COMPARISON OF HIGHWAY PAVEMENT FRICTION MEASUREMENTS TAKEN IN THE CORNERING-SLIP AND SKID MODES

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Friction tests using smooth and treaded tires with 10- and 24-psi tire-inflation pressures on wet and dry surfaces were taken with a Mu-meter and the Texas Highway Department research skid trailer. Fifteen pavement surfaces that exhibited widely different friction levels, friction-velocity gradients, drainage capabilities, mineralogical properties, and texture classifications were investigated. Pavement macrotexture tests were conducted by volumetric and mechanical roughness detector methods. Comparisons and relationships between various friction parameters as obtained with both instruments were made. Statistical analyses and typical plots are given. Friction tests obtained with both instruments compared favorably, provided similar tire tread configurations were used. On an average, slightly higher friction forces were available in the slip mode of operation (measured by Mu-meter) than in the skid mode (measured by skid trailer). The importance of providing adequate drainage in the tire-pavement contact area is stressed. Tests made with smooth and treaded tires in both the slip and skid mode emphasized the importance of pavement surface macrotexture at speeds of 40 mph or more.

•FRICTION measurements of tire-pavement interaction are considered highly acceptable for evaluating the skid-resistant properties of pavement surfaces and are essential to the determination of what occurs at the tire-pavement interface under different environmental conditions. Research by numerous investigators has shown that experimental studies under actual field conditions are a necessary supplement to theoretical analyses and laboratory investigations. For this reason, the work reported in this study was field-oriented.

Skid resistance is often reported as a friction coefficient, or as the ratio of the friction force (drag) to the load of the bodies sliding over each other. More recent practice is to multiply the friction coefficient by 100, report the value as a whole number, and call it a skid number. A skid number is valid for specific conditions only, that is, for the tester and pavement combination and the environmental operational conditions present. Similar reasoning may be applied to the cornering-slip mode.

Attempts have been made to characterize the skid-resistant properties of pavement surfaces in a qualitative manner such as surface macrotexture, drainage characteristics of the road surface, and aggregate size, shape, microtexture, and mineralogy. The majority of these are not convenient survey measures nor has the relative magnitude of their influences been universally accepted; thus, characterizations at present are mainly dependent on implicit information from friction tests.

The principal causes of pavement slipperiness are (a) the presence in the tire-pavement contact area of water that, with increasing vehicle speeds, lowers the obtainable frictional drag and raises the frictional demand and (b) higher traffic volumes

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that, through pavement wear and aggregate polish, drastically reduce built-in friction potential of most new pavement surface types.

Many parameters affect the interactions at the tire-pavement interface. The principal ones are (a) mode of operation, (b) pavement surface characteristics, mainly macroscopic and microscopic roughness and drainage capability, (c) water-film thickness at the interface, (d) tire-tread depth and elastic and damping properties of the tire rubber, and (e) vehicle speed. Thus, if friction coefficients are to be meaningful for evaluation or comparison purposes, the foregoing factors must be given consideration. Standardization of certain friction testing procedures and equipment can naturally reduce the number of variables used in survey work. Ideally, pavement surface type would remain as the only variable and, for the test mode used, differences in friction values could be attributed to this factor.

The American Society for Testing and Materials Committee E-17 has contributed greatly to the standardization of friction testing methods. One tentative and one standard method have been sponsored and approved by ASTM Committee E-17 and accepted by the Society—ASTM Designation E 274-65T (Skid Resistance of Pavements Using a Two-Wheel Trailer) and ASTM Designation E 303-66 (Measuring Surface Frictional Properties Using the British Portable Tester) respectively. In addition, ASTM Designation E 249-66 (Standard Tire for Pavement Tests) has been adopted as a standard.

For research purposes it is desirable to use more than one type of measuring mechanism. This provides information concerning the relative slipperiness of given pavement surface types under different modes and, in addition, with judicious use of other factors, friction properties of certain pavement surface types can be better evaluated under different operating conditions.

Experiments have shown that different friction levels must be expected for variable, but normal, operating modes of a tire, i.e., rolling and slipping during braking, driving, and cornering (1, 2, 3). Skidding is not a normal operating mode because the vehicle is essentially out of control when this condition exists. It has been determined from theory and experiments that the friction developed between a pavement surface and a tire operating under slip depends, for the most part, on the quantity of slip and that maximum friction occurs at about 10 to 20 percent slip (4). Primarily slip resistance has been found to reflect the adhesion properties and skid resistance, the hysteresis properties of a given tire-pavement matching (4). The question as to whether skid or slip is the better mode for evaluating potential slipperiness of pavement surfaces has been discussed by Meyer and others (4, 5). They have stated the following:

> It is arguable that skid resistance is more significant from the safety standpoint than slip resistance, on the grounds that it is most important that a vehicle come to the quickest possible stop once it is out of control. On the other hand, one can take the stand that the critical slip resistance is more important because it defines the point up to which the vehicle will remain under control.

It might also be added that the most effective braking occurs during the slip mode. In total lockup, frictional drag is significantly reduced compared to the drag for the 15 to 20 percent slip mode.

The purpose of this paper, however, is not to question which mode is the better or to discuss the mechanics and mechanisms of the two modes but, rather, to present data obtained with both modes and on various types of surfaces under stated conditions. Data comparisons are given with due regard for test variables. Properties of the pavement surfaces that are reflected in the test results are discussed.

CLASSIFICATION OF SURFACES TESTED

Previous research has indicated that pavement surfaces of a given type, i.e., asphalt concrete, portland cement concrete, and surface treatments, vary tremendously in skid-resistant properties. This variation is primarily a function of the type of aggregate contained in the particular surface. It is conceivable that aggregate type affects, to a similar degree, cornering-slip-resistant properties. Thus, it was decided that, to adequately investigate and compare cornering-slip- and skid-resistant charac-

teristics, measurements would have to be made and analyzed for several types of pavement surfaces.

The term surface as used in this paper is defined as a section of pavement on which the wearing course is essentially identical over the entire length under study. Fifteen pavement surfaces were tested: (a) 9 hot-mix asphalt concretes, (b) 2 portland cement concretes, (c) 3 chip-sealed surface treatments, and (d) 1 flushed seal. Surfaces were chosen so as to exhibit widely different friction levels, friction-velocity gradients, drainage capabilities, mineralogical properties, and textural classifications. The surfaces were classified as to the mineralogy, size, and shape of the coarse aggregate they contained. This information is given in Table 1.

EQUIPMENT USED FOR FRICTION TESTS

The Soiltest ML-400 Mu-meter friction recorder and the Texas Highway Department research skid trailer were used to measure cornering and skid-resistance respectively (Figs. 1 and 2).

Mu-Meter

This instrument is a continuously recording, friction-measuring trailer that determines the frictional characteristics of treadless tires operating in the cornering-slip mode (12, 17, 18, 19). It measures the cornering force generated between the test surface and the pneumatic tires on two running wheels that are set at a fixed 7½-deg toe-out (yaw) angle to the line of drag.

In operation, friction produced as the running wheels are moved forward over the surface is sensed by a load cell. The resulting hydraulic pressure is transmitted

TABLE 1

DESCRIPTION OF THE FIFTEEN SURFACES

Surface Number	Route	County	Surface Type	Aggregate		1968 Average Daily Traffic	Construction Date
				Type	Size[a]		
3	Texas-6	Brazos	Hot mix	Lignite boiler slag	3/16	4,200	1965
4	Texas-6	Robertson and Falls	Hot mix	Rounded river gravel	5/8	1,420	1968
11	Texas-14	Limestone	Hot mix	Crushed river gravel	1/2	3,655	1967
13	US-84	Freestone	Hot mix	Crushed sandstone	3/8	1,310	1965
17	Farm-1687	Brazos	Hot mix	Open-graded lightweight	3/8	700	1968
18	Farm-1687	Brazos	Hot mix	Open-graded lightweight	5/8	700	1968
22	Texas-14	Limestone	Portland cement concrete	Rounded river gravel	1½	920	1936
28	Farm-2038	Brazos	Surface treatment	Rounded river gravel	5/8	135	1968
31	Texas-30	Grimes	Surface treatment	Crushed limestone	3/8	820	1968
33	Farm-416	Navarro	Surface treatment	Lightweight	1/2	100	1964
T-1	Texas A&M	Brazos	Hot mix	Rounded river gravel	5/8	None	1968
T-2	Texas A&M	Brazos	Hot mix	Crushed river gravel	1/4	None	1968
T-3	Texas A&M	Brazos	Hot mix, Terrazzo finish	Crushed limestone	1/2	None	1968
T-4	Texas A&M	Brazos	Clay-filled tar emulsion (Jennite) seal			None	1968
T-5	Texas A&M	Brazos	Portland cement concrete	Rounded river gravel	1½	None	1953

[a]All aggregates top size.

Figure 1. Mu-meter friction trailer.

Figure 2. Texas Highway Department research skid trailer.

through a flexible line to the recorder's Bourdon tube and indicating mechanism. The recorder stylus makes a trace on the moving pressure-sensitive chart paper. A third wheel serves, in effect, as a recorder drive mechanism. Split-rim wheels are used, and the tires are pneumatic, 6-ply, size 4.00 × 16 with smooth treads. Under normal operating conditions, 10- and 30-psi tire pressures are used in the running and recording wheels respectively. Friction values are read directly from the chart paper, multiplied by 100, and reported as cornering-slip numbers at the corresponding test velocity. Gradient (or slope) of the cornering-slip number-velocity curve is then calculated (the numerical difference of the cornering-slip numbers at 20 and 60 mph divided by the velocity difference of 40 mph).

$$\text{Gradient} = (SN_{20} - SN_{60})/40$$

The percentage of decrease in friction between 20 and 60 mph, termed percentage of gradient, was calculated. This takes into account the fact that the absolute decrease in cornering-slip number above 20 mph will be influenced to some extent by the cornering-slip number at that velocity. A curve of a given gradient positioned low on the friction-velocity graph would have a higher percentage of gradient than would a curve with the same gradient positioned high on the graph. If a surface has low friction at 20 mph, the decrease at higher velocities cannot be large. Thus, percentage of gradient is defined as the percentage of the gradient (obtained under test conditions) to a theoretical gradient if the cornering slip number at 60 mph were zero.

$$\text{Percentage of gradient} = \{[(SN_{20} - SN_{60})/40]/(SN_{20}-{}^{0}/40)\} \times 100$$
$$= [(SN_{20} - SN_{60})/SN_{20}] \times 100$$

Trailer

This instrument, used by the Texas Highway Department, conforms substantially to requirements of ASTM Designation E 274-65T. It utilizes the E-17 circumferentially grooved, treaded tires inflated to 24 psi. The drag forces are measured with strain gages, and the self-watering system uses a centrifugal pump that applies approximately 0.020-in. water-film thickness to the pavement surface. The development and calibration of the trailer are given elsewhere (9, 20).

Force values were taken from the chart paper, converted to friction coefficient values, multiplied by 100, and reported as skid numbers at the corresponding test velocity. Gradient and percentage of gradient were calculated in the same manner as explained previously except appropriate skid numbers were used.

FRICTION-TESTING PROCEDURES AND CONDITIONS

Documented research indicates that the drainage capability of a given surface, as determined from skid tests, varies considerably with respect to test velocity, water-film thickness, tire-tread depth, and inflation pressure. E-17 circumferentially grooved, treaded tires inflated to 24 psi are normally used at test speeds of 40 mph on pavement surfaces with approximately 0.020 in. of water-film thickness as a basis for reporting and comparing pavement skid resistance. These standard conditions were used in an attempt to better evaluate their relative effects on the cornering-slip and skid modes. In addition, other variations were incorporated into the study to gain a better insight of the overall problem.

Two series of 20-, 40-, 60-, and 80-mph friction tests were conducted with each instrument under different conditions and at four places on each surface. On several surfaces, 80-mph tests were not attempted because of poor roadway geometrics or high traffic densities. Instead, tests at top speeds of less than 80 mph were taken on these surfaces. Reported cornering-slip and skid numbers for a given test method on each surface represent average values for four places tested on that particular surface.

The testing sequence at each place was as follows:

1. A series of 20-, 40-, 60-, and 80-mph tests with the Mu-meter on dry pavement;
2. A series of 20-, 40-, 60-, and 80-mph tests with the trailer on pavement wet by the trailer's self-contained, internal watering system; and
3. A series of 20-, 40-, 60-, and 80-mph tests with the trailer and Mu-meter on pavement wet by a separate water truck.

In the third sequence, the measurements were taken concurrently with the Mu-meter lagging approximately 100 ft behind the trailer at each respective test speed. Measurements were made in the wheelpath with the position of the Mu-meter wheels nearly the same as that of the skid trailer wheels. Comparisons made between the two devices require that careful consideration be given to this factor, particularly if those data being compared came from a highway with high traffic volumes and especially if the pavement surface shows evidence of being worn and polished in the wheelpath.

The trailer watering system was calibrated to supply sufficient water to create a surface film 0.020 in. thick on the pavement. Procedures for wetting with the water truck were planned to ensure an equivalent water-film thickness. This procedure required wetting the pavement at a controlled rate with three passes of the water truck, prior to the 20-mph test. The first two passes were applied merely to cool the pavement to effect a constant evaporation rate and to wet the pavement so that an incipient runoff condition would exist. A third pass was required to obtain the 0.020-in. water-film thickness for the 20-mph test. Prior to the second and each succeeding test at a location, i. e., before the 40-, 60-, and 80-mph tests were made, an additional watering was required to replenish water lost by evaporation, splash, and runoff.

Times between watering and testing were varied from 30 to 90 sec from one surface to another and from day to day to compensate for varying pavement cross slopes, ambient temperatures, wind velocities, and humidities. This was necessary to maintain a constant volume of water on the pavements.

Test equipment and conditions are given in Table 2. The tests were conducted during August and September 1969. Air temperatures were generally in the 80- to 95-deg range, and the rainfall had been abnormally low for approximately 60 days preceding the tests. No seasonal or temperature corrections were applied to the friction numbers.

MACROTEXTURE TESTS

Numerous methods have been employed to directly or indirectly measure pavement surface macrotexture, including the sand patch test, mechanical roughness detectors, the grease smear test, the outflow meter, impression techniques, light reflection, and stereo-photography. The two procedures used in this study, profilograph and putty impression, represent examples of a mechanical roughness (profile) detector and an impression (volumetric) technique respectively. Details of the profilograph method

TABLE 2

TEST EQUIPMENT AND CONDITIONS

Test Condition Number	Equipment	Tires		Surface Condition	Wetting System
		Pressure (psi)	Type		
TC-1	Mu-meter	10	Smooth	Dry	
TC-2	Trailer	24	E-17 circumferentially grooved	Wet	Internal
TC-3	Trailer	24	E-17 circumferentially grooved	Wet	External
TC-4	Mu-meter	10	Smooth	Wet	External
TC-5	Mu-meter	24	Smooth	Dry	
TC-6	Trailer	24	Smooth	Wet	External
TC-7	Mu-meter	24	Smooth	Wet	External

have been reported by Ashkar (8), Gallaway (10, 11), and Rose (6), and details of the putty impression method have been reported by Stephens (7), Gallaway (10, 11), and Rose (6).

An average of five tests were taken at each of the four places friction measurements had been taken previously for a total of 20 per surface (test pavement). Individual test spots at each place were located in the outer wheelpath, spaced approximately 50 ft apart.

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

A tabulation of cornering-slip and skid numbers, friction-velocity gradients, and percentage of gradients are given in Table 3. Macrotexture measures are given in Table 4. Average cornering-slip and skid numbers and average gradients and percentage of gradients are also given in Table 3.

Average friction number-velocity values for the test surfaces are plotted for the seven test conditions and shown in Figure 3. Ten of the surfaces were tested under five different test conditions (Fig. 3b). Data were obtained on an additional five surfaces

TABLE 3

CORNERING-SLIP AND SKID NUMBERS, FRICTION-VELOCITY GRADIENTS, PERCENTAGE OF GRADIENTS,

Surface Number	TC-1					TC-5				TC-4					TC-7	
	SN_{20}	SN_{40}	SN_{60}	Gradient	Percentage of Gradient	SN_{20}	SN_{40}	SN_{60}	Gradient	SN_{20}	SN_{40}	SN_{60}	Gradient	Percentage of Gradient	SN_{20}	SN_{40}
3	83	82	80	0.08	4	72	71	71	0.03	46	29	19	0.68	59	52	28
4	64	64	65	0.00	0					48	33	25	0.57	48		
11	56	56	56	0.00	0					44	32	25	0.47	43		
13	70	69	69	0.03	1	71	70	71	0.00	67	50	40	0.68	40	68	52
17	76	76	75	0.03	1	81	79	77	0.10	67	68	68	0.00	0	73	72
18	77	77	76	0.03	1	79	77	78	0.03	69	71	71	0.00	0	73	73
22	73	73	73	0.00	0					54	38	30	0.60	44		
28	79	80	79	0.00	0					52	53	48	0.10	8	46	42
31	80	78	77	0.08	4					70	55	35	0.88	50		
33	62	61	59	0.08	5					61	59	56	0.13	8		
T-1	69	68	69	0.00	0	67	67	67	0.00	62	47	36	0.65	42		
T-2	72	72	71	0.03	1	69	67	67	0.05	66	62	58	0.20	12		
T-3	68	67	67	0.03	1	67	68	68	0.00	68	42	25	1.07	63		
T-4	67	67	67	0.00	0	69	67	67	0.05	39	19	10	0.73	74	44	20
T-5	73	73	71	0.05	3	76	73	73	0.08	56	38	27	0.73	52	64	50
														Average for Number of		
15	71	71	70	0.03	1					58	46	38	0.50	36		
10	73	73	72	0.03	1					59	48	40	0.48	36		
5	77	77	76			76	74	74		61	54	49			62	53

Note: For the Mu-meter tests, TC-1, TC-5, TC-4, and TC-7, SN = slip number; for the trailer tests, TC-2, TC-3, and TC-6, SN = skid number.

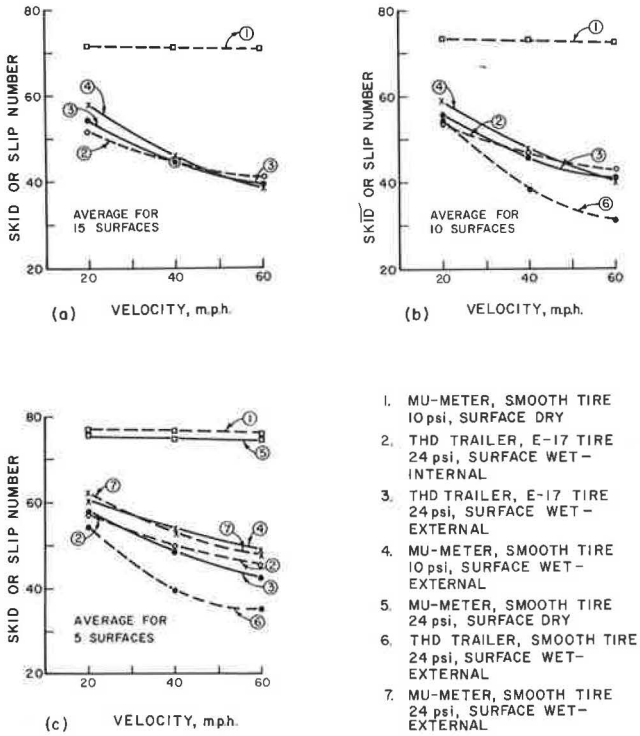

Figure 3. Average friction-velocity comparisons for different test conditions in the skid and cornering-slip modes.

AND MACROTEXTURE VALUES FOR SURFACES AND TEST CONDITIONS

TC-7		TC-2				TC-3					TC-6					Surface Number
SN_{60}	Gradient	SN_{20}	SN_{40}	SN_{60}	Gradient	SN_{20}	SN_{40}	SN_{60}	Gradient	Percentage of Gradient	SN_{20}	SN_{40}	SN_{60}	Gradient	Percentage of Gradient	
19	0.83	50	40	35	0.38	54	40	33	0.52	39	36	17	15	0.52	58	3
		37	31	29	0.20	41	30	23	0.45	44						4
		35	30	32	0.08	43	35	31	0.30	28						11
41	0.68	66	58	54	0.30	65	53	44	0.52	32	57	32	28	0.73	51	13
70	0.08	66	57	49	0.43	64	55	49	0.37	23	68	55	53	0.37	22	17
72	0.03	65	58	50	0.38	65	57	50	0.37	23	71	60	53	0.45	25	18
		50	40	35	0.38	51	40	33	0.45	35						22
39	0.18	41	36	39	0.05	42	38	39	0.08	07	39	34	30	0.23	23	28
		47	38	31	0.40	57	43	29	0.70	49						31
		64	63	62	0.05	69	62	59	0.25	15						33
		50	42	38	0.30	64	53	46	0.45	28	54	40	30	0.60	44	T-1
		54	48	44	0.25	63	55	47	0.40	25	67	51	38	0.73	43	T-2
		72	64	61	0.28	68	59	51	0.43	25	77	45	27	1.25	65	T-3
12	0.80	26	18	17	0.23	26	16	13	0.33	50	29	15	10	0.47	66	T-4
41	0.58	49	46	40	0.23	49	40	36	0.33	27	46	33	27	0.47	41	T-5
Surfaces Tested																
		52	45	42		55	45	39	0.40	30						15
		54	47	43		56	46	41	0.38	28	54	38	31	0.58	44	10
48		58	50	45		58	49	43			54	40	36			5

with only four test conditions (Fig. 3a). Figure 3c shows complete data as obtained with the seven conditions on five surfaces.

The Mu-meter results indicate that cornering-slip numbers are not affected by velocity increase on dry pavements. On wet pavements, both Mu-meter (smooth tire) and trailer (E-17 tire) results reflect the characteristic decrease in friction with increased velocity. On the average, at 20 mph, the Mu-meter indicates slightly higher friction than does the trailer; whereas at 60 mph, both instruments indicate the same magnitude (Fig. 3a, test conditions 3 and 4). Results from the trailer operating with a smooth tire (test condition 6) compared favorably with

TABLE 4

AVERAGE MACROTEXTURE MEASUREMENTS

Surface Number	Depth by Putty Impression (in.)	Peak Height by Profilograph (in.)
3	0.0090	0.0212
4	0.0234	0.0252
11	0.0340	0.0279
13	0.0182	0.0182
17	0.0224	0.0190
18	0.0412	0.0333
22	0.0115	0.0191
28	0.0563	0.0570
31	0.0432	0.0174
33	0.0648	0.0557
T-1	0.0224	0.0235
T-2	0.0235	0.0195
T-3	0.0093	0.0149
T-4	0.0019	0.0136
T-5	0.0280	0.0203

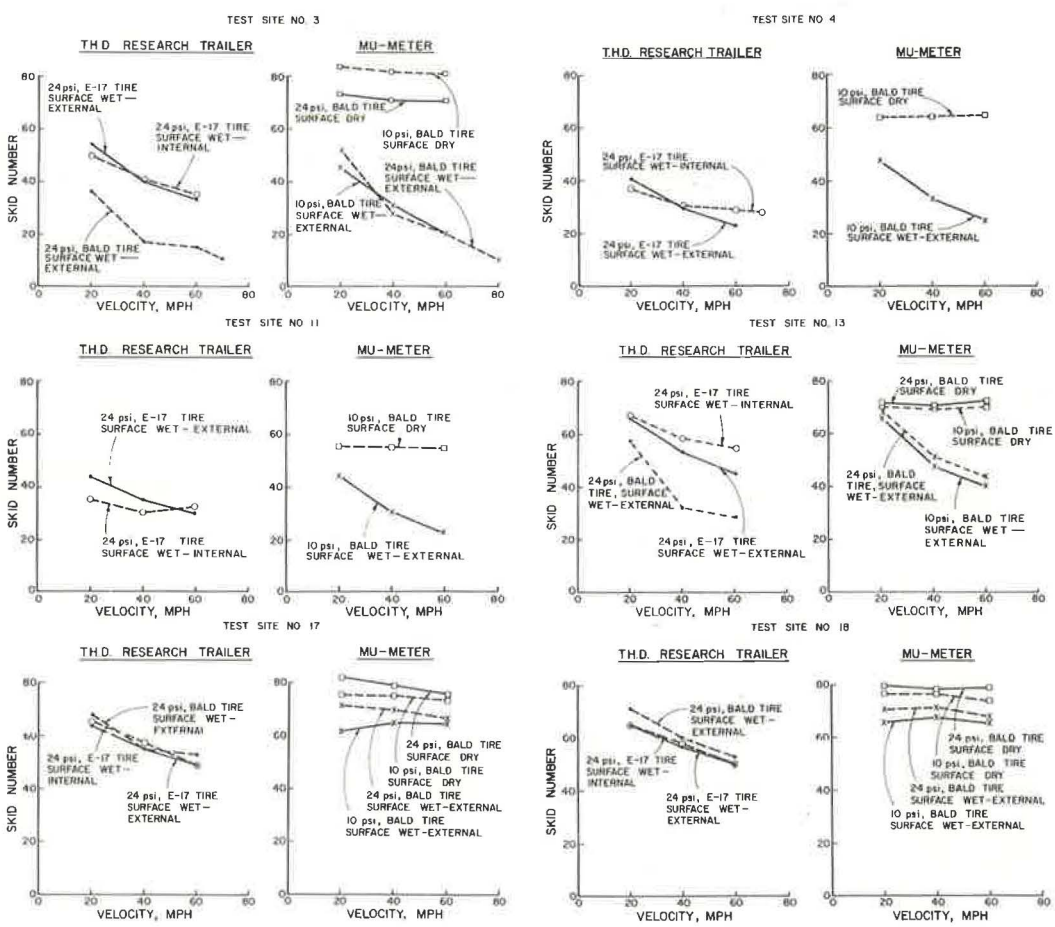

Figure 4. Trailer and Mu-meter friction values.

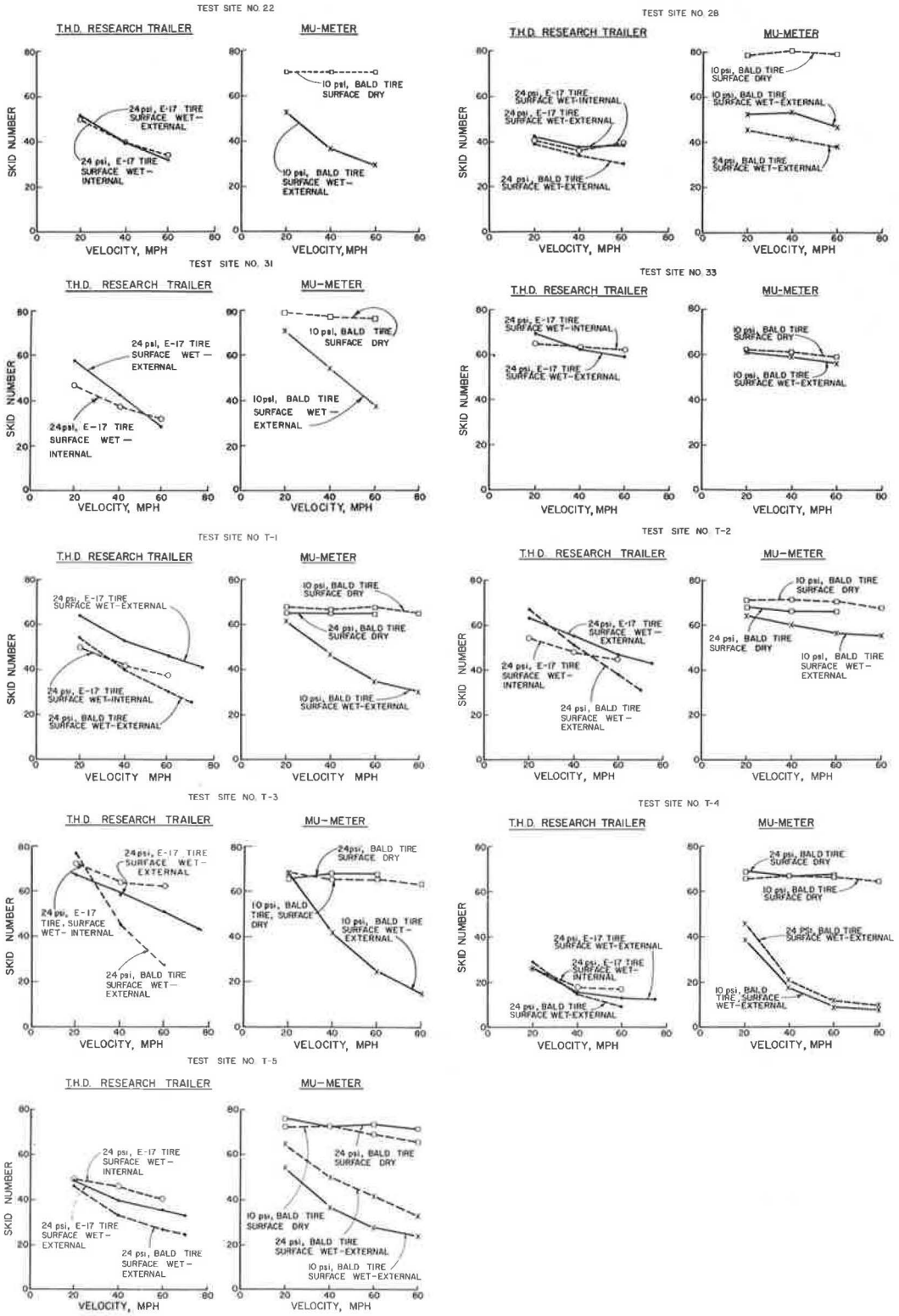

Figure 4. Continued.

both the Mu-meter (smooth tire) and the trailer (E-17 tire) at 20 mph; however, much lower values were obtained at higher speeds (Fig. 3b). This is to be expected when consideration is given to the fact that the Mu-meter operates in the cornering-slip mode, whereas the trailer operates in the skid mode. Thus, higher friction values are expected in the cornering-slip mode if other conditions are maintained constant.

The use of a treaded tire on the trailer will generally provide sufficient drainage at high speeds to increase the friction to that of an instrument operating in the cornering-slip mode with a smooth tire. At the lower speeds, however, drainage effects are reduced and the overriding effects of the cornering-slip mode prevail; thus, the Mu-meter records slightly higher friction values (Figs. 3a and 3b). It must be remembered, however, that these conclusions are specific and will not necessarily hold for all surface types, equipment, variables, and environmental conditions. For example, the curves shown in Figure 3c for test conditions 3 and 4 differ appreciably when the average curves represent only five surfaces.

The friction number-velocity data given in Table 3 are plotted with respect to individual and surfaces shown in Figure 4. From these figures, effects of the different

TABLE 5

STATISTICAL COMPARISONS OF FRICTION NUMBERS OBTAINED AT VARIOUS SPEEDS AND TEST CONDITIONS

Variables[a]		Number of Comparisons	Figure Number	Regression Line	Correlation Coefficient	Coefficient of Determination	Standard Deviation
Y	X						
$SN_{20}(3)$	$SN_{20}(4)$	15	5a	Y = -6.38 + 1.05X	0.86	0.75	6.55
$SN_{40}(3)$	$SN_{40}(4)$	15	5a	Y = 14.66 + 0.65X	0.78	0.61	8.20
$SN_{60}(3)$	$SN_{60}(4)$	15	5a	Y = 20.13 + 0.49X	0.73	0.54	8.58
$SN_{20}(4)$	$SN_{20}(6)$	10	5b	Y = 26.35 + 0.60X	0.94	0.89	3.68
$SN_{40}(4)$	$SN_{40}(6)$	10	5b	Y = 9.20 + 1.01X	0.92	0.84	7.05
$SN_{60}(4)$	$SN_{60}(6)$	10	5b	Y = -4.02 + 1.42X	0.96	0.91	6.45
$SN_{20}(3)$	$SN_{20}(6)$	10	5c	Y = 17.67 + 0.70X	0.86	0.74	7.30
$SN_{40}(3)$	$SN_{40}(6)$	10	5c	Y = 19.44 + 0.71X	0.81	0.65	8.29
$SN_{60}(3)$	$SN_{60}(6)$	10	5c	Y = 21.32 + 0.63X	0.76	0.58	7.93
$SN_{20}(3)$	$SN_{20}(2)$	15	5d	Y = 9.81 + 0.87X	0.92	0.85	4.97
$SN_{40}(3)$	$SN_{40}(2)$	15	5d	Y = 5.62 + 0.88X	0.93	0.87	4.68
$SN_{60}(3)$	$SN_{60}(2)$	15	5d	Y = 1.25 + 0.92X	0.93	0.87	4.60
$SN_{20}(1)$	$SN_{20}(4)$	15	5e	Y = 59.26 + 0.21X	0.29	0.09	7.23
$SN_{40}(1)$	$SN_{40}(4)$	15	5e	Y = 64.10 + 0.15X	0.30	0.09	7.19
$SN_{60}(1)$	$SN_{60}(4)$	15	5e	Y = 67.13 + 0.08X	0.22	0.05	6.97
$SN_{20}(4)$	$SN_{20}(7)$	7	5f	Y = 4.67 + 0.87X	0.93	0.86	4.79
$SN_{40}(4)$	$SN_{40}(7)$	7	5f	Y = 3.34 + 0.90X	0.94	0.89	7.17
$SN_{60}(4)$	$SN_{60}(7)$	7	5f	Y = -1.06 + 0.99X	0.96	0.92	7.34
$SN_{20}(1)$	$SN_{20}(5)$	9	5f	Y = 30.64 + 0.58X	0.59	0.34	4.46
$SN_{40}(1)$	$SN_{40}(5)$	9	5f	Y = 20.62 + 0.73X	0.63	0.40	4.31
$SN_{60}(1)$	$SN_{60}(5)$	9	5f	Y = 25.47 + 0.65X	0.63	0.39	3.71

[a]SN = skid or slip number, subscript indicates speed in mph, and numbers in parentheses indicate test conditions.

TABLE 6

STATISTICAL COMPARISONS OF GRADIENTS, PERCENTAGES OF GRADIENTS, AND FRICTION NUMBERS OBTAINED WITH THE VARIOUS TEST CONDITIONS

Variables[a]		Number of Comparisons	Figure Number	Regression Line	Correlation Coefficient	Coefficient of Determination	Standard Deviation
Y	X						
G(3)	G(6)	10	6a	Y = 0.24 + 0.24X	0.54	0.29	0.11
G(4)	G(3)	15	6b	Y = -0.04 + 1.37X	0.58	0.33	0.28
G(4)	G(6)	10	6c	Y = -0.02 + 0.87X	0.65	0.42	0.30
PG(3)	PG(6)	10	7a	Y = 5.61 + 0.51X	0.75	0.56	7.84
PG(4)	PG(3)	15	7b	Y = -7.68 + 1.47X	0.73	0.53	17.05
PG(4)	PG(6)	10	7c	Y = -32.34 + 1.54X	0.92	0.84	11.84
$SN_{40}(6)$	G(6)	10	8a	Y = 34.00 + 7.21X	0.13	0.02	15.83
$SN_{40}(6)$	lnG(6)	10		Y = 40.23 + 3.20 lnX	0.10	0.01	15.90
$SN_{40}(4)$	G(4)	15	8b	Y = 61.25 - 29.66X	0.65	0.42	11.92
$SN_{40}(4)$	lnG(4)	15		Y = 37.07 - 7.41 lnX	0.74	0.56	10.45
$SN_{40}(3)$	G(3)	15	8c	Y = 42.18 + 7.29X	0.08	0.01	13.12
$SN_{40}(3)$	lnG(3)	15		Y = 48.18 + 3.09 lnX	0.12	0.01	13.06
$SN_{40}(6)$	PG(6)	10	9a	Y = 63.08 - 0.57X	0.62	0.39	12.48
$SN_{40}(6)$	lnPG(6)	10		Y = 119.58 - 21.96 lnX	0.61	0.37	12.65
$SN_{40}(4)$	PG(4)	15	9b	Y = 66.31 - 0.55X	0.87	0.75	7.78
$SN_{40}(4)$	lnPG(4)	15		Y = 72.99 - 8.69 lnX	0.82	0.68	8.90
$SN_{40}(3)$	PG(3)	15	9c	Y = 63.66 - 0.62X	0.58	0.34	10.70
$SN_{40}(3)$	lnPG(3)	15		Y = 77.93 - 9.94 lnX	0.38	0.15	12.13

[a]G = gradient (slope) at the friction speed curve between 20 and 60 mph; PG = percentages of gradient of the friction speed curve between 20 and 60 mph; SN = skid or slip number; subscript indicates speed in mph; ln = lay to the base e; and numbers in parentheses indicate test conditions.

tire inflation pressures, tire-tread depths, wet or dry surface conditions, and modes used in this study can be made for individual surfaces.

In order to get a better understanding and to assist in discussing the following figures, we conducted statistical analyses on the various relationships. Results are given in Tables 5 and 6 and shown in Figures 5 through 9.

Comparisons of friction numbers obtained with various test conditions are given in Figure 5. Test results are shown in the top left of Figure 5 as obtained with each instrument operating under respective standard test conditions, i. e., trailer with E17 tire, 24 psi, and Mu-meter with smooth tire, 10 psi, with the exception that an external means was used for wetting the pavement to ensure equivalent water-film thickness. Average values, with respect to velocity are very close. Considerable data scatter exists, particularly at higher velocities; however, individual surfaces tend to maintain relative positions. The correlation coefficients decrease with increasing speed, which is expected because the relative drainage abilities of the two tires differ markedly; however, drainage also contributes to the lower correlation at higher speeds. On an average, as speed increased, the skid number became lower than the cornering-slip number. This was also borne out by the regression coefficients. At 20 mph the slip-mode measure is greater than the skid mode measure; at 60 mph the reverse is true. At the higher speeds, the relative drainage abilities of the two tires affect the friction level more than the operating mode.

Figure 5, top right, also shows Mu-meter-trailer friction comparisons; however, these comparisons differ from those shown at the top left in one respect—a smooth tire was used on the trailer. This represents an attempt to equalize the relative drainage capabilities of the test vehicles and thus get a better insight into the cornering-slip mode and skid mode comparison. Cornering-slip numbers obtained at each speed were, on an average, higher than corresponding skid numbers. This is to be expected because available friction during the slip (cornering-rolling) mode is higher than available friction in skid (sliding) mode, provided other variable factors do not exist. Also, constant and substantially higher correlation coefficients were obtained for these relationships than were obtained for those shown in Figure 5 top left. This constancy indicates that the relative drainage capabilities of the vehicles were essentially identical at the given speeds. Although on an average both methods measured a decrease in friction levels with corresponding increases in speed, the range in trailer values became smaller and the range in Mu-meter values became larger with increase in speed.

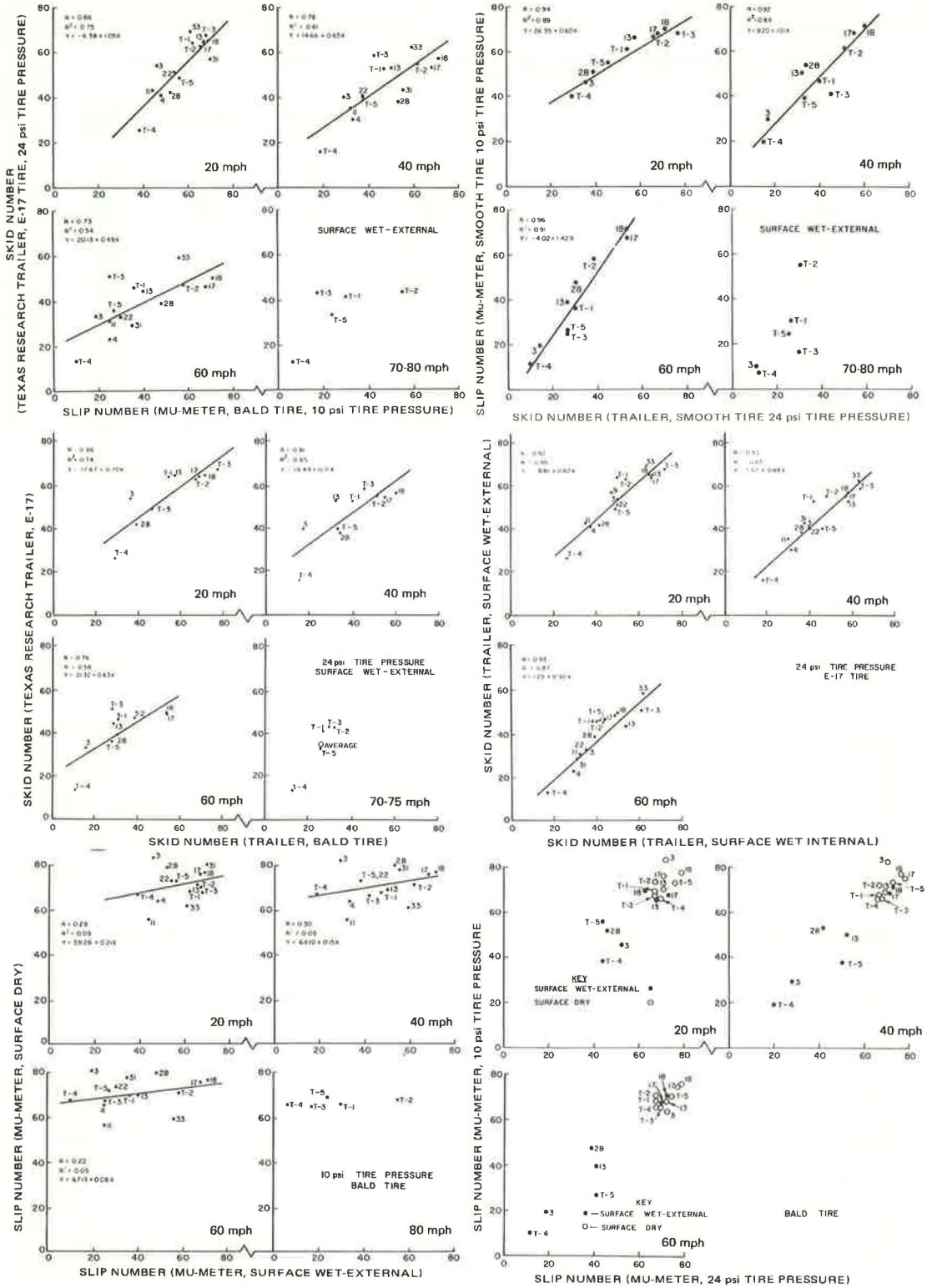

Figure 5. Friction comparisons of the various test conditions.

Various velocity comparisons of skid (trailer) tests with treaded and smooth tires are shown in Figure 5 middle left. Relative positions of the surfaces, with respect to increased velocities, are not maintained. Except for surfaces 17 and 18, the surfaces tend to deteriorate in skid resistance (with increasing velocity) at faster and more variable rates when tested with a smooth tire than when tested with the E-17 tire. This points out the relative drainage capabilities of the different tires as well as the different types of surfaces. The correlation coefficient was also lower at the higher speed.

Figure 5, middle right, shows that skid numbers obtained with the trailer at various speeds with respect to the 2 pavement wetting processes were quite similar. In general, the internal watering procedures resulted in slightly lower skid numbers at 20 mph and slightly higher skid numbers for the 60-mph tests when compared to corresponding skid tests using external watering procedures. Variations in the wetting procedures, resulting in different water-film thickness, probably account for the differences. Average 40-mph skid numbers were identical for the 15 surfaces. Consistently high correlation coefficients were obtained at each speed.

Figure 5, bottom left, shows that surface type and test velocity have little effect on dry-pavement cornering-slip number. In addition, dry-pavement slip numbers correlate poorly with wet-pavement cornering-slip numbers as evidenced by the extremely low correlation coefficients.

Limited data, comparing cornering-slip numbers obtained with tire inflation pressures of 10 and 24 psi, are shown in Figure 5, bottom right. Tire inflation effects were negligible. Correlation coefficients were high when the surfaces were tested in the wet condition. Although lower correlation coefficients were obtained when the surfaces were tested in the dry condition, all the surfaces were grouped rather closely together as far as cornering-slip number variations are concerned, thus rendering correlation somewhat meaningless in this comparison.

Comparisons of friction-velocity gradients obtained from 20- to 60-mph tests on the various surfaces are shown in Figure 6. Figure 6a shows that steeper gradients were obtained on most surfaces with the smooth tire on the trailer than with the E-17 tire. Also, the range in gradients obtained with the smooth tire was greater than that obtained with the E-17 tire. These results indicate that different types of surfaces vary appreciably in ability to drain water from under a tire. Similar conclusions can be drawn from test results shown in Figure 6b. Although smooth-tire tests were taken with the Mu-meter in this case, the range and magnitude of the gradients were likewise greater than those obtained with the treaded tire. Figure 6c shows that the test mode also influences gradient. Surfaces that had steeper gradients when tested with the trailer were suspected as having higher microtexture (although this was not measured). Microtexture would tend to heat up and melt to a limited degree the sliding rubber, thus providing additional lubrication and resulting in lower available friction. This would not be the case with the "rolling" tire on the Mu-meter. Correlation coefficients obtained in these comparisons were not very high.

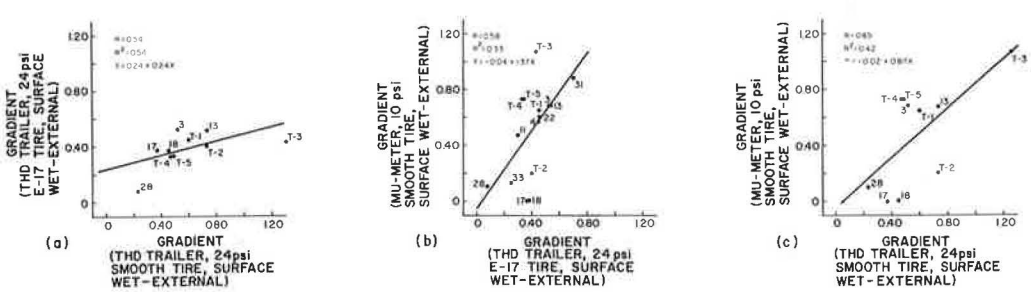

Figure 6. Comparison of friction-velocity gradients taken at 20 to 60 mph.

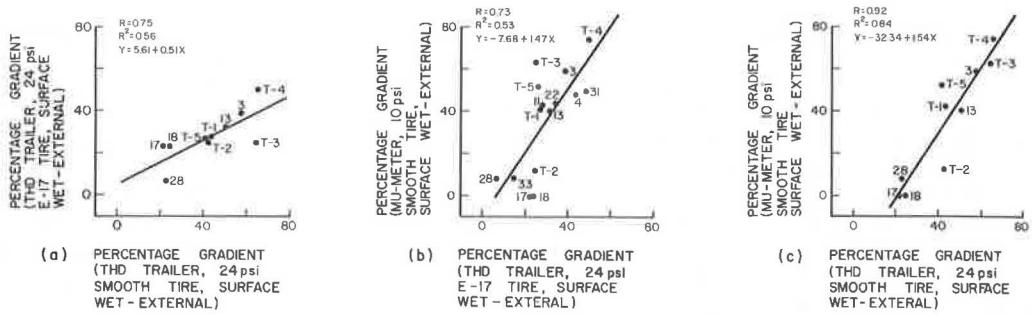

Figure 7. Comparisons of friction-velocity percentage of gradients taken at 20 to 60 mph.

Comparisons of friction number-velocity percentage of gradients obtained from 20- to 60-mph tests on the various surfaces are shown in Figure 7. Similar conclusions can be drawn from data shown in Figures 7a and 7b as were drawn from those shown in Figures 6a and 6b. However, Figure 7c shows a much higher correlation between percentage of gradient as obtained with smooth tires on the Mu-meter and trailer. Figure 6c does not show nearly as high a correlation.

Comparisons of 40-mph friction numbers and 20- to 60-mph friction number-velocity gradients for the various surfaces are shown in Figure 8. The trailer plots shown in Figures 8a and 8c do not indicate that skid number and gradient are negatively related, although the band of values is quite wide. The Mu-meter tests indicate that to some extent higher friction surfaces are associated with flatter gradient surfaces. Such was not evidenced from the trailer tests.

Comparisons of 40-mph friction numbers and 20- to 60-mph friction number-velocity percentage gradients for the various surfaces are shown in Figure 9. A negative relationship is indicated for each test condition, with the best relationship obtained using the Mu-meter. This indicates that surfaces with high 40-mph friction numbers tend to degrade less in available friction with increased speed than do surfaces with low 40-mph friction numbers. Points positioned to the right of the best-fit line represent surfaces that are deceptive, i.e., for a given friction number at 40 mph, the amount of the available friction at 60 mph is quite low when compared with surfaces positioned to the left of the line at the given 40-mph friction number.

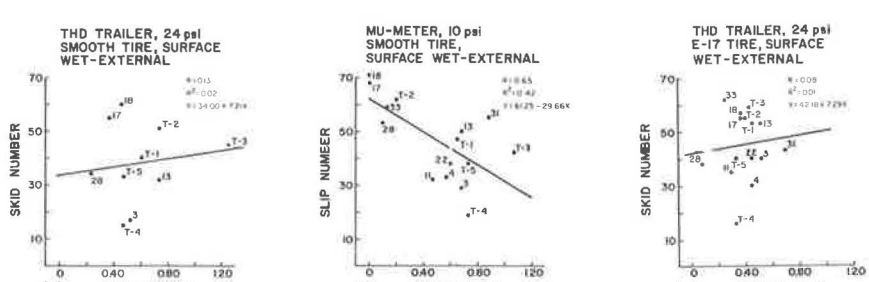

Figure 8. Comparison of friction numbers at 40 mph and friction-velocity gradients at 20 to 60 mph.

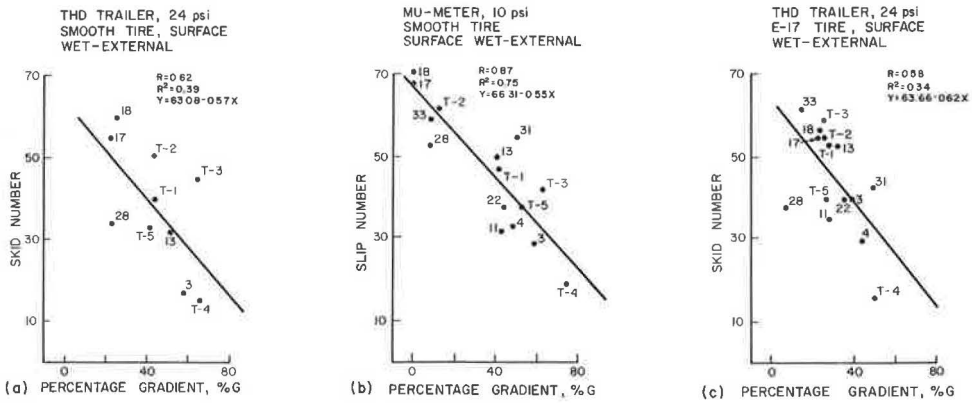

Figure 9. Comparison of friction numbers at 40 mph and friction-velocity percentage of gradients at 20 to 60 mph.

CONCLUSIONS

Based on the test procedures, equipment, and environmental conditions associated with the collection of data presented in this report the following conclusions appear to be warranted.

1. Good correlations were found to exist between the Mu-meter and the Texas Highway Department skid trailer at speeds of 20, 40, and 60 mph provided that both instruments utilized treadless or smooth tires and further provided that the surfaces being tested were wet to similar degrees. Correlation coefficients ranged from 0.92 to 0.96.
2. Comparisons made in the wet condition with the trailer using ASTM E-17 treaded tires and the Mu-meter using smooth tires yielded correlation coefficients that ranged from 0.86 to 0.75 for speeds from 20 to 60 mph.
3. Analysis of the data indicates that the relative drainage capabilities of the smooth and treaded tires becomes highly critical for certain surfaces (pavements) with limited rugosity.
4. The external and internal watering systems used were not equally efficient. At higher speeds (60 to 80 mph) the internal watering system used by the trailer becomes measurably less effective, probably due to splash and wind effects.
5. For the water-film thickness used in this study (approximately 0.020 in.), friction measurements on surfaces with macrotexture greater than about 0.025 in. were essentially the same for smooth and treaded tires. Although numerical values of microtexture were not available for these comparisons, the surfaces were considered to have about equal microtexture.
6. Numerous tests on clean, dry surfaces with the Mu-meter indicated little variation with speed or surface type with all surfaces exhibiting high values. A similar statement can be made for locked-wheel stops on clean, dry surfaces.
7. Comparisons of the percentage of gradients of the friction-velocity curves when Mu-meter and the trailer were operating with smooth tires gave a correlation coefficient of 0.92, whereas in a similar comparison made between the Mu-meter (smooth tires) and the trailer with E-17 treaded tires the correlation coefficient was much lower.
8. Variation of the Mu-meter tire pressure produced little effect on tests made on wet surfaces.

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