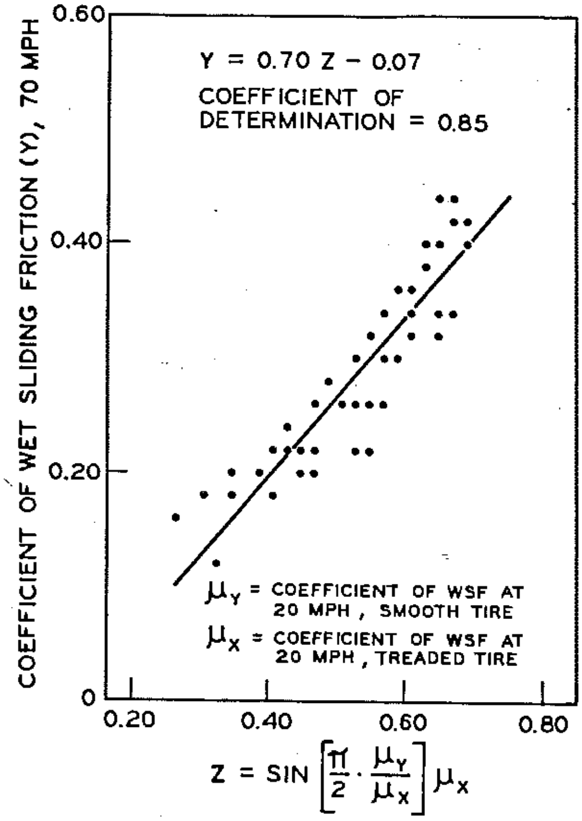
where μy_{ij} = smooth tread tire wet sliding friction value at site i for test speed j.

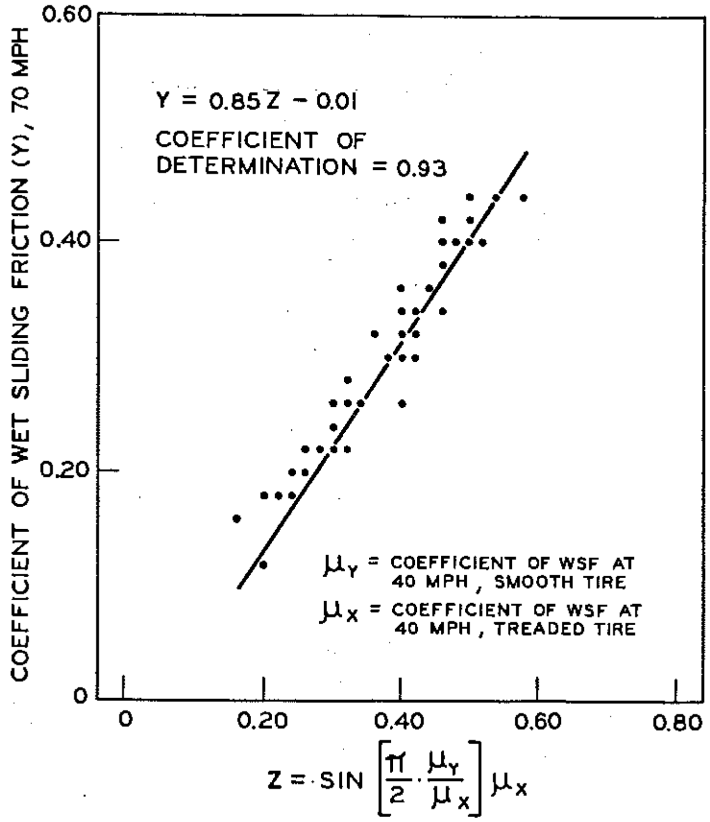
μx_{ij} = treaded tire wet sliding friction value at site i for test speed j.

Values of Z were computed for all test sites for test speeds of 20 and 40 mph. A linear regression was then carried out relating Z_{ij} to actual friction values measured at speeds greater than j and using a treaded tire. That is, actual wet sliding friction (wsf) values at 70 mph measured with a treaded tire were regressed on Z for 20 and 40 mph; actual wsf values at 40 mph measured with a treaded tire were regressed on Z at 20 mph. Figure 8 shows scatter diagrams of the relationships between Z and actual wsf (treaded tire) values at higher speeds. Coefficients of determination were very high. The regression equation explains all but about seven percent of the variation between 40 mph Z values and actual 70 mph values, all but about 10 percent of the relationship between 20 and 40 mph Z values, and all but about 15 percent of the variation between 20 mph Z values and 70 mph wsf values.

An investigation was also made of the relationship between wsf values measured exclusively with ASTM treaded tires at 20, 40, and 70 mph. Figure 9 shows scatter diagrams of wsf values at 20 and 40 mph related to wsf values at 70 mph as well as the relationship between 20 and 40 mph values. Although six different statistical models were tested for best fit of the data, only an exponential model was slightly better than the linear model. Linear models were selected for use because of the ease of application.

Scatter about the regression lines was narrow enough so estimation of high speed wsf values from low speed tests could be made with confidence. However, the use of a smooth tread tire test provided improved accuracy in all three cases, as listed below.





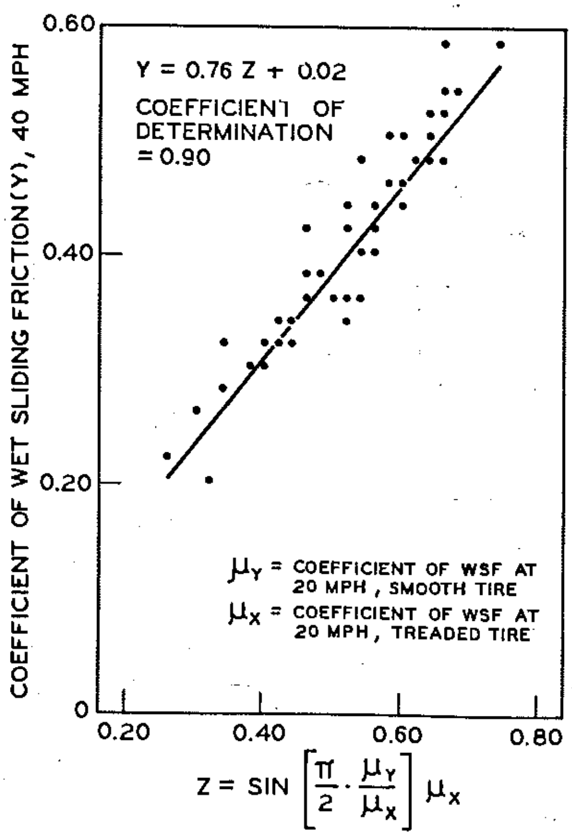
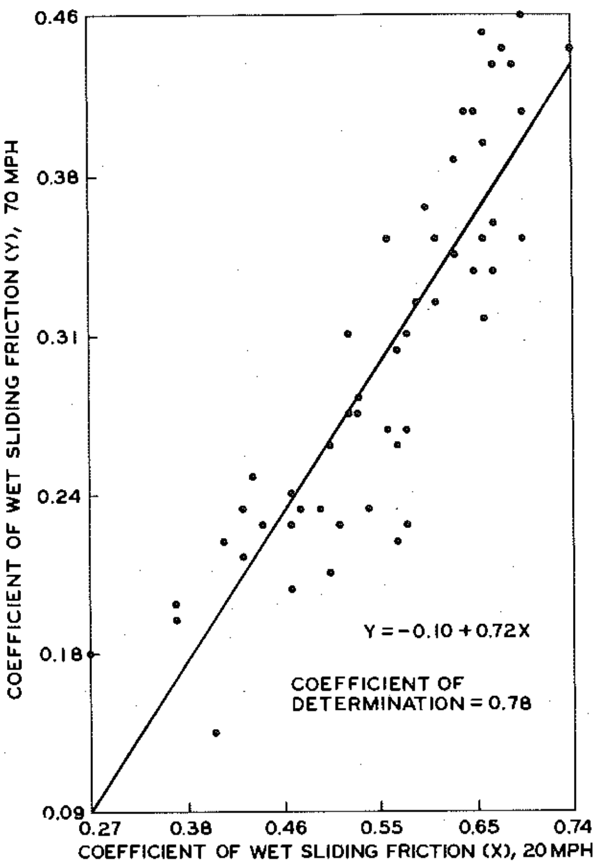
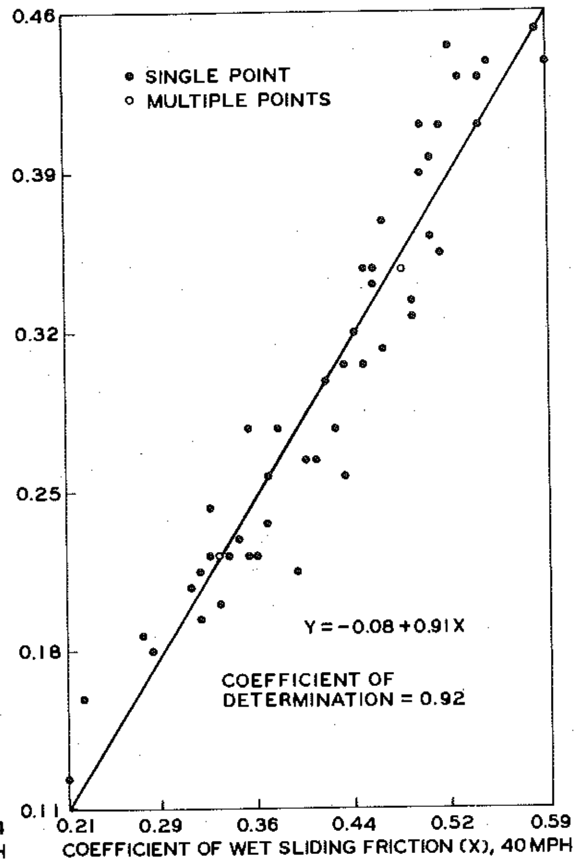


Figure 8. Correlations between coefficient of wet sliding friction measured with treaded tire and functions of coefficients of wet sliding friction measured at lower speeds.





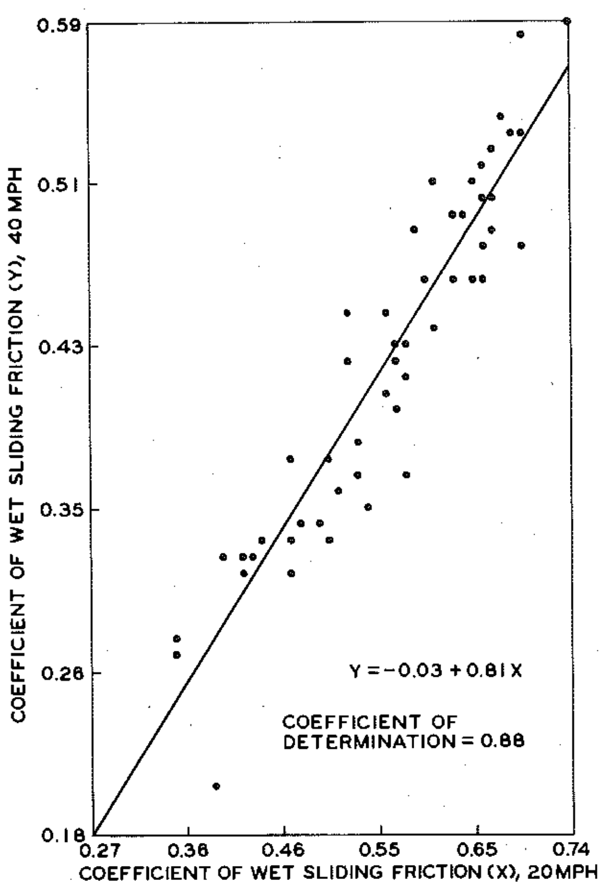


Figure 9. Correlations between coefficients of wet sliding friction measured at different speeds with ASTM treaded tires.

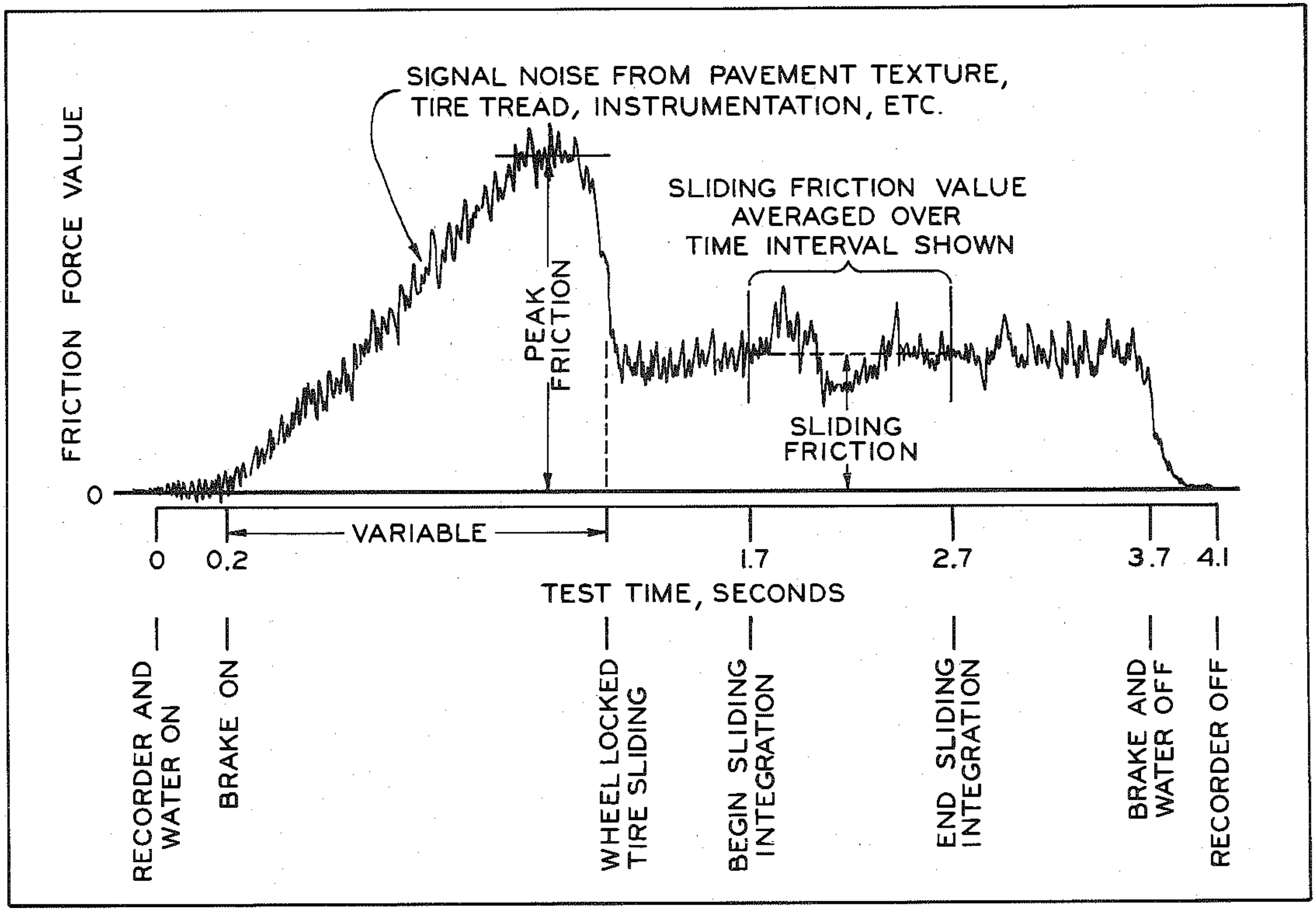


Figure 10. Typical record of skid test cycle (controlled lock mode, maximum rate of braking).

Actual Test Speed	Speed at Which Wsf Values are Estimated	Coefficients of Determination From Regression Using: Only ASTM Treaded Tire at Low Speed	Z Values Computed Using Smooth Tire and ASTM Treaded Tire at Low Speed
20	40	0.88	0.90
20	70	0.78	0.85
40	70	0.92	0.93

In the extreme case of estimating 70 mph wsf values from 20 mph tests, about 7 percent more variation is removed using the smooth tire method than by using the simple treaded tire correlation.

Sliding Versus Peak Friction

When a brake is applied to a rolling wheel until rolling ceases and sliding begins, the frictional force between tire and pavement varies continuously from free rolling to wheel lockup. Figure 10 shows a typical analog trace of the frictional force developed during a single skid test. Just before the wheel locks up and the tire begins to slide, friction develops to a peak, usually at between 10 and 15 percent slip[2]. As lockup continues, friction decreases rapidly to a constant value during zero wheel rotation (100 percent slip).

For this investigation, friction measurements were made in the routine manner except that both peak and sliding friction values were taken from the traces; whereas in the routine operation only sliding values are recorded. Peak values are measured over only a short length of pavement since they occur for a very brief period relative to the time of complete lockup.

[2] Slip is defined as

$$S = \frac{W_o - W}{W_o} \times 100$$

where: S = percent slip
W = angular wheel velocity at time of measurement
W_o = angular velocity if wheel were freely rolling

Also, since each test was sequential rather than simultaneous, locked wheel measurements were not made on the same spot as the peak measurements. Therefore, test surface homogeneity along wheelpaths was an important criterion in selecting test sites.

Tests using treaded tires were made at sites which included new and old pavement surfaces containing natural aggregates, slags, expanded shale, and latex mortar. Different concrete textures were selected, including sawed grooves. Bituminous surfaces in various states of polish and flushing were tested. During this part of the overall study, smooth tire tests were made on only five concrete surfaces and one bituminous. Test speeds with the treaded tire varied from 20 to 77 mph. With the smooth tire, test speeds were limited to 40 mph for 75 tests and 70 mph for three tests. Each test produced an analog trace providing both a peak and a sliding friction value.

Non-locking braking systems, which are being used on some cars and trucks, are designed to keep wheels rotating, even under panic stop conditions, thus assuring operation near the peak friction condition. Panic stops using non-locking braking systems provide two safety benefits; first, pavement-tire friction is higher than under locked wheel condition and second, vehicle control is not lost as it is when wheels are locked. In this study, it was decided to try to quantify the benefits in improved friction under non-lockup braking.

Figure 11 shows scatter diagrams relating wet sliding friction to wet peak friction, measured at various speeds. Correlation between sliding and peak friction values is excellent except for speeds above 40 mph tested with a treaded tire; scatter diagrams for individual test speeds are not plotted.

Average improvements in coefficients for peak compared to wet sliding friction are given in Table 3.

Table 3 shows peak friction values to be significantly higher than sliding friction values in all cases and the relative differences become greater with increasing speeds. Also, peak to sliding differences appear greater for smooth tires than for treaded ones. In view of these tests, non-locking braking systems appear to be a sound investment in safe driving. Because there is an inverse relationship between friction coefficient and stopping distance, stopping distances would decrease proportionally with increasing friction force.

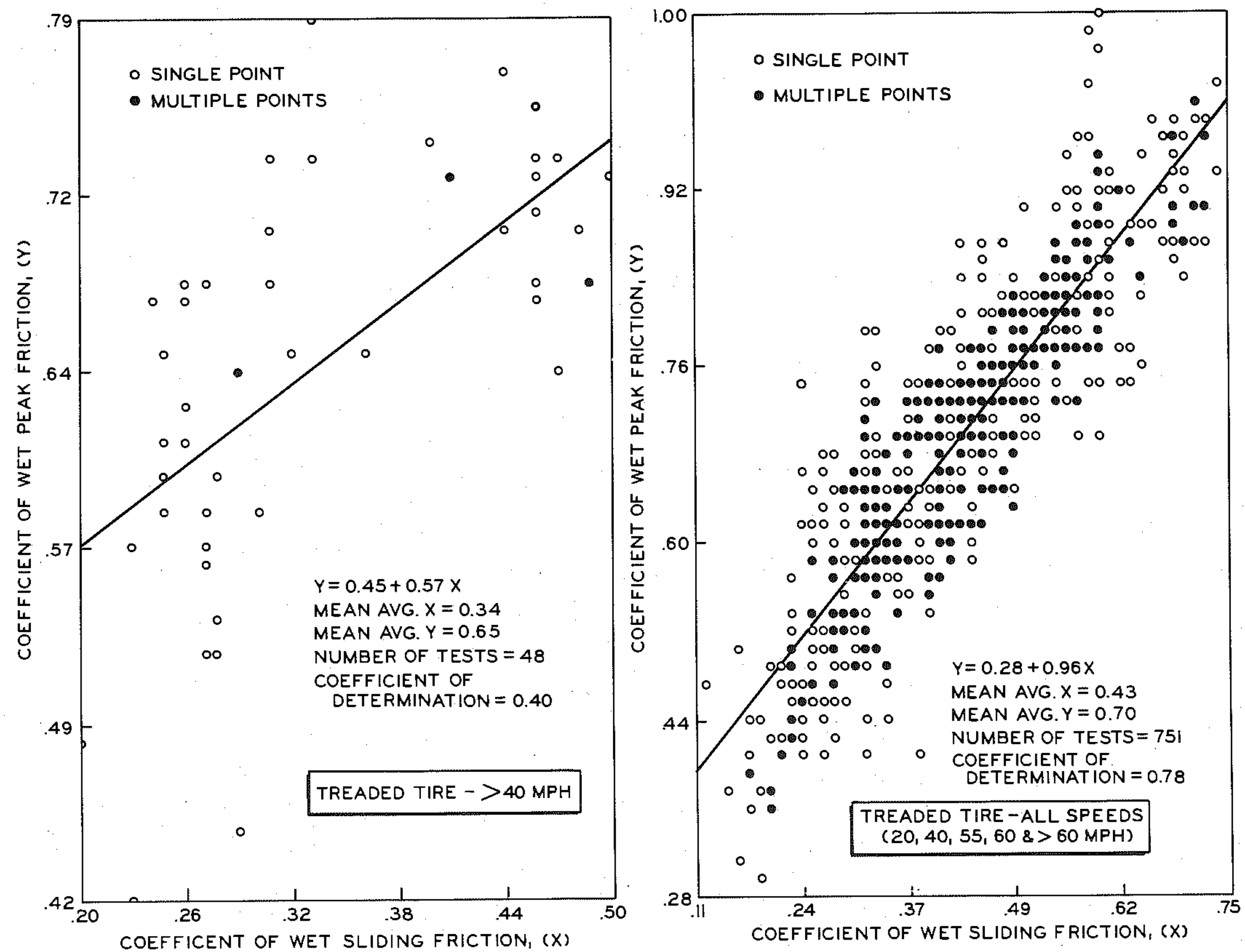


Figure 11. Correlation of coefficient of wet peak friction and coefficient of wet sliding friction.

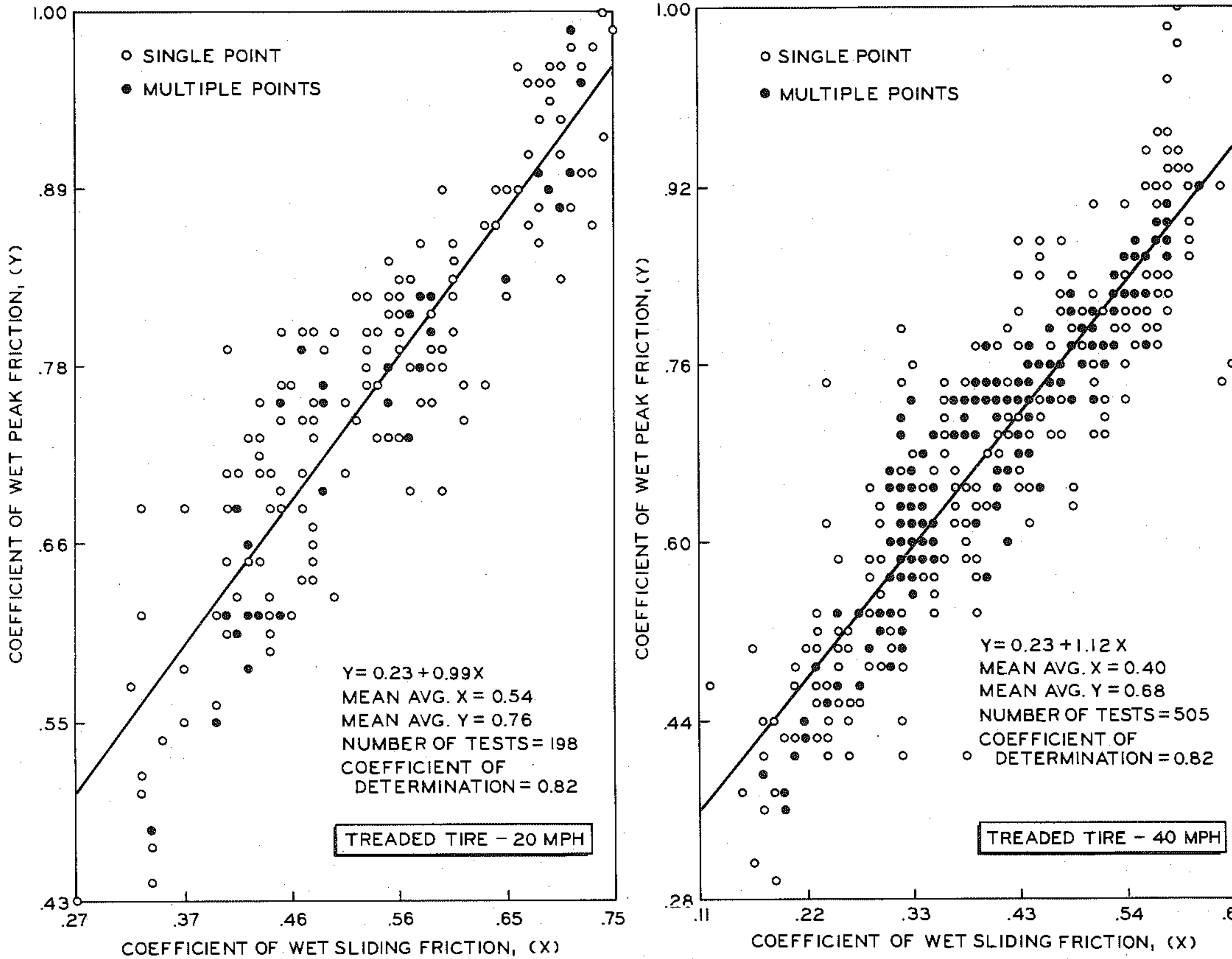


Figure 11 (Cont.). Correlation of coefficient of wet peak friction and coefficient of wet sliding friction.

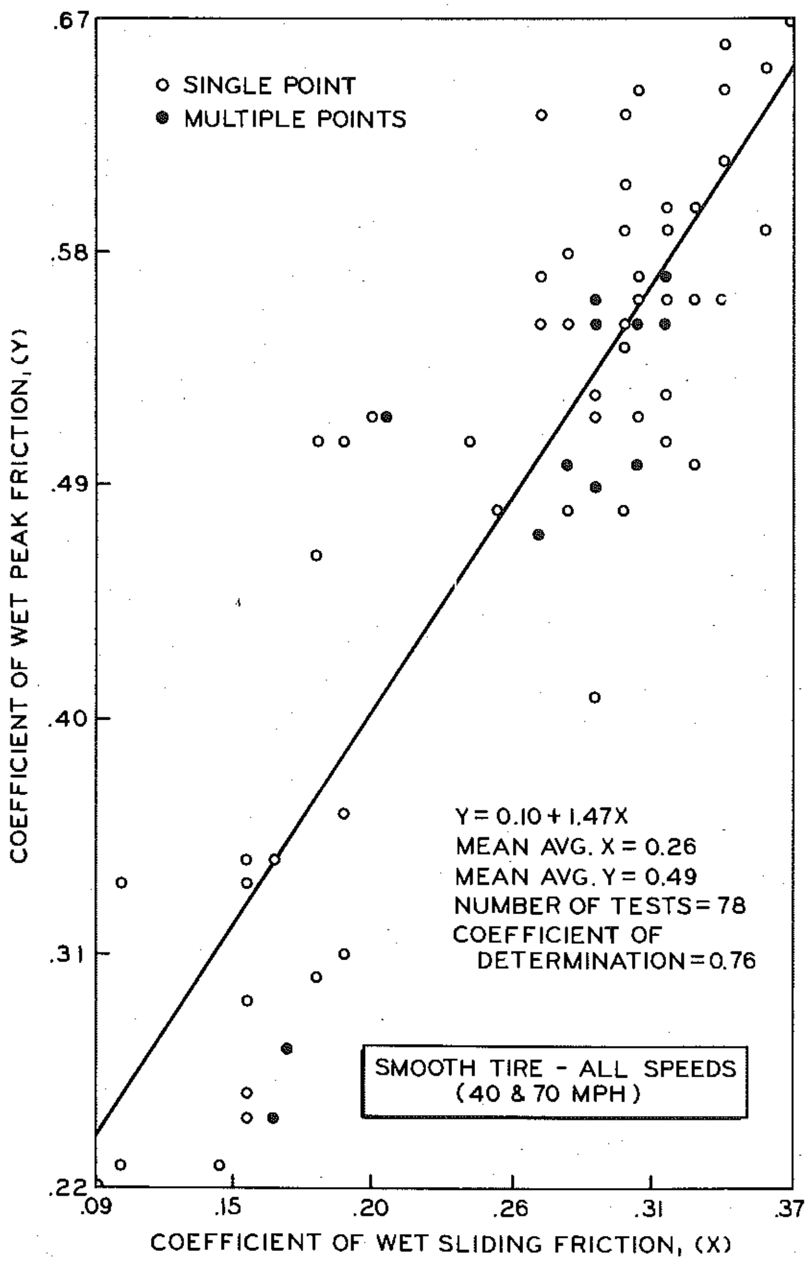


Figure 11 (Cont.). Correlation of coefficient of wet peak friction and coefficient of wet sliding friction.

TABLE 3
RELATIONSHIP BETWEEN PEAK AND
SLIDING WET FRICTION FORCES

Test Speed	Average Percent Gain in Friction, Peak Over Sliding	
	Treaded Tire	Smooth Tire
All speeds*	61	87
20 mph	43	--
40 mph	69	86
Greater than 40 mph	90	172

* Test speeds using treaded tire varied from 20 to 77 mph. For the smooth tire, 75 tests were made at 40 mph and only three were made at 70 mph.

Effects of Temperature

As long ago as 1934, Moyer (5) showed that wet pavement-tire friction increased with decreasing temperatures. The complexity of the friction-temperature problem, however, is indicated by the fact that despite years of research since Moyer's work, there is still no widely accepted method for relating pavement friction with temperature change.

Tire Rubber Temperature - Kummer (6) made laboratory tests to show how rubber friction is altered with temperature. He separated rubber friction into two components; 1) adhesion: the molecular bond between two surfaces, and 2) hysteresis: energy used by rubber deforming as it moves over a rough surface. The adhesion component is important on smooth pavement surfaces where contact areas are large, while coarse textured surfaces, which cause considerable rubber deformation, mobilize hysteresis friction. Kummer's tests showed the adhesion frictional component to increase with increasing temperature while the hysteresis component decreased. Because a water film between tire and pavement would interfere with adhesion, the hysteresis component would be most important on a wet pavement. Thus, friction measured on wet surfaces should increase as temperature decreases. Since the hysteresis component is dominant on wet surfaces, skid tests made on coarsely textured roads, which mobilize hysteresis friction, would be most affected by temperature. Therefore, if correction factors for temperature variation are developed, it may be necessary to include the effect of surface texture differences.

This Department is currently making laboratory tests which support the theory just described, showing that wet friction tests made on coarsely textured specimens are affected much more by varying temperatures than are those made on finely textured surfaces. Results of the laboratory tests will be published in a Departmental report in the future.

Air Temperature - Because of the difficulty in obtaining tire/pavement interface temperatures, measurements of air temperature and sometimes pavement temperatures are taken when skid tests are made with the trailer units. A pyrometer used for measuring pavement temperatures did not provide reliable readings because of the problem in trying to make contact between the instrument and coarse textured pavement surfaces. Hence, in this study only air temperatures were used. Figure 12 shows scatter diagrams of a relationship between wet coefficients of pavement friction and air (ambient) temperature. Data on Figure 12 are from tests made on the barricaded roadway at the Grass Lake Weigh Station and at the nearby I 94 pavement. The correlations between temperature and friction are only fair. It is likely that a good deal of the data scatter results from the fact that the effects of seasonal variation overwhelm changes in friction caused by temperature. Figures 13 and 14 show scatter diagrams of average monthly friction coefficients vs. average monthly high and average monthly temperatures, respectively. Average temperature values were taken from reports by the Michigan Weather Service; their point of measurement was about 10 miles from the skid test sites. The correlation with friction is better with the broad average monthly and average monthly high temperatures than with air temperatures measured carefully when each test was taken.

Why should a relatively crude measurement be better than a more precise one? At least a portion of the improved correlation is due to the fact that the lowest average monthly temperature occurs during the winter and early spring months when friction coefficients are known to be high because of seasonal factors.

The effect of seasonal variations is also shown in Figures 12, 13, and 14 because the data curves measured in a traffic wheelpath have steeper slopes than the other curves. For reasons discussed later in this report, pavement friction is affected by traffic interacting with certain freezing and moisture factors, while there is no such an interaction between traffic and temperature. Also, in wheelpath areas which had been polished and had less texture than the non-traffic areas, the adhesion component of friction should be more important than the hysteresis component. For reasons discussed earlier, adhesion should reflect less decrease in friction due to

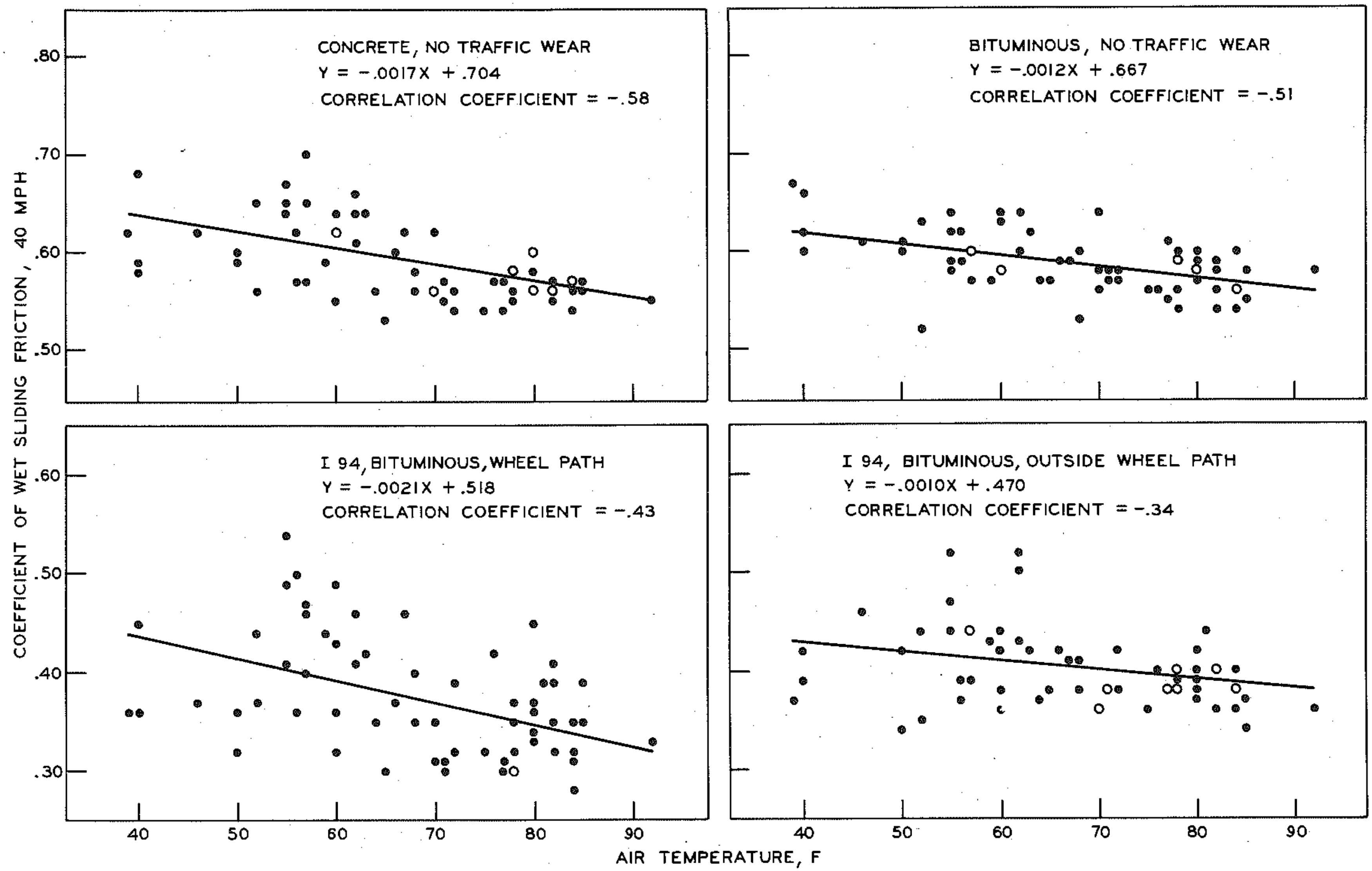


Figure 12. Relationships of air temperature and wet sliding coefficient of friction.

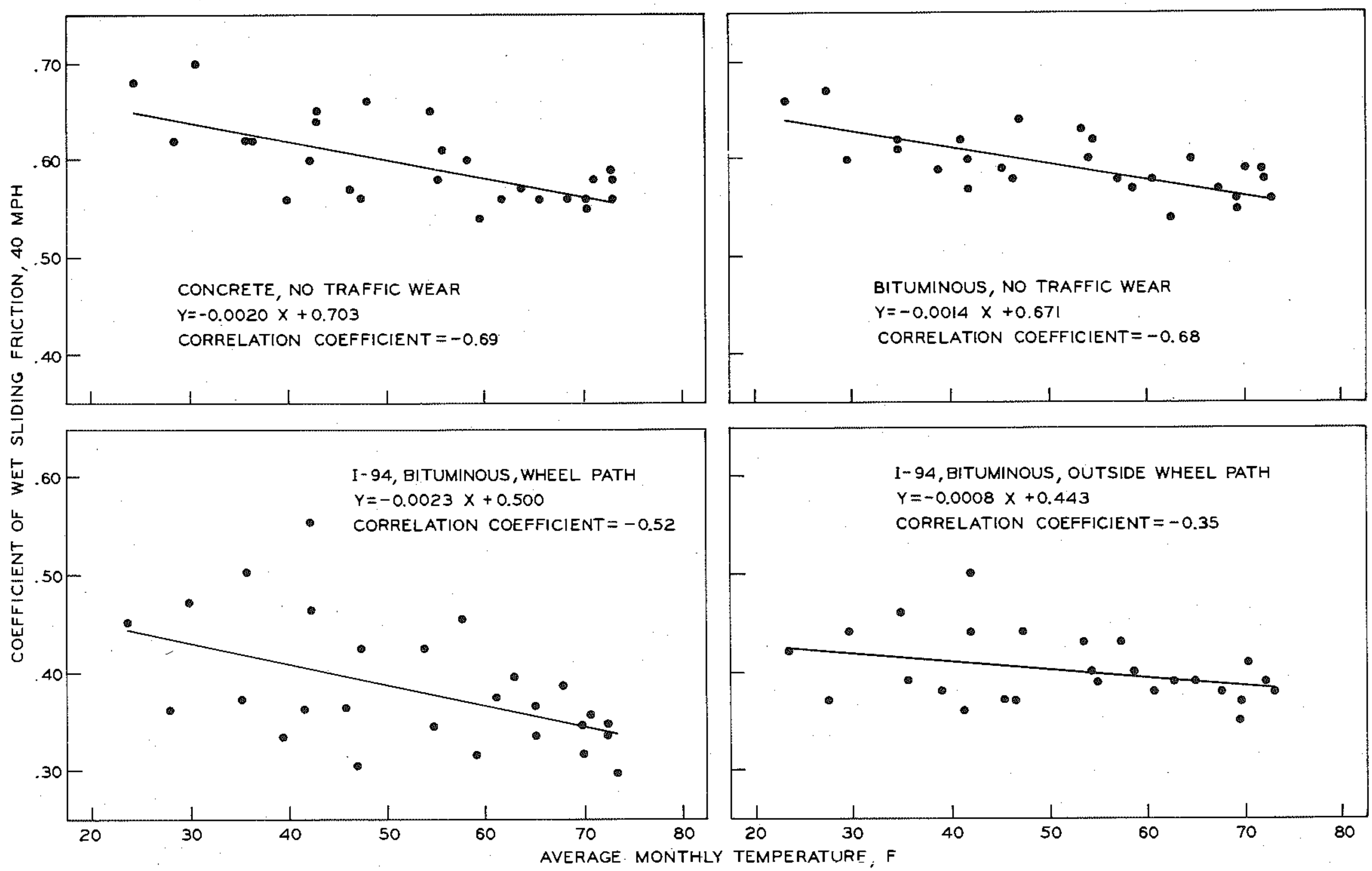


Figure 13. Relationships of average monthly high temperature with coefficient of wet sliding friction.

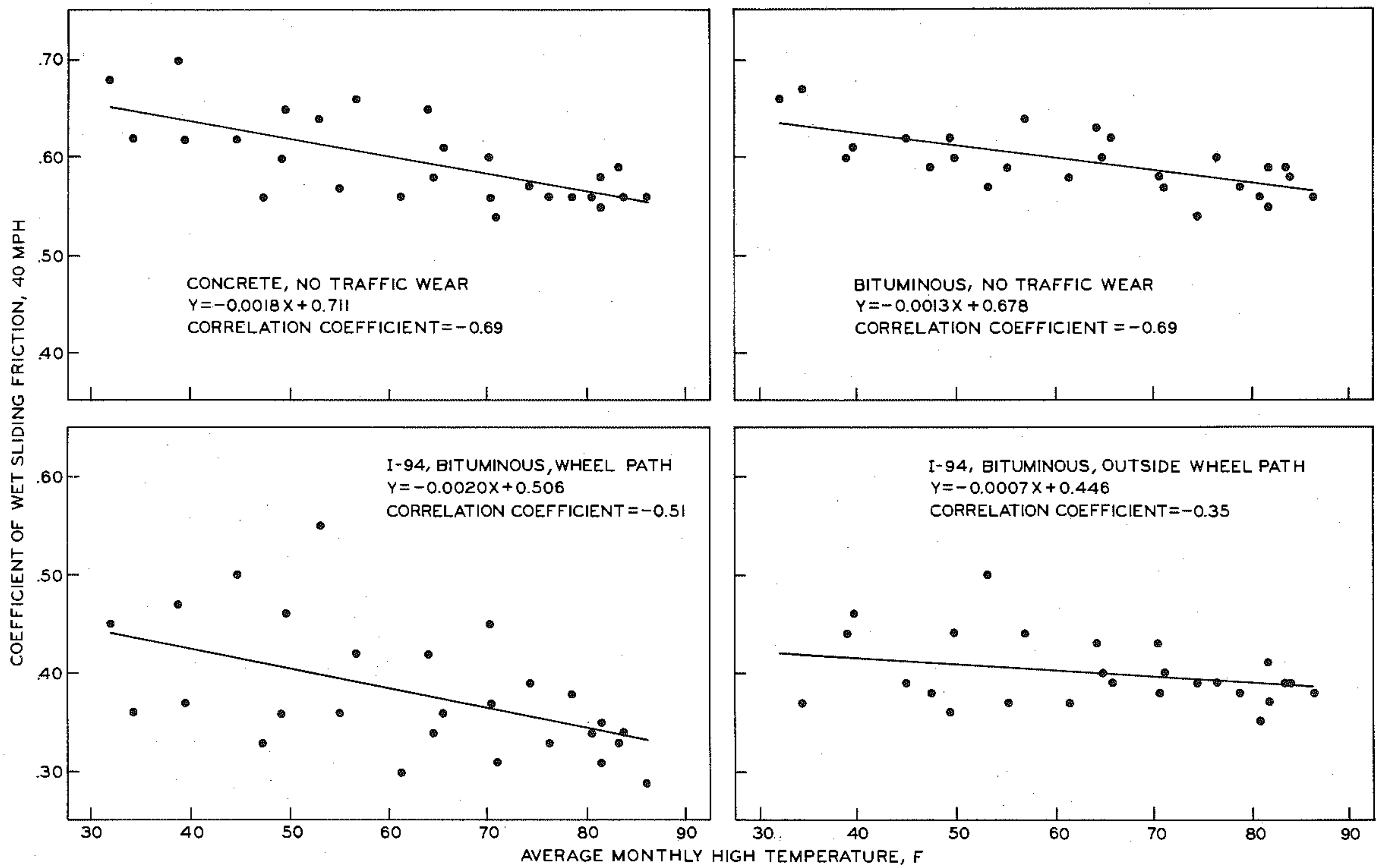


Figure 14. Relationships between average monthly temperature and average monthly coefficient of wet sliding friction.

higher temperature than hysteresis but the steeper curves for wheelpaths indicated just the opposite effect. Therefore, it appears that our study of temperature effects was masked by other seasonal factors.

Seasonal Variations in Friction Measurements

In 1931, it was discovered in Great Britain (7) that wet skid test results varied markedly with seasons of the year. The effect of such variations on driving safety was later pointed out by Giles and Sabey (8) who showed that there was a relationship between season and the ratio of wet to dry surface accidents. Even though summer months were driest, that was the season when the largest proportion of wet skidding accidents occurred; there were only about one-third as many accidents during the wetter winter months. They discussed seasonal variations in wet pavement friction as a factor in accident frequency but did not examine seasonal differences in vehicle miles driven. Therefore, the effects of frictional variations due to season and traffic intensity could not be separated with data given in their report. Temperature was probably another factor influencing seasonal pavement friction during the study.

Investigating the causes of seasonal changes in wet pavement friction led Giles and Sabey to microscopically examine samples of individual stones taken from pavements. They found that in summer, the aggregate appeared more polished than in winter. Further, when slid over blocks of rubber, pavement stones taken in winter showed greater friction than those taken in summer.

At least a portion of the winter increase in pavement friction can be attributed to increased exposure of surfaces to water. MacLean and Shergold (9) found that disintegrated loose material on the pavement became coarser during wet weather and, in conjunction with traffic, increased surface roughness. Giles and Sabey increased the texture of stones by merely soaking them.

A second factor increasing pavement friction is frost-induced fracture along cleavage planes (10). This weathering appears to be accelerated by traffic action and photomicrographs indicate that roughening of surface stones begins with the first frosts of fall.

A third factor which increases friction in winter is simply the reduced temperature of the test tire.

Prior to beginning the study described in this report, the Research Laboratory, as a rough check on its workhorse tester, has seasonally monitored wet friction on a few pavements. Additional pavement sites were seasonally tested as a part of this study, with a total of 14 pavement sites being used. Scatter diagrams of the variation, with months, of average coefficients of wet sliding friction are shown in Figure 15. Each point on the scatter diagram represents an average of multiple tests made during a given month in a single year. The data were adjusted to eliminate annual or long-term changes in friction. In a few cases, data points are scattered erratically but at the majority of sites, coefficients averaged lower during summer and fall than in winter and spring. The scatter of points, though, strongly shows the danger of assigning friction values to a pavement based on a set of tests taken at any one time.

Using data of Figure 15, months were ranked, in order of increasing friction values, first across all years at individual sites and then by averaging ranks across all sites; Table 4 summarizes rankings. Overall rankings, with low ranking months having lowest friction values, are as follows:

Rank	Month
1 (lowest friction)	October
2	September
3	July
4	June
5	November
6	August
7	May
8	December
9	February } tied
10	April } tied
11	March
12 (highest friction)	January

As expected, friction measurements made during summer and fall are lower than those made during late winter and early spring; lowest friction values were measured in October.

A summary of ranges of coefficients of wet sliding friction values measured during several years at each site is presented in Table 5. Each value in the table represents the difference between the lowest and highest average monthly value for the year designated. Since all but four sites were

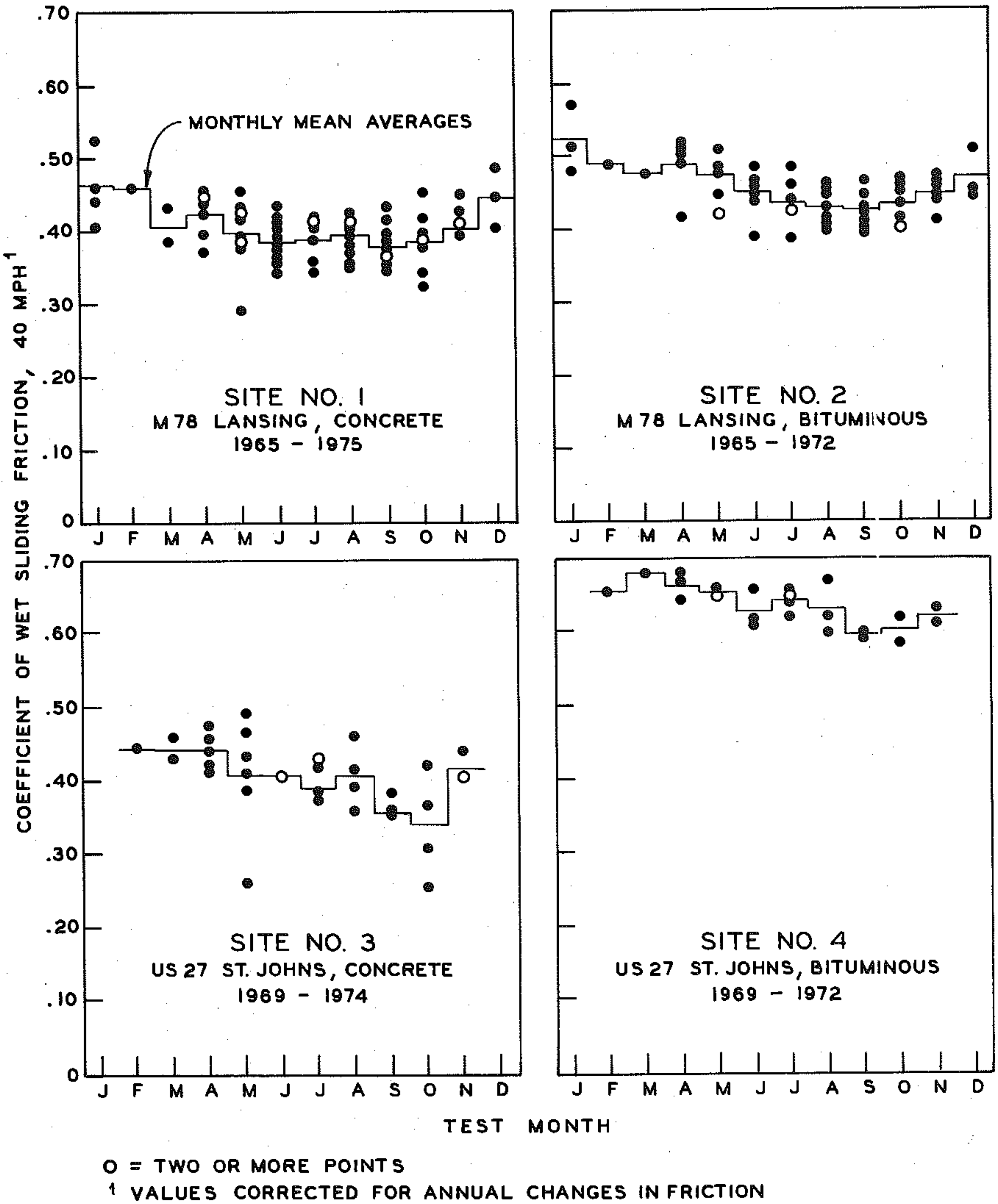
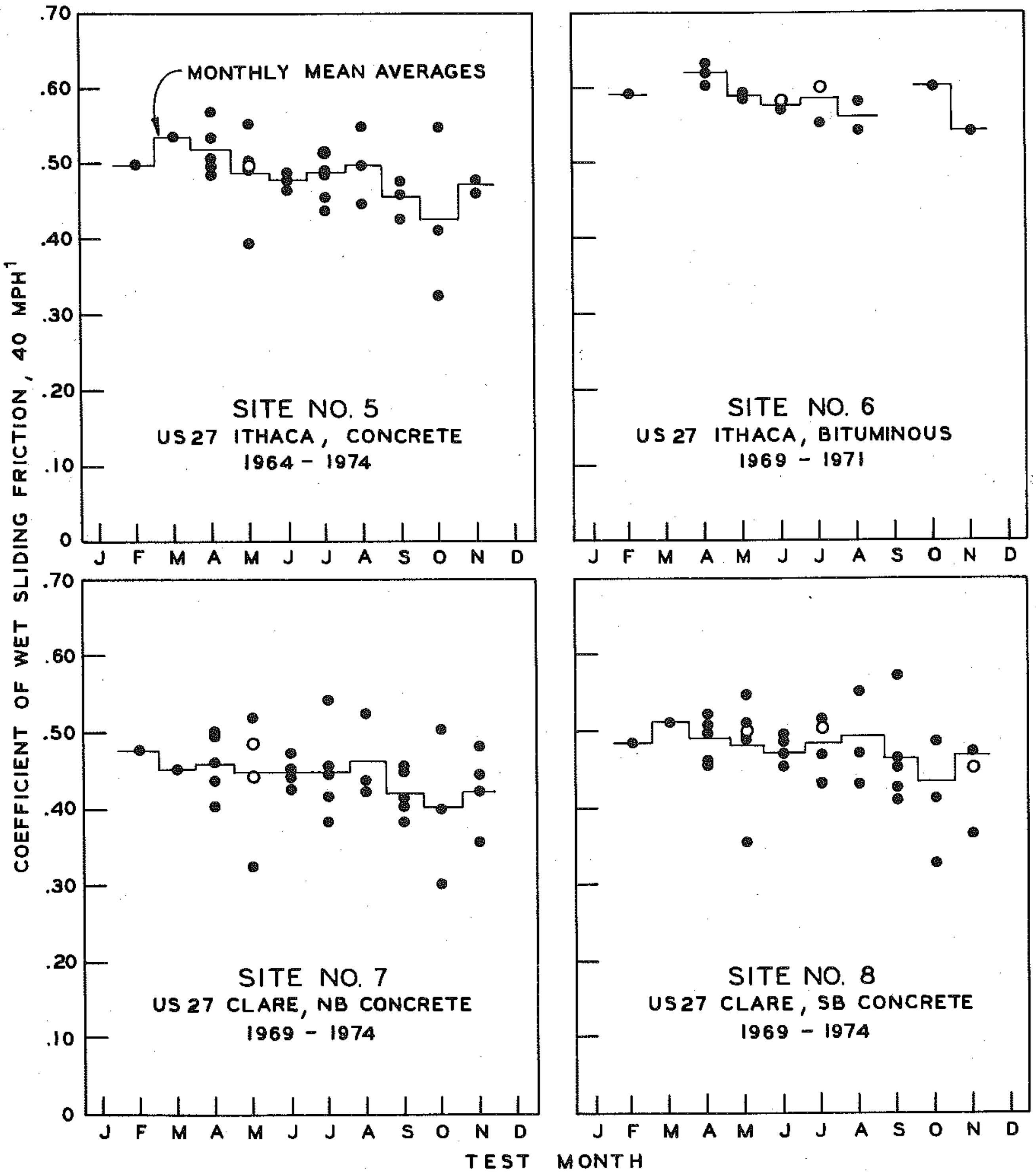


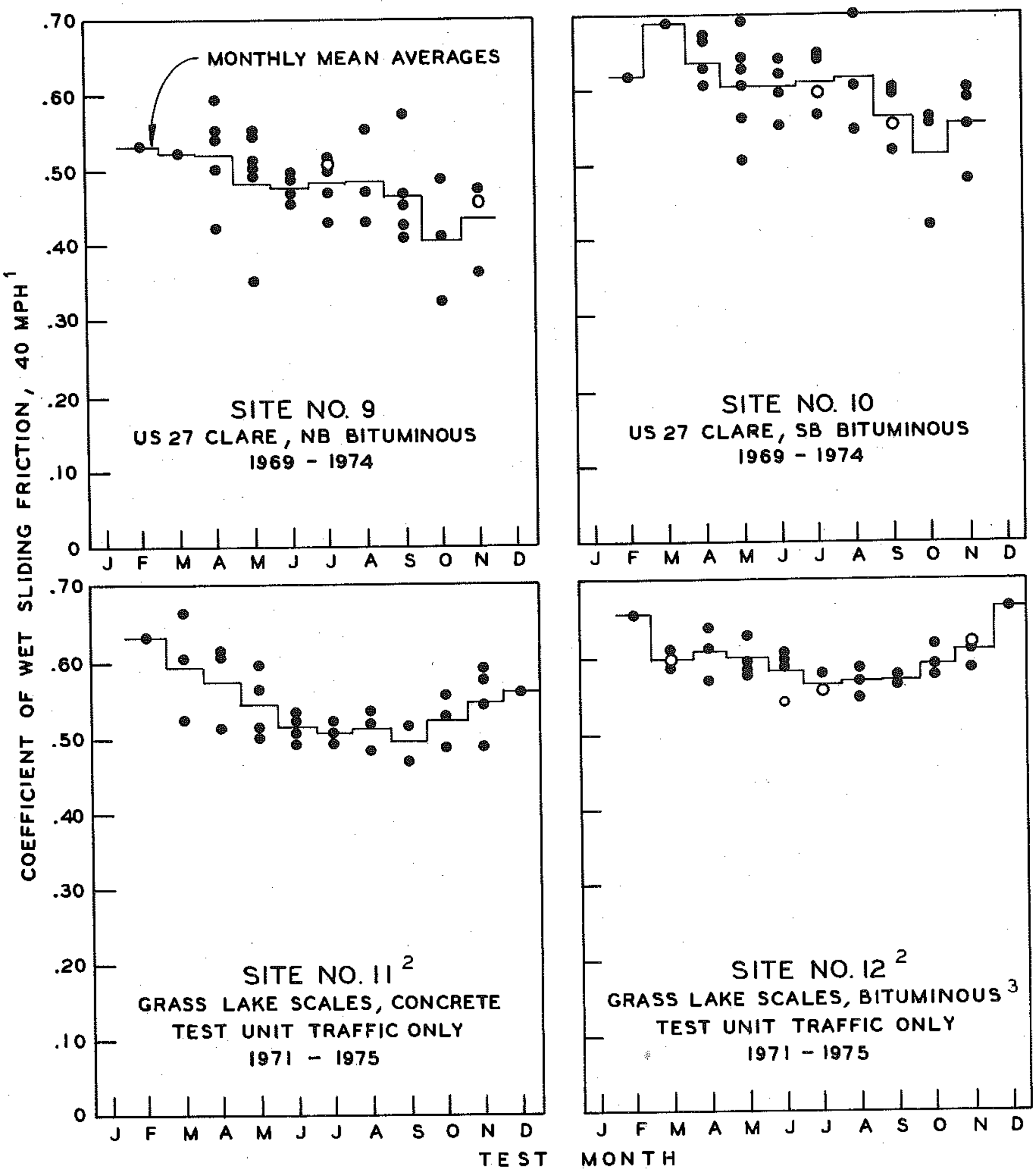
Figure 15. Variation of friction with months.



O = TWO OR MORE POINTS

1 VALUES CORRECTED FOR ANNUAL CHANGES IN FRICTION

Figure 15 (Cont.). Variation of friction with months.



O = TWO OR MORE POINTS
1 VALUES CORRECTED FOR ANNUAL CHANGES IN FRICTION
2 LAW TESTER UNIT
3 SAME SURFACE FOR SITES 12, 13, AND 14

Figure 15 (Cont.). Variation of friction with months.

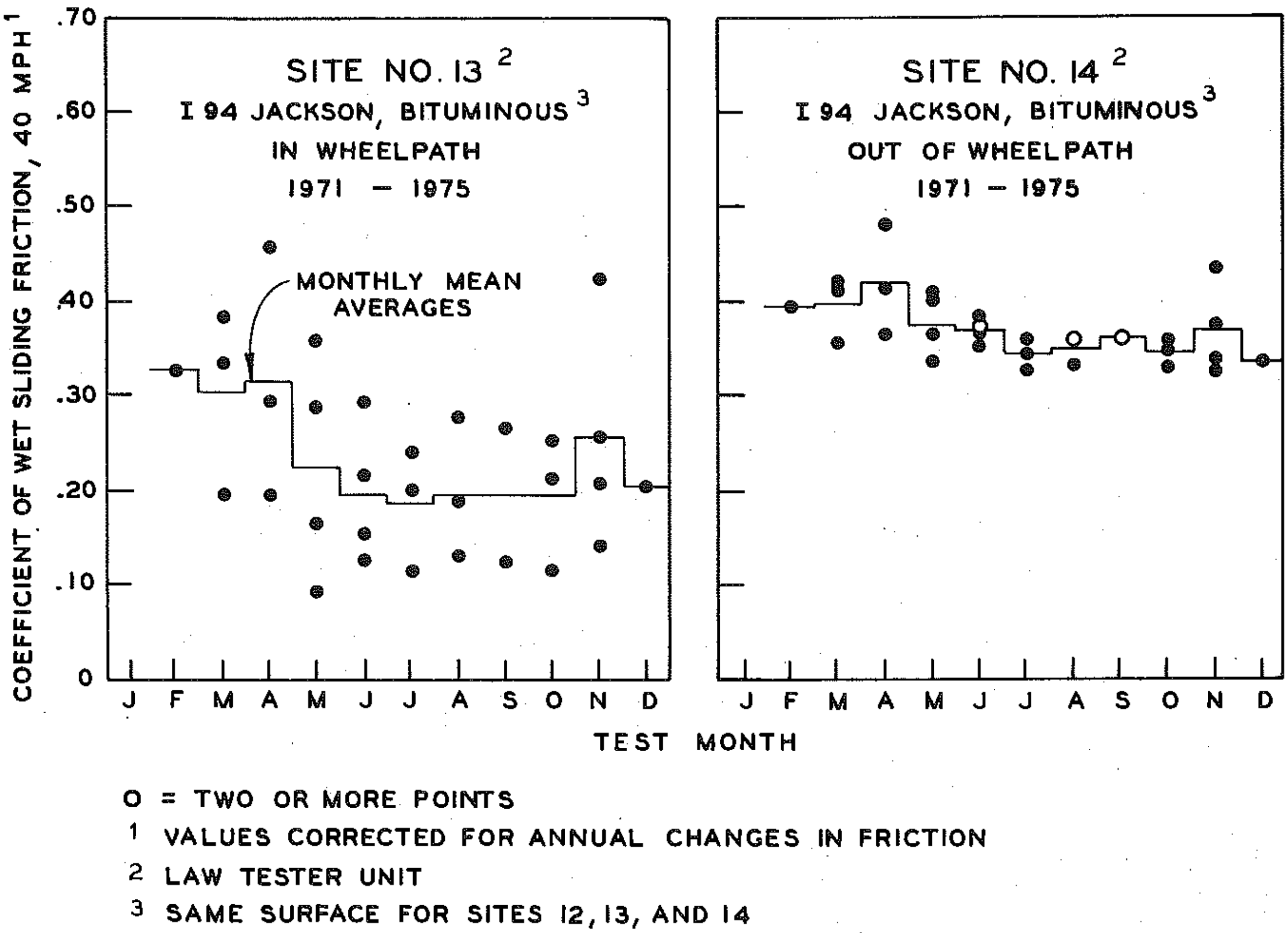


Figure 15 (Cont.). Variation of friction with months.

TABLE 4
RANKINGS AT INDIVIDUAL SITES OF AVERAGE
WET SLIDING COEFFICIENTS OF FRICTION (40 mph)

Site No.*	Month												Test Period	
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	From	To
1	11.5	11.5	7.5	9	6	4.5	2	4.5	2	2	7.5	10	1/65	6/75
2	10	11.5	7	9	8	6	2.5	2.5	2.5	2.5	5	11.5	1/65	9/72
2A	9	--	7	8	4.5	3	---	4.5	2	1	6	--	11/72	6/75
3	--	8	9.5	9.5	5.5	4	3	5.5	2	1	7	--	4/69	6/75
4	--	6	10	8.5	8.5	4	6	6	1.5	1.5	3	--	4/69	9/72
4A	--	--	6	7	3.5	---	2	---	3.5	1	5	--	11/72	6/75
5	--	7.5	10	9	6	4	4	7.5	2	1	4	--	4/69	6/75
6	--	6	---	8	4	4	4	2	---	7	1	--	4/69	8/71
6A	--	--	8	6	5	---	3.5	7	3.5	1	2	--	11/71	6/75
7	--	8.5	10	6.5	6.5	4.5	4.5	8.5	2	1	3	--	4/69	6/75
8	--	4.5	10	7	7	2.5	7	9	4.5	1	2.5	--	4/69	6/75
9	--	8.5	10	8.5	6	4	6	6	3	1	2	--	4/69	6/75
10	--	7	10	9	4.5	4.5	7	7	3	1	2	--	4/69	6/75
11	--	11	10	9	6.5	4.5	2	3	1	4.5	6.5	8	11/71	6/75
12	--	10	6.5	8.5	6.5	4	1.5	1.5	4	4	8.5	11	11/71	6/75
13	--	10	9	11	7	5	1	3	3	3	8	6	11/71	6/75
14	--	9	10	11	8	6.5	1.5	3.5	5	3.5	6.5	1.5	11/71	6/75
No. of Cells	3	14	16	17	17	15	16	16	16	17	17	6		
Average Monthly Rank	10.2	8.5	8.9	8.5	6.1	4.3	3.6	5.1	2.8	2.2	4.7	8.0		
Rank	12	9.5	11	9.5	7	4	3	6	2	1	5	8	1/65	6/75

* Locations are indicated on Figure 15.

TABLE 5

ANNUAL DIFFERENCES BETWEEN AVERAGE MONTHLY HIGH FRICTION AND AVERAGE MONTHLY LOW FRICTION (40 mph) FOR INDIVIDUAL TEST SITES

Workhorse Tester

Test Site	Test Year 1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
1	0.07	0.07	0.01[1]	0.06	0.06	0.14	0.06	0.05	0.20	0.14	0.08
2	0.07	0.08	0.03	0.07	0.07	0.16	0.08	0.06	--	--	--
2A	--	--	--	--	--	--	--	--	0.28	0.16	0.09
3	--	--	--	--	0.08	0.07	0.08	0.11	0.22	0.17	0.06
4	--	--	--	--	0.09	0.06	0.06	0.07	--	--	--
4A	--	--	--	--	--	--	--	--	0.31[2]	0.17	0.07
5	--	--	--	--	0.03	0.10	0.07	0.09	0.24	0.14	0.04
6	--	--	--	--	0.08	0.06	0.06	--	--	--	--
6A	--	--	--	--	--	--	--	0.12	0.24	0.19	0.07
7	--	--	--	--	0.14	0.09	0.08	0.08	0.16	0.13	0.06
8	--	--	--	--	0.12	0.06	0.08	0.08	0.16	0.12	0.03
9	--	--	--	--	0.11	0.10	0.14	0.10	0.22	0.17	0.08
10	--	--	--	--	0.10	0.07	0.11	0.10	0.25	0.18	0.13

[1] Only tested during months 8, 9, 10 and 11 this year.
[2] Initial full service year of 1972 bituminous surface.

Grand Average Range = 0.11
Standard Deviation = 0.06

tested with the workhorse unit, only data from that tester are listed. For some reason, possibly the effects of severe freeze-thaw and precipitation quantities, all sites experienced the widest variation in friction during 1973.

A summary of ranges of average monthly wet coefficients combined for all sites, is shown in Table 6. The table shows that, at one site, wet coefficient of friction values varied up to 0.31 within a single year. Since, within any year, ranges of friction values vary between sites, some error would be involved if a single factor were used to correct test values to a standard month. Even at a given site, ranges vary between years.

What can be done, with the current state of technology, to ensure that friction values at a site are representative of existing conditions? If a

TABLE 6
SUMMARY FOR TEST SITES 1 THROUGH 10
OF RANGES OF AVERAGE MONTHLY
COEFFICIENTS OF WET SLIDING FRICTION

Test Year	Number of Sites	Lowest Range at a Site	Highest Range at a Site	Average for All Sites	Standard Deviation
65	2	0.07	0.07	0.07	--
66	2	0.07	0.08	0.08	--
67	2	0.01	0.03	0.02	--
68	2	0.06	0.07	0.06	--
69	10	0.03	0.14	0.09	0.03
70	10	0.06	0.16	0.09	0.04
71	10	0.06	0.14	0.08	0.03
72	10	0.05	0.12	0.09	0.02
73	10	0.16	0.31	0.23	0.05
74	10	0.12	0.19	0.16	0.02
75	10	0.03	0.13	0.07	0.03

knowledge of the lowest annual friction were desired, testing should be confined to June through November. If, because of some urgency, testing had to be done during December through May, about 0.11 (the grand average range of the data shown in Table 5) should be subtracted from measured values.

DISCUSSION

If anything, the investigation described in this report has emphasized that measurements of wet pavement friction can vary depending upon when and how they are made. Therefore, to be relevant, measurements should be made under conditions which represent those most critical to the problem.

Since some states have no law requiring minimum tread depths or where only 2/32 in. tread depth--which is little better than no tread--is required, vehicles with smooth tires are bound to be an existing condition. Under such a condition, there will be vehicles traveling on the highways that, on wet pavements, require an average of 50 percent more and may take over 150 percent more distance to stop than similar vehicles equipped with treaded tires. Therefore, in analyzing a wet pavement accident problem, smooth tire friction tests provide valuable information. Such tests are also useful in evaluating pavement textures.

It would be impossible to provide all pavement surfaces with textures which would ensure smooth tire friction levels currently considered minimal for treaded tires. However, smooth tire friction tests are relevant because they describe realistic conditions.

In the past, much pavement friction testing has been conducted at a uniform speed of 40 mph. However, with most pavement surfaces wet friction decreases with increasing speed. Therefore, to be relevant, tests should be made at operating traffic speed. If that is impractical, friction values representative of traffic speed conditions may be accurately estimated from low speed test data using a method described in this report.

Vehicle speed is even more important than pavement friction in wet weather stopping. This is because stopping distance is inversely proportional to friction coefficient but varies with the square of velocity. During this study, it was found that for pavements having wet coefficients of friction ranging from 0.32 to 0.71, computed stopping distances from identical speeds varied by a factor of about 2.5. However, for those same surfaces, when speed was varied from 20 to 70 mph, stopping distances varied by a factor of about 25. This suggests that whenever wet accidents are a problem, reduced wet weather speeds would probably produce dramatic results. Of course, in many cases, it would be difficult to induce drivers to reduce wet weather speeds. If the trend continues toward increasing numbers of damage suits against public agencies, however, reduced wet weather speed limits might provide a defense.

In this investigation, temperature effects could not be separated from seasonal effects on pavement friction measurements. The reason was primarily because all tests were made in the field under relatively uncontrolled conditions, but it appears that seasonal effects are more influential than temperature effects. Thus, to test a pavement in its worst condition, the condition most likely to cause wet skid problems, measurements should be made from June to early November.

CONCLUSIONS

1) Stopping distances on wet Michigan highways for a vehicle with smooth tires average 50 percent greater and may be over 150 percent greater than a vehicle with treaded tires. This is a strong argument for prohibiting smooth tires.

2) Friction tests made with smooth tires provide a valuable tool for evaluating pavement textures. Certain texture configurations which have similar friction under treaded tires are very different under smooth tires.

3) Friction values for a given test speed may be reliably estimated from values measured at lower speeds.

4) Seasonal variations in wet coefficient of friction values are significant, averaging 0.11 and varying up to at least 0.31.

5) In realistically evaluating a wet skid area, consideration should be given to the fact that pavement friction can easily cause stopping distances to vary by a factor of 2.5. Over these same pavement surfaces, changing speeds from 20 to 70 mph, varied stopping distances by a factor of 25. Thus, speed reduction in wet weather should be considered a superior alternative for rectifying the problem of wet skidding accidents.

6) Even though the MDSHT workhorse and K. J. Law testers yield different friction values for any surface, the correlation between the two units is so good that very small error is involved in transforming test values to a common standard.

7) Repeatability of the testing units is very good; average standard deviation, in terms of coefficients of friction at 40 mph, for the workhorse is 0.019 and for the Law unit is 0.0133.

8) In correcting temperature effects on tire-pavement friction, factors used for coarse textured surfaces must be different than for smooth textured surfaces.

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APPENDIX

CORRELATION OF MICHIGAN WORKHORSE AND K. J. LAW PAVEMENT FRICTION TESTING UNITS

I - A simple linear regression was performed on the test data where:

y = K. J. Law machine wsf coefficient reading
x = workhorse machine wsf coefficient reading
} superscripts indicate test speeds

Statistical models considered ($i = 1, 2, \ldots, 63$)

$$y_i^{20} = B_0^{20} + B_1^{20} x_i + E_i$$
$$y_i^{40} = B_0^{40} + B_1^{40} x_i + E_i$$
} K. J. Law in terms of workhorse unit

$$x_i^{20} = A_0^{20} + A_1^{20} y_i + E_i$$
$$x_i^{40} = A_0^{40} + A_1^{40} y_i + E_i$$
} workhorse in terms of K. J. Law unit

The E_i were assumed identically distributed $N(O, \sigma_i^2)$, σ_i^2 possibly different for each of the four basic models above but constant within each model.

Within each model, the E_i's are independent. The E_i's represent experimental error. The resulting estimates were:

$$Y_i^{20} = -0.0526 + 0.8838X_i$$

$$Y_i^{40} = -0.0230 + 0.8356X_i$$

$$X_i^{20} = 0.0694 + 1.1126Y_i$$

$$X_i^{40} = 0.0348 + 1.1783Y_i$$

Estimate of p, the Pearson product moment correlation coefficient is 0.9915 in the 20 mph case and 0.9924 in the 40 mph case. The coefficient of determination is thus 0.98 for both the 20 and 40 mph correlation.

Assumptions:

The regression estimates should differ for different speeds.

The regression estimates should not distinguish between bituminous and concrete surfaces or between high, low, and medium wsf coefficients.

There is no simple relationship between the least squares estimator for Y in terms of X and X in terms of Y since in each case different errors are being minimized. The values given are least squares estimators and as such, minimize the appropriate experimental error.

II - Confidence Intervals (CI) for estimates (95 percent CI were calculated)

$\hat{B}_0{}^{20} = \left[-.0526 \pm .0204\right]$ $\hat{B}_1{}^{20} = \left[.8838 \pm .0298\right]$

$\hat{B}_0{}^{40} = \left[-.0230 \pm .0214\right]$ $\hat{B}_1{}^{40} = \left[.8356 \pm .0282\right]$

$\hat{A}_0{}^{20} = \left[.0694 \pm .0190\right]$ $\hat{A}_1{}^{20} = \left[1.1126 \pm .0372\right]$

$\hat{A}_0{}^{40} = \left[.0348 \pm .0158\right]$ $\hat{A}_1{}^{40} = \left[1.1783 \pm .0366\right]$

III - Test of hypothesis that regression lines were the same for 20 and 40 mph in the $Y_i = B_0 + B_1 X_i + E_i$ case. That is, that two instruments could be correlated without regard to speed at which wsf was measured.

Result: hypothesis is rejected for $\alpha > 0.25$.

$F = 1.294$

$F_{.75} = 1.4$ $F_{.5} = 0.65$

IV - 'Repeatability'

A measure was desired of each instrument's tendency to give different wsf values for repeated tests on the same test section under identical conditions. This may be expressed in terms of variance, large variance where repeatability is poor, small variance where repeatability is good.

$$\mathrm{Var}(X_{jklmn}) = \frac{1}{3-1} \sum (X_{ijklmn} - \overline{X}_{\cdot jklmn})^2$$

X_{ijklmn} = i^{th} test reading, test section j, pavement type k, coefficient level, instrument m, speed n.

$\overline{X}_{\cdot jklmn}$ = mean value of the three test readings for jklmn.

Var (X_{jklmn}) was calculated for each test section under each set of conditions. Average variances were calculated for each instrument at each speed over pavement types, coefficient levels, and overall to investigate average repeatability under various conditions.

$$\text{Avg var overall} = \frac{1}{42} \sum_l \sum_k \sum_j (X_{ijklmn} - \bar{X}_{\bullet jklmn})^2$$

$$\text{Avg var (bit.)} = \frac{1}{18} \sum_l \sum_j (X_{ij\text{ bit } lmn} - \bar{X}_{\bullet j\text{ bit } lmn})^2$$

$$\text{Avg var (conc.)} = \frac{1}{24} \sum_k \sum_j (X_{ij\text{ conc } lmn} - \bar{X}_{\bullet j\text{ conc } lmn})^2$$

$$\text{Avg var } (\mu_l) = \frac{1}{12} \sum_k \sum_j (X_{ijklm} - \bar{X}_{\bullet jklmn})^2 \quad \text{for } l = \text{high, medium, low}$$

$$= \frac{1}{6} \sum_k \sum_j (X_{ijklmn} - \bar{X}_{\bullet jklmn})^2 \quad \text{for } l = \text{extra}$$

Results:

Average Variances and Standard Deviations	20 mph		40 mph	
	Workhorse Skid Test Unit	Law Skid Test Unit	Workhorse Skid Test Unit	Law Skid Test Unit
average variance (all cond)	0.000480	0.000209	0.000373	0.000178
standard deviation	0.0219	0.0145	0.0193	0.0133
average variance (bit)	0.000650	0.000177	0.000288	0.000094
standard deviation	0.0255	0.0133	0.0170	0.0097
average variance (conc)	0.000354	0.000233	0.000437	0.000241
standard deviation	0.0188	0.0153	0.0209	0.0155
average variance (high)	0.000200	0.000066	0.000191	0.000166
standard deviation	0.0141	0.0081	0.0138	0.0129
average variance (med)	0.000583	0.000225	0.000250	0.000108
standard deviation	0.0241	0.0150	0.0158	0.0104
average variance (low)	0.000700	0.000183	0.000491	0.000066
standard deviation	0.0265	0.0135	0.0222	0.0981
average variance (extra)	0.000333	0.000483	0.000733	0.000566
standard deviation	0.0182	0.0220	0.0271	0.0238

Confidence Interval (CI), 95 percent

Computations for predicting an individual value on one skid unit given a value on the other (95 percent confidence intervals).

Prediction of K. J. Law from workhorse at 20 mph:

$$CI = -.0526 + .8838X \pm \left\{ .0006 \left[\frac{64}{63} + \frac{(X - .6521)^2}{2.7038} \right] \right\}^{\frac{1}{2}} (2.00)$$

Prediction of K. J. Law from workhorse at 40 mph:

$$CI = -.0230 + .8356X \pm (2.00) \left\{ .0005 \left[\frac{64}{63} + \frac{(X - .4994)^2}{2.5286} \right] \right\}^{\frac{1}{2}}$$

Prediction of workhorse from K. J. Law at 20 mph:

$$CI = .0694 + 1.1126Y \pm (2.00) \left\{ .0007 \left[\frac{64}{63} + \frac{(Y - .5237)^2}{2.1477} \right] \right\}^{\frac{1}{2}}$$

Prediction of workhorse from K. J. Law at 40 mph

$$CI = .0348 + 1.1783Y \pm (2.00) \left\{ .0006 \left[\frac{64}{63} + \frac{(Y - .3943)^2}{1.7931} \right] \right\}^{\frac{1}{2}}$$