HIGHWAY FRICTION MEASUREMENTS WITH MU-METER AND LOCKED WHEEL TRAILER

by

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Texas Highway Department or the Federal Highway Administration.

OBJECTIVES

The objectives of this phase of the research were as: to investigate, through field studies performed on full scale pavements, the effect water drainage on friction values obtained from two devices, one operating in the slip mode and the other operating in the skid mode.

ACKNOWLEDGEMENTS

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ABSTRACT

Friction tests at 20, 40, 60, and 80 mph, on wet and dry surfaces using smooth and treaded tires, with 10 and 24 psi tire inflation pressures were taken with a Mu-Meter and the Texas Highway Department research skid trailer. Fifteen pavement surfaces which 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. Effects of macrotexture on the friction parameters were also analyzed. Statistical analyses and typical plots are given.

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 above about 40 mph.

SUMMARY

The summary statements listed below are tentative and therefore subject to revision as data from this and other studies are accumulated and evaluated. Furthermore, these statements are predicated on the test procedures, equipment, and environmental conditions associated with the data gathering process.

1. The Mu-Meter and skid trailer correlate rather well when smooth-treaded tires are used on both instruments. Correlation coefficients of 0.94, 0.92, and 0.96 were obtained at 20, 40, and 60 mph respectively. These represent approximately 10 percent unexplained variation. Average results reveal slightly higher friction when measured with the Mu-Meter as compared to the trailer. This is expected since available friction in the slip mode is greater.

2. Friction numbers obtained with the E-17 treaded tire (trailer) correlated poorly with those obtained with smooth tires on both the trailer and Mu-Meter. Nearly identical correlation coefficients, averaging 0.86, 0.80, and 0.75 at 20, 40, and 60 mph, respectively were obtained for both comparisons. The decrease in correlation with increased speeds is a function of the relative drainage capabilities of the E-17 (tread) and smooth tires, with relative differences greater at higher speeds when drainage becomes very critical for surfaces with poor drainage capabilities. Friction does not differ greatly on surfaces with good drainage capabilities when measured with either treaded or smooth tires.

3. Comparison of external versus internal pavement wetting processes for the skid trailer tests revealed correlation coefficients of 0.92, 0.93, and 0.93 at 20, 40, and 60 mph respectively. At 20 mph the external process gave a slightly higher average value, whereas, at 60 mph the reverse was

true. At 40 mph the averages were identical.

4. Extremely poor correlation was obtained between dry and wet pavement friction tests with the Mu-Meter. Dry pavement friction was unaffected by test speed variations and in addition, was only affected to a small extent by surface type. All surfaces exhibited high friction properties when tested in the dry condition.

5. Variations in tire pressure had little influence on Mu-Meter values on wet roads.

6. Gradients of the friction velocity curves as obtained with both instruments correlated poorly. Better correlations were obtained for percentage gradients comparisons, with the Mu-Meter and trailer (smooth tire) having a correlation coefficient of 0.92. This also points up the relative drainage capabilities of E-17 (treaded) and smooth tires.

7. Skid number-gradient correlations were poor for the Mu-Meter and extremely poor for the trailer. Better correlations were obtained between skid numbers and percentage gradients, with the Mu-Meter again having the highest correlation coefficient of 0.87.

8. Forty mph skid numbers obtained with each instrument correlated poorly with macrotexture. The highest correlation coefficient of 0.56 was obtained with Mu-Meter results.

9. Relatively poor correlation coefficients were obtained for gradient-macrotexture comparisons. Substantially higher coefficients ranging from 0.60-0.85 were obtained with both instruments for wet pavement percentage gradient-macrotexture comparisons.

IMPLEMENTATION

In the United States the majority of state highway departments, federal agencies, etc., rely almost exclusively on coefficient of friction values derived from skid mode friction tests for purposes of evaluating various pavement surface types and other factors in relation to their relative effect on the achievement of adequate contact forces between wet pavement surfaces and vehicle tires.

Different friction levels exist for variable, but normal operating modes of a tire; i.e., rolling and slipping during braking, driving and cornering. For research purposes, it is desirable to utilize both the slip and skid mode to better evaluate the relative slipperiness of given pavement surface types under different operating conditions. These data should prove useful in the selection of surface types and roadway geometrics compatible with service demands and point up the desirability of tailoring the pavement surface design to the operator-vehicle needs. For example, the design for a high speed, heavy traffic volume highway should include provisions for adequate and rapid drainage from the tire pavement interface. The critical nature of the cornering operation appears to warrent a closer look at the pertinent facets of the slip mode of operation, particularly for vehicles with essentially smooth tires.

KEY WORDS

Coefficient of Friction, Slip Resistance, Skid Resistance, Slip Number, Skid Number, Friction Number, Macrotexture, Mode, Friction-Velocity Gradient, and Percentage Gradient.

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INTRODUCTION

Friction measurements of the tire-pavement combination 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. It is for this reason that 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 slip mode.

Attempts have been made to characterize the skid-resistant properties of pavement surfaces in qualitative manners such as surface macrotexture, drainage characteristics of the road surface and aggregate size, shape, micro-texture, 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 1) the presence of water in the tire-pavement contact area which, with increasing vehicle speeds, lowers the obtainable frictional drag and raises the frictional demand, and

2) higher traffic volumes which, 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. Considered to have major effects are: 1) mode of operation, i.e., rolling, brake slip, drive slip, and cornering slip (1),* 2) pavement surface characteristics, mainly macro- and microscopic roughness and drainage capability, 3) water film thickness at the interface, 4) tire tread depth and elastic and damping properties of the tire rubber, and 5) vehicle speed. Thus, if friction coefficients are to be meaningful for evaluation or comparison purposes, the above factors must be given consideration. Standardization of certain friction testing procedures and equipment can naturally reduce the number of variables employed 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 on Skid Resistance and accepted by the Society; these being respectively, 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). 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 utilize more than one type of measuring mechanism. This provides information as to the relative

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* Numbers in parenthesis refer to listed references at the end of this paper.

slipperiness of given pavement surface types under different modes and, in addition, with judicious variance 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 since 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:

> 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 lock-up, frictional drag is significantly reduced compared to the drag for the 15 to 20 percent slip mode.

It is, however, not the purpose of this paper to belabor 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, on various type surfaces under stated conditions. Data comparisons are given with due regard for test variables. Properties of the pavement surfaces which are reflected in the test results are discussed. Macrotexture values obtained with two methods are compared with slip and skid numbers and friction-velocity gradients and percentage gradients.

CLASSIFICATION OF SURFACES TESTED

Previous research has indicated that pavement surfaces of a given type, i.e., asphalt concrete, portland cement concrete, surface treatments, etc. 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, slip resistant properties. Thus, it was decided that in order to adequately investigate and compare slip and skid resistance characteristics, 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 including: 1) nine hot mix asphalt concrete, 2) two portland cement concrete, 3) three surface treatments, and 4) one flushed seal were tested. 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 contained therein. This information is listed in Table 1.

TABLE 1: DESCRIPTION OF THE FIFTEEN SURFACES

Surface Number	Route	County	Surface Type	Average Daily Traffic (1968)	Construction Date
3	St 6	Brazos	Lignite Boiler Slag Hot Mix, 3/16 inch Top Size	4200	1965
4	St 6	Robertson and Falls	Rounded River Gravel Hot Mix, 5/8-inch Top Size	1420	1968
11	St 14	Lime-stone	Crushed River Gravel Hot Mix, 1/2-inch Top Size	3655	1967
13	US 84	Freestone	Crushed Sandstone Hot Mix, 3/8-inch Top Size	1310	1965
17	FM 1687	Brazos	Open Graded Light-weight Aggregate Hot Mix, 3/8-inch Top Size	700	1968
18	FM 1687	Brazos	Open Graded Light-weight Aggregate Hot Mix, 5/8-inch Top Size	700	1968
22	St 14	Limestone	Rounded River Gravel Portland Cement Con-crete, 1 1/2-inch Top Size	920	1936
28	FM 2038	Brazos	Rounded River Gravel Surface Treatment, 5/8 inch Top Size	135	1968
31	St 30	Grimes	Crushed Limestone Surface Treatment, 3/8 inch Top Size	820	1968
33	FM 416	Navarro	Lightweight Aggre-gate Surface Treat-ment, 1/2 in.Top Sz.	100	1964
T-1	Texas A&M	Brazos	Rounded River Gravel Hot Mix, 5/8-inch Top Size	none	1968
T-2	Texas A&M	Brazos	Crushed River Gravel Hot Mix, 1/4-inch Top Size	none	1968
T-3	Texas A&M	Brazos	Crushed Limestone Hot Mix, 1/2-inch Top Size, Terrazzo Finish	none	1968
T-4	Texas A&M	Brazos	Clay-Filled Tar Emul-sion (Jennite) Seal	none	1968
T-5	Texas A&M	Brazos	Rounded River Gravel Portland Cement Con-crete, 1 1/2-inch Top Size	none	1953

EQUIPMENT USED FOR FRICTION TESTS

Means for measuring slip and skid resistance were provided by the Soiltest ML-400 Mu-Meter Friction Recorder and the Texas Highway Department Research Skid Trailer, respectively. Photographs are contained in Figures 1 and 2.

Mu-Meter

This instrument is a continuous-recording friction-measuring trailer which determines the frictional characteristics of treadless tires operating in the cornering slip mode. It is considered to measure the cornering-force friction coefficient generated between the test surface and the penumatic tires on two running wheels which are set at a fixed 7½-degree 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 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.

Wheels are the split-rim type. Tires are pneumatic, 6-ply, size 4.00 x 16 with smooth treads. Ten 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 slip numbers at the corresponding test velocity.

Gradient (or slope) of the slip number-velocity curve was calculated; this being the numercial difference of the slip numbers at 20 and 60 mph divided by the velocity difference of 40 mph.

$$\text{Gradient} = \frac{\text{slip number}_{20} - \text{slip number}_{60}}{40} = \frac{SN_{20} - SN_{60}}{40}$$

The percentage decrease in friction between 20 and 60 mph, termed percentage gradient, was calculated. This takes into account that the absolute decrease in slip number above 20 mph will be influenced to some extent by the slip number at that velocity. A curve of a given gradient positioned low on the friction-velocity graph would have a higher percentage gradient than 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 gradient is defined as the percentage of the gradient (obtained under test conditions) to a theoretical gradient if the slip number at 60 mph were zero.

$$\text{Percentage Gradient} = \frac{\dfrac{\text{slip number}_{20} - \text{slip number}_{60}}{40}}{\dfrac{\text{slip number}_{20} - 0}{40}} \times 100 = \frac{SN_{20} - SN_{60}}{SN_{20}} \times 100$$

Trailer

This instrument, used by the Texas Highway Department Research Section of D-8 conforms substantially to ASTM Designation E 274-65T (Skid Resistance of Pavements Using a Two-Wheel Trailer). 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 which applies approximately 0.020-inch water film thickness to the pavement surface. The development and calibration of the trailer is given in a departmental research report (9).

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 gradient were calculated in the same manner as explained previously except appropriate skid numbers were used.

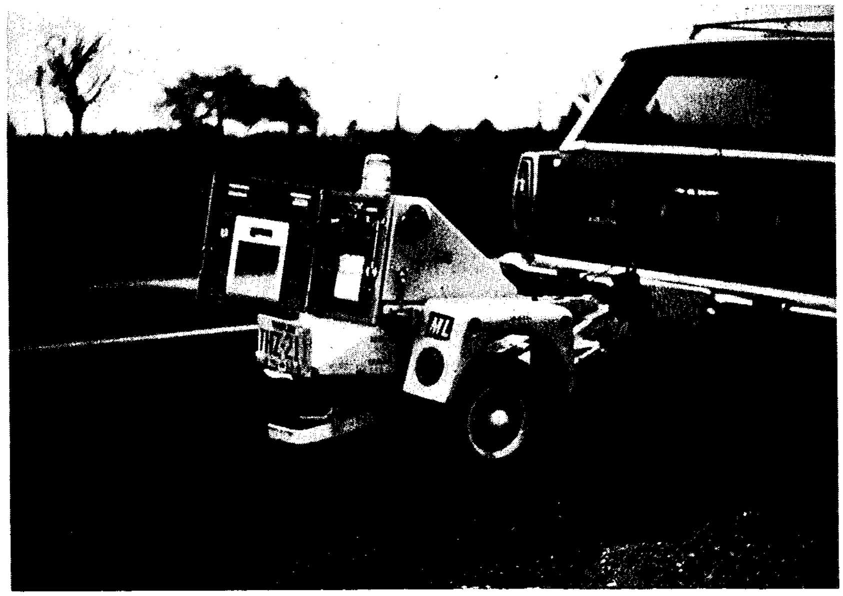

Figure 1. Mu-Meter Friction Trailer.

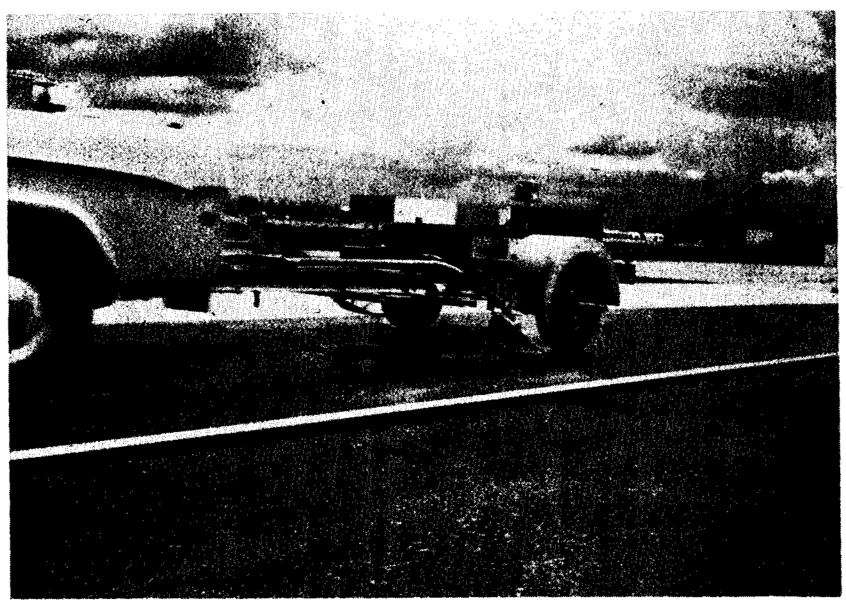

Figure 2. Texas Highway Department Research Skid Trailer.

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. Forty mile-per-hour test velocity, approximately 0.020-inch water film thickness, and E-17 circumferentially grooved, treaded tires inflated to 24 psi are normally used 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 slip and skid modes. Additionally, other variations were incorporated into the study to gain a better insight to the overall problems.

Two series of 20, 40, 60, and 80 mph friction tests were conducted with each instrument, under differing conditions, 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 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 wetted 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 wetted by a separate water truck. In the third sequence the measurements were taken concurrently with the Mu-Meter lagging approximately

100 feet behind the trailer at each respective test speed. Measurements were made in the wheel path with the position of the Mu-Meter wheels nearly the same as the skid trailer wheels. Comparisons made between the two devices would 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 wheel path.

The trailer watering system was calibrated to supply sufficient water to create a surface film 0.020-inches thick on the pavement. Procedures for wetting with the water truck were planned so as to insure 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 bring about 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-inch 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 seconds from one surface to another and from day to day in order 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.

Fifteen surfaces were tested using the following equipment and conditions.

1. Mu-Meter - 10 psi, smooth (or treadless) tire, surface dry.

2. Trailer - 24 psi, E-17 circumferentially grooved tire, surface wet internally.

3. Trailer - 24 psi, E-17 circumferentially grooved tire, surface wet externally.

4. Mu-Meter - 10 psi, smooth tire, surface wet externally.

Tests were also conducted on several of the surfaces using the following additional conditions:

5. Mu-Meter - 24 psi, smooth tire, surface dry

6. Trailer - 24 psi, smooth tire, surface wet externally

7. Mu-Meter - 24 psi, smooth tire, surface wet externally

The same testing procedure was used as outlined previously, except trailer tests with internal watering were not included.

The tests were conducted during August and September, 1969. Air temperatures were generally in the 80-95°F 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.

EQUIPMENT AND PROCEDURE USED FOR 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 among others. 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. Photographs are contained in Figures 3 and 4.

Profilograph

The instrument used for this test was developed by the Texas Highway Department (6,8). It is designed to scribe a magnified profile of the surface texture as a probe is drawn across the surface. That is, the probe is placed on the pavement surface and as the probe is drawn over the surface irregularities, the vertical movement of the probe is magnified through a linkage system. The probe and linkage system are attached to a carriage which is forced to move in a horizontal manner parallel to the pavement surface by a framework with adjustable legs. The vertical and horizontal movements result in a duplicated (but magnified) texture profile which is scribed on a chart. Average peak height can then be determined. Also, the upward vertical excursions are recorded on a counter of which the counter reading, at any time, is the cumulative vertical peak heights of the texture through the length traversed by the probe.

An average of three tests were taken at each location for a total of twelve per surface (test pavement). Individual test spots at each location were located in the outer wheel path, spaced approximately 50 feet apart.

Putty Impression

This method was initially developed (7) as a means of providing surface texture correction factors for nuclear density measurements and was later modified slightly for use in friction research (6).

Equipment consists of 1) a 6-inch diameter by 1-inch thick metal plate with a 4-inch diameter, 1/16-inch deep recess machined into one side, and 2) a 15.90-gram ball of silicone putty. When placed on a smooth surface, 15.90-grams of putty will smooth out to a 4-inch diameter circle, 1/16-inch deep, thus completely filling the recess.

The silicone putty is formed into an approximate sphere and placed on the pavement surface. The recess in the plate is centered over the putty and pressed down in firm contact with the road surface. The more irregular the surface texture (the higher the macrotexture) the smaller the resulting putty diameter because more material is required to fill the surface texture. Average texture depth, based on volume per unit area, is calculated from an average of four diameter measurements.

Two tests were taken at each location for a total of eight per surface. Individual test spots at each location were located in the outer wheel path, spaced approximatley 50 feet apart.

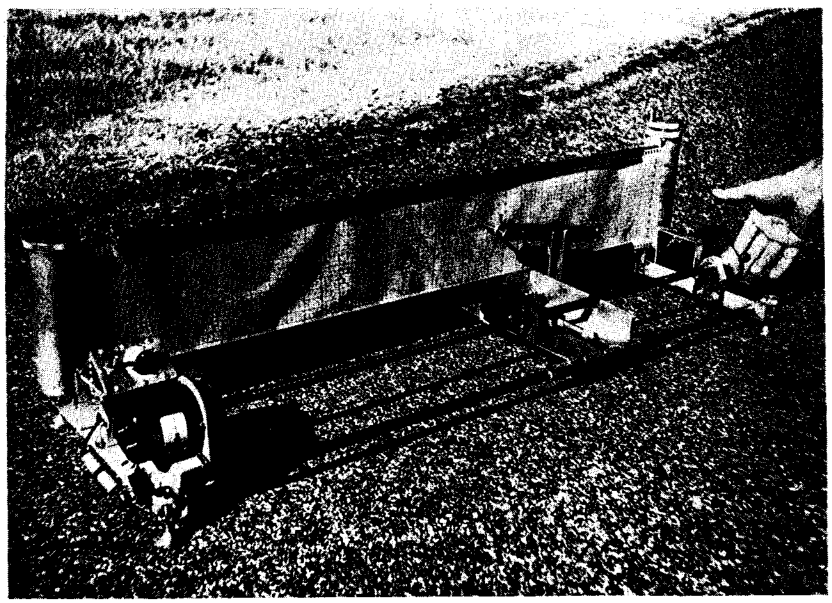

Figure 3. Profilograph Equipment Used for Macro-Texture Measurements.

Figure 4. Putty Impression Equipment Used for Macro-Texture Measurements.

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

It is important to again note that several variables were introduced under controlled conditions for the tests. These are enumerated as follows:

1. Test surfaces, classified with respect to type, mineralogical classification, and aggregate size configuration.

2. Friction mechanism and method, cornering slip with the Mu-Meter, and skidding slide with the trailer. Values are reported as slip and skid numbers respectively.

3. Pavement condition with respect to absence or presence of water film; dry implies no water film, wet implies approximately 0.020-inch water film thickness.

4. Process for wetting pavement, internal implies utilization of the skid trailer's self-contained watering system, external implies use of a water truck as a separate operation.

5. Tire crown configuration with respect to absence or presence of grooves - smooth (or bald) tire implies no tread, E-17 tire implies the standard circumferentially grooved tread.

6. Tire inflation pressure, 10 or 24 psi as indicated.

Thus it is evident that data analysis and conclusions should be made with due respect for the prevailing test conditions and differences in equipment. A tabulation of slip and skid numbers, friction-velocity gradients and percentage gradients, and macrotexture measures is contained in Table 2. Average slip and skid numbers for the test surfaces are given in Table 3 and average gradients and percentage gradients given in Table 4.

TABLE 2: SLIP AND SKID NUMBERS, FRICTION-VELOCITY GRADIENTS, PERCENTAGE GRADIENTS AND MACROTEXTURE VALUES FOR THE FIFTEEN SURFACES

Surface Number	Mu-Meter, Smooth Tire, Dry Pavement, 10 psi Tire Pressure, Slip Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Percentage Gradient 20-60 mph	Mu-Meter, Smooth Tire, Dry Pavement, 24 psi Tire Pressure, Slip Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Mu-Meter, Smooth Tire, External Wet Pavement, 10 psi Tire Pressure, Slip Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Percentage Gradient 20-60 mph	Mu-Meter, Smooth Tire, External Wet Pavement, 24 psi Tire Pressure, Slip Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Trailer, E-17 Tire, Internal Wet Pavement, 24 psi Tire Pressure, Skid Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Trailer, E-17 Tire, External Wet Pavement, 24 psi Tire Pressure, Skid Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Percentage Gradient 20-60 mph	Trailer, Smooth Tire, External Wet Pavement, 24 psi Tire Pressure, Skid Number 20 mph	40 mph	60 mph	Gradient 20-60 mph	Percentage Gradient 20-60 mph	Putty Impression, Macrotexture, Average Texture Depth (Inch)	Profilograph, Macrotexture, Average Peak Height (Inch)
3	83	82	80	0.08	4	72	71	71	0.03	46	29	19	0.68	59	52	28	19	0.83	50	40	35	0.38	54	40	33	0.52	39	36	17	15	0.52	58	.0090	.0212
4	64	64	65	0.00	0					48	33	25	0.57	48					37	31	29	0.20	41	30	23	0.45	44						.0234	.0252
11	56	56	56	0.00	0					44	32	25	0.47	43					35	30	32	0.08	43	35	31	0.30	28						.0340	.0279
13	70	69	69	0.03	1	71	70	71	0.00	67	50	40	0.68	40	68	52	41	0.68	66	58	54	0.30	65	53	44	0.52	32	57	32	28	0.73	51	.0182	.0182
17	76	76	75	0.03	1	81	79	77	0.10	67	68	68	0.00	0	73	72	70	0.08	66	57	49	0.43	64	55	49	0.37	23	68	55	53	0.37	22	.0224	.0190
18	77	77	76	0.03	1	79	77	78	0.03	69	71	71	0.00	0	73	73	72	0.03	65	58	50	0.38	65	57	50	0.37	23	71	60	53	0.45	25	.0412	.0333
22	73	73	73	0.00	0					54	38	30	0.60	44					50	40	35	0.38	51	40	33	0.45	35						.0115	.0191
28	79	80	79	0.00	0					52	53	48	0.10	8	46	42	39	0.18	41	36	39	0.05	42	38	39	0.08	07	39	34	30	0.23	23	.0563	.0570
31	80	78	77	0.08	4					70	55	35	0.88	50					47	38	31	0.40	57	43	29	0.70	49						.0432	.0174
33	62	61	59	0.08	5					61	59	56	0.13	8					64	63	62	0.05	69	62	59	0.25	15						.0648	.0557
T-1	69	68	69	0.00	0	67	67	67	0.00	62	47	36	0.65	42					50	42	38	0.30	64	53	46	0.45	28	54	40	30	0.60	44	.0224	.0235
T-2	72	72	71	0.03	1	69	67	67	0.05	66	62	58	0.20	12					54	48	44	0.25	63	55	47	0.40	25	67	51	38	0.73	43	.0235	.0195
T-3	68	67	67	0.03	1	67	68	68	0.00	68	42	25	1.07	63					72	64	61	0.28	68	59	51	0.43	25	77	45	27	1.25	65	.0093	.0149
T-4	67	67	67	0.00	0	69	67	67	0.05	39	19	10	0.73	74	44	20	12	0.80	26	18	17	0.23	26	16	13	0.33	50	29	15	10	0.47	66	.0019	.0136
T-5	73	73	71	0.05	3	76	73	73	0.08	56	38	27	0.73	52	64	50	41	0.58	49	46	40	0.23	49	40	36	0.33	27	46	33	27	0.47	41	.0280	.0203

TABLE 3: AVERAGE SLIP AND SKID NUMBERS FOR THE TEST SURFACES

	Mu-Meter				Trailer			
	Smooth Tire				E-17 Tire		Smooth Tire	
	Dry Pavement		External Wet Pavement		Internal Wet Pavement	External Wet Pavement		
	10 psi Tire Pressure	24 psi Tire Pressure	10 psi Tire Pressure	24 psi Tire Pressure	24 psi Tire Pressure			
Velocity	Slip Number				Skid Number			
20 MPH	71		58		52	55		Averages for 15 surfaces
40 MPH	71		46		45	45		
60 MPH	70		38		42	39		
20 MPH	73		59		54	56	54	Averages for 10 surfaces
40 MPH	73		48		47	46	38	
60 MPH	72		40		43	41	31	
20 MPH	77	76	61	62	58	58	54	Averages for 5 surfaces
40 MPH	77	74	54	53	50	49	40	
60 MPH	76	74	49	48	45	43	36	

TABLE 4: AVERAGE GRADIENTS AND PERCENTAGE GRADIENTS FOR THE TEST SURFACES

Velocity Range	Mu-Meter				Tralier			
	Smooth Tire				E-17 Tire		Smooth Tire	
	Dry Pavement		External Wet Pavement		External Wet Pavement			
	10 psi Tire Pressure				24 psi Tire Pressure			
	Gradient	Percentage Gradient	Gradient	Percentage Gradient	Gradient	Percentage Gradient	Gradient	Percentage Gradient
20-60 mph*	.03	1%	.50	36%	.40	30%		
20-60 mph**	.03	1%	.48	35%	.38	28%	.58	44%

*Averages for 15 surfaces.
**Averages for 10 surfaces.

Average friction number-velocity values for the test surfaces are plotted with respect to the seven test conditions in Figure 5. Ten of the surfaces were tested under five different test conditions; these data are shown in Figure 5-B. Data were obtained on an additional five surfaces with only four test conditions; these results are given in Figure 5-A. Figure 5-C contains complete data as obtained with the seven conditions on five surfaces.

The Mu-Meter results indicate that slip numbers are not affected by velocity increase on dry pavements. On wet pavements both the Mu-Meter (smooth tire) and trailer (E-17 tire) results reflect the characteristic decrease in friction with increase velocity. On the average, at 20 mph, the Mu-Meter indicates slightly higher friction than the trailer; whereas at 60 mph, both instruments indicate the same magnitude. (See Figure 5-A, condition 3 and 4.) Results from the trailer operating with a smooth tire (condition 6) compared favorably with both the Mu-Meter (smooth tire) and the trailer (E-17 tire) at 20 mph; however, much lower values were obtained at higher speeds. (See Figure 5-B.) This is to be expected when consideration is given to the fact that the Mu-Meter is operating in the slip mode, whereas the trailer is operating in the skid mode, thus, higher friction values are expected in the 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 slip mode with a smooth tire. At the lower speeds, however, drainage effects are reduced and the overriding effects of the slip mode prevail; thus, the Mu-Meter records slightly higher friction values. (See Figure 5-A and B, conditions 3 and 4.) It must be remembered, however, that these conclusions are specific and will not

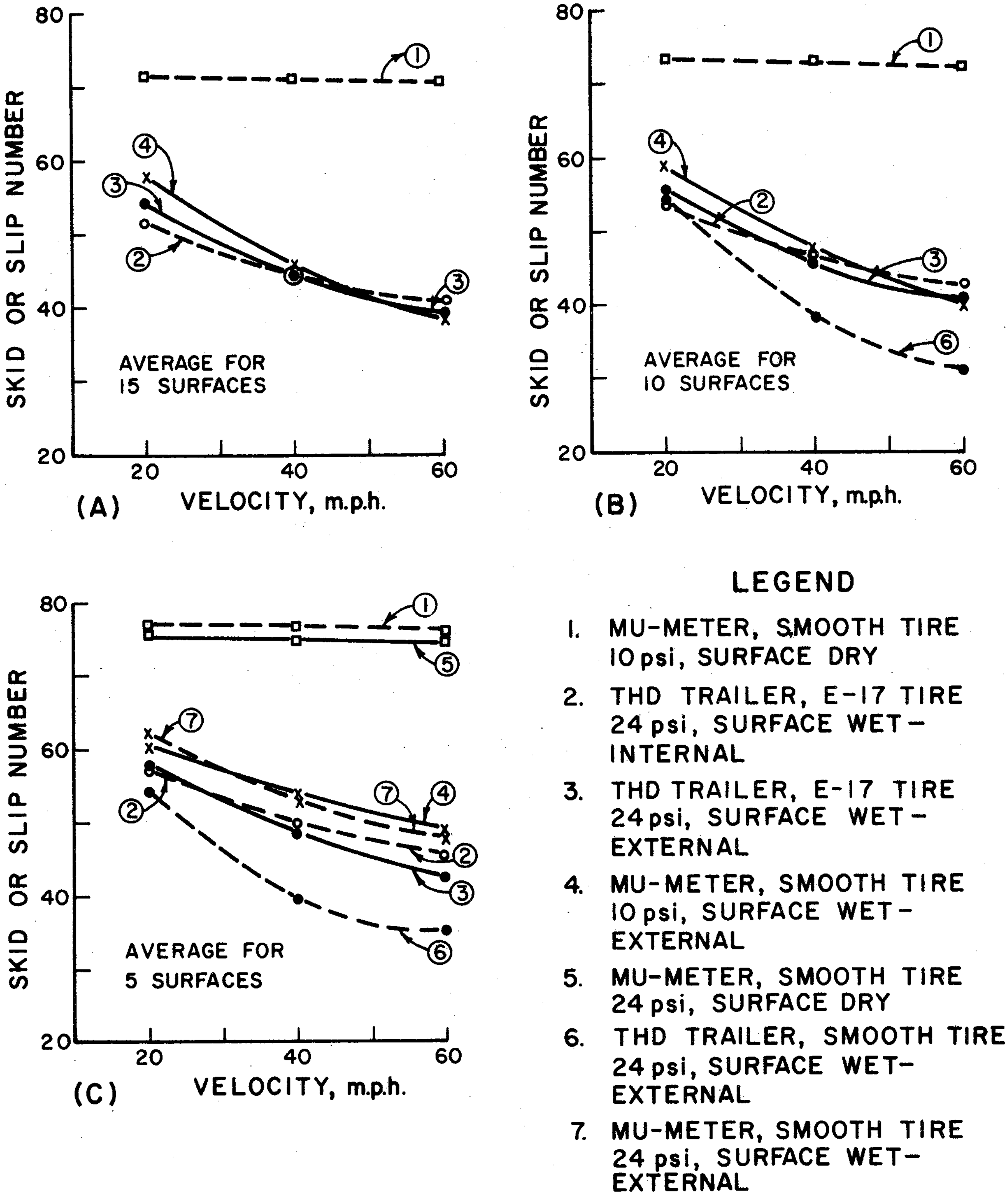

FIGURE 5. AVERAGE FRICTION-VELOCITY COMPARISONS FOR DIFFERENT TEST CONDITIONS.

necessarily hold for all surface types, equipment, variables and/or environmental conditions. For example, in Figure 5-C, the curves for conditions 3 and 4 differ appreciably when the average curves represent only five surfaces.

Figures 6-A-G, Appendix A, show friction number-velocity plots obtained from the test surfaces using the seven test condition combinations covered in the study. These data are summarized in Figure 5. The range in friction numbers found on the surfaces are eivdent from these data.

The reader's attention is directed to the vertical scale difference in Figures 6-A and 6-E. In these figures the vertical scales have been doubled to avoid over crowding of the curves. It is also of interest to note that surface T-4, a poor performer when wet, gives highly acceptable values when tested dry in the slip mode (see Figure 6-A and 6-E). Surface T-4 represents a flushed bituminous pavement.

It is also interesting to note that surfaces 17 and 18, open-graded lightweight aggregate hot mix, exhibit essentially flat gradients at about 70 slip number when tested wet in the slip mode (Figures 6-D and 6-G); but assume lower skid numbers and steeper gradients when tested wet in the skid mode (Figures 6-B, 6-C, and 6-F). A comparison of Figure 6-C and 6-F indicates that these surfaces have essentially the same skid numbers and gradients when tested with a treaded or smooth tire. The macrotexture of these pavements is comparable to that of many other Texas highways that have completely different skid and slip "foot prints", but the microtexture is different. The coarse aggregate in these pavements is essentially all lightweight expanded clay or shale aggregate and if one examines the aggregate particle structure, it will be noted that such material is composed of a mass of air bubbles in a matrix of inorganic mineral matter that forms the bubble walls. As the pavement (aggregate) wears in service, the aggregate surface texture (microtexture) is constantly renewed. From these data it appears that microtexture is quite important in slip or cornering.

The friction number-velocity data contained in Figures 6a-6g are separated with respect to individual surfaces in Figures 7a-7o in Appendix B. From these figures, effects of the different tire inflation pressures, tire tread depths, surface conditions with respect to wet or day, 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 succeeding figures, statistical analyses were conducted on the various relationships. Results are appended in tabular form in Tables 5, 6, and 7. Also these data are appended along with their respective graphs in Figures 8-18.

Comparisons of friction numbers obtained with various test conditions are given in Figures 8a-8f, Appendix C.

Figure 8a shows test results as obtained with each instrument operating under respective standard test conditions, i.e., trailer with E-17 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 insure 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 since the relative drainage abilities of the two tires differ markedly; however, drainage is not as critical at lower speeds as it is at higher speeds. Also the surfaces differ more in their relative drainage abilities at the higher speeds which also contributes to the lower correlation at higher speeds. It is also interesting to note, that, on an average, as speed increased, the skid number became lower than the slip number. This is also born out by the regression coefficients. At 20 mph the slip mode measure is greater than the skid mode measure-- but 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.

Contained in Figure 8b are also Mu-Meter - trailer friction comparisons; however, these comparisons differ from Figure 8a 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 slip and skid mode comparison. Slip numbers obtained at each speed were, on an average, higher than corresponding skid numbers. This is to be expected since available friction during the slip (rolling) mode is higher than available friction in the 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 in Figure 8a. This constancy indicates that the relative drainage capabilities of the vehicles were essentially identical at the given speeds. It is also interesting to note that, although on an average both methods measured a decrease in friction levels with corresponding increases in speed, the range in trailer values became smaller with increase in speed, whereas the range in Mu-Meter values became larger with increase in speed.

Various velocity comparisons of skid (trailer) tests with treaded and smooth tires are shown in Figure 8c. Relative positions of the surfaces, with respect to increased velocities, are not maintained. Excepting 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 type surfaces. Note also that the correlation coefficient was lower at the higher speed.

As can be seen from Figure 8d, skid numbers obtained with the trailer at various speeds with respect to the two 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 utilizing external watering procedures. Variations in the wetting procedures, resulting in different water film thicknesses, 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.

As shown in Figure 8e, surface type and test velocity have little effect on dry pavement slip number. In addition, dry pavement slip numbers correlate poorly with wet pavement slip numbers as evidenced by the extremely low correlation coefficients.

Limited data, comparing slip numbers obtained with tire inflation pressures of 10 and 24 psi, are shown in Figure 8f. 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, it can be noted that all the surfaces were grouped rather close together as far as slip number variations are concerned; thus, rendering correlation somewhat meaningless in this comparison.

Comparisons of friction velocity gradients obtained from 20 to 60 mph on the various surfaces are given in Figure 9, Appendix D. Plot "a" indicates that steeper gradients were obtained on most surfaces when tested with the smooth tire on the trailer than with the E-17 tire. Also, note that the range in gradients obtained with the smooth tire was greater than that obtained with the E-17 tire. These results indicate that different type surfaces vary appreciably in ability to drain water from under a tire. Similar conclusions can be drawn from Figure 9b. 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. The plot in Figure 9c indicates that the test mode also influences gradient. Surfaces which 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.

Comparisons of friction number velocity percentage gradients obtained from 20-60 mph on the various surfaces are shown in Figure 10, Appendix D. Similar conclusions can be drawn from plots "a" and "b" as were drawn from Figure 9, plots "a" and "b" respectively. However, Figure 10c reveals a much higher correlation between percentage gradient as obtained with smooth tires on the Mu-Meter and trailer; whereas Figure 9c did not indicate nearly as high a correlation.

Comparisons of 40 mph friction numbers and 20-60 mph friction number velocity gradients for the various surfaces are presented in Figure 11,

Appendix D. The trailer plots in "a" and "c" do not reveal 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 20-60 mph friction number velocity percentage gradients for the various surfaces are presented in Figure 12, Appendix D. 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 surfaces with low 40 mph friction numbers. Points positioned to the right of the best-fit line represent surfaces which 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.

Relationships between 40 mph friction numbers measured under differing conditions and macrotexture measured by the profilograph and putty impression methods are presented in Figures 13 and 14, Appendix D. In general the plots indicate a slight positive relationship between friction number and macrotexture; however, the spread of data points is extremely wide. Better comparisons were in evidence when macrotexture was measured by the putty impression method. Microtexture effects and interrelationships with macrotexture are reflected in the friction numbers, thus the individual effects of these two factors could not be evaluated. Measurement of microtexture is beyond the scope of this study.

Relationships between 20 to 60 mph friction number velocity gradients, measured under differing conditions, and macrotexture, measured by the putty impression and profilograph methods, are presented in Figures 15 and 16, Appendix E. In general, excepting tests on dry surfaces, a negative relationship between gradient and macrotexture was obtained. Gradients, obtained with the E-17 tire on the trailer, correlated best with texture measured by the profilograph; whereas, gradients obtained with the Mu-Meter correlated best with texture measured by the putty method.

Relationships between 20 to 60 mph friction number velocity percentage gradients, measured under differing conditions, and macrotexture, measured by the putty impression and profilograph methods, are presented in Figures 17 and 18, Appendix E. With the exception of dry pavement tests, negative relationships between percentage gradient and macrotexture exist. Correlation coefficients are correspondingly higher than those obtained in the gradient texture comparisons, Figures 15 and 16.

CONCLUSIONS

Based on the test procedures, the environmental conditions and the equipment utilized in these studies the following tentative conclusions appear warranted.

1. The skid trailer and the Mu-Meter correlate quite well provided both instruments are equipped with smooth (treadless) tires and are operated on pavement surfaces wetted alike. Correlation coefficients of 0.94, 0.92 and 0.96 were obtained at 20, 40 and 60 mph, respectively.

2. When the Mu-Meter with smooth tires is compared with the trailer equipped with ASTM E-17 treaded tires, the correlation coefficients dropped to 0.86, 0.80 and 0.75 at 20, 40 and 60 mph, respectively. The decrease in the correlation coefficient with increased speed is attributed to the relative difference in the drainage capabilities of the smooth versus the treaded tires.

3. For the water film thickness (approximately 0.020 inches) used in these studies friction values obtained on highly textured surfaces with either smooth or ASTM treaded tires do not differ appreciably. This statement further assumes that the microtexture of that part of the surface contacting the tire rubber is essentially the same.

4. Internal versus external pavement wetting processes for the skid trailer exhibited correlation coefficient of 0.92, 0.93 and 0.93 at speeds of 20, 40 and 60 mph, respectively. In some instances the efficiency of the internal watering system was reduced at high speeds due to splash and wind effects.

5. The Mu-Meter gave high values on all clean dry surfaces at speeds from 20 to 80 mph; however, the correlations between values obtained on pavements in the wet and dry condition were quite poor (See Figure 7 in Appendix A).

6. At a fixed gross load, tire pressure had little influence on Mu-Meter values obtained from tests on wet pavements.

7. To point out the relative drainage capabilities of the E-17 (treaded) and smooth tires, a good correlation (correlation coefficient of 0.92) was found to exist between the percentage gradients of the Mu-Meter and the trailer when both were equipped with smooth tires.

8. Macrotexture and 40 mph trailer skid values showed little correlation. A somewhat better correlation was found to exist between Mu-Meter results and macrotexture (correlation coefficient equal to 0.56).

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APPENDIX A

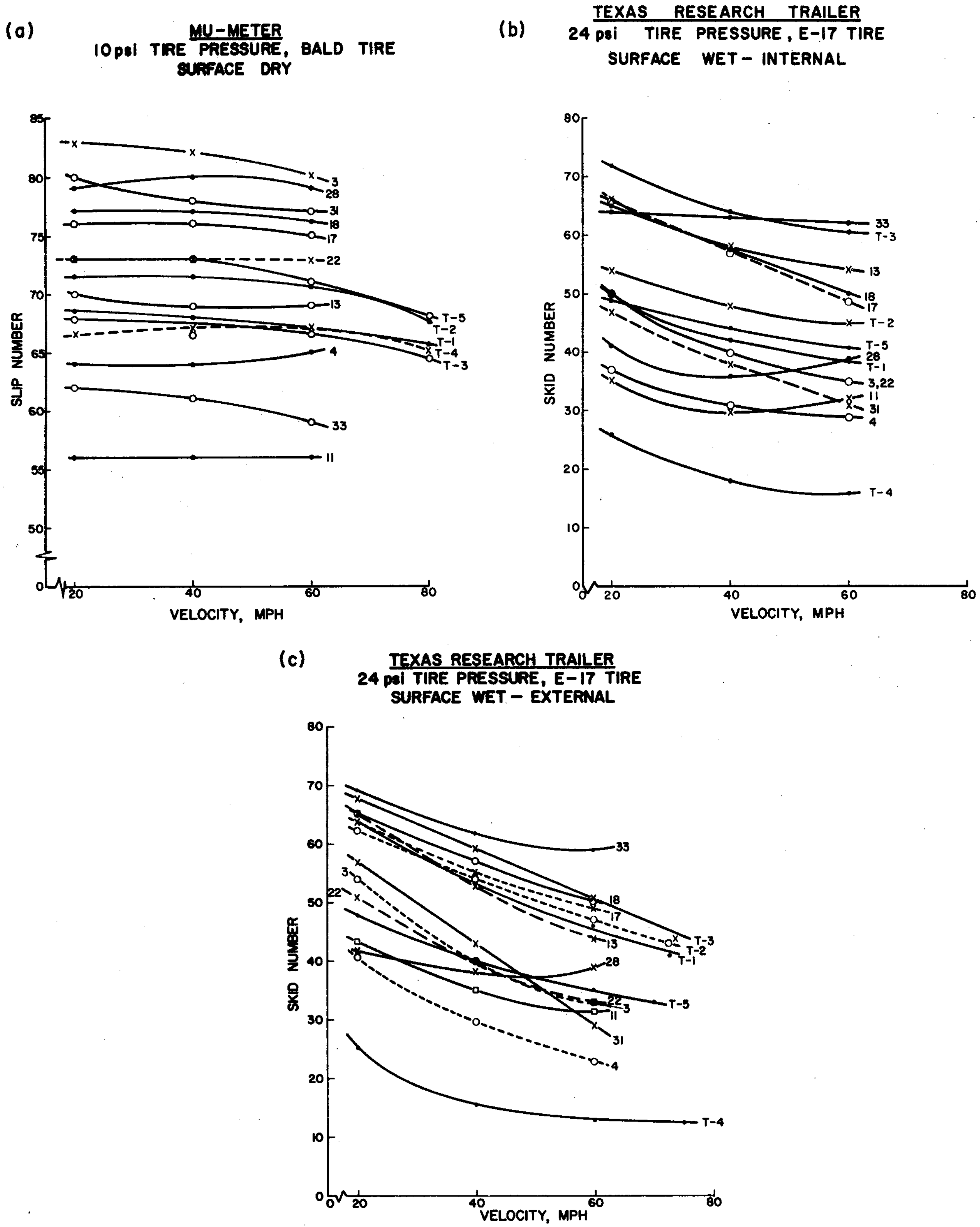

FIGURE 6. EFFECT OF PAVEMENT TYPE ON FRICTION VALUES.

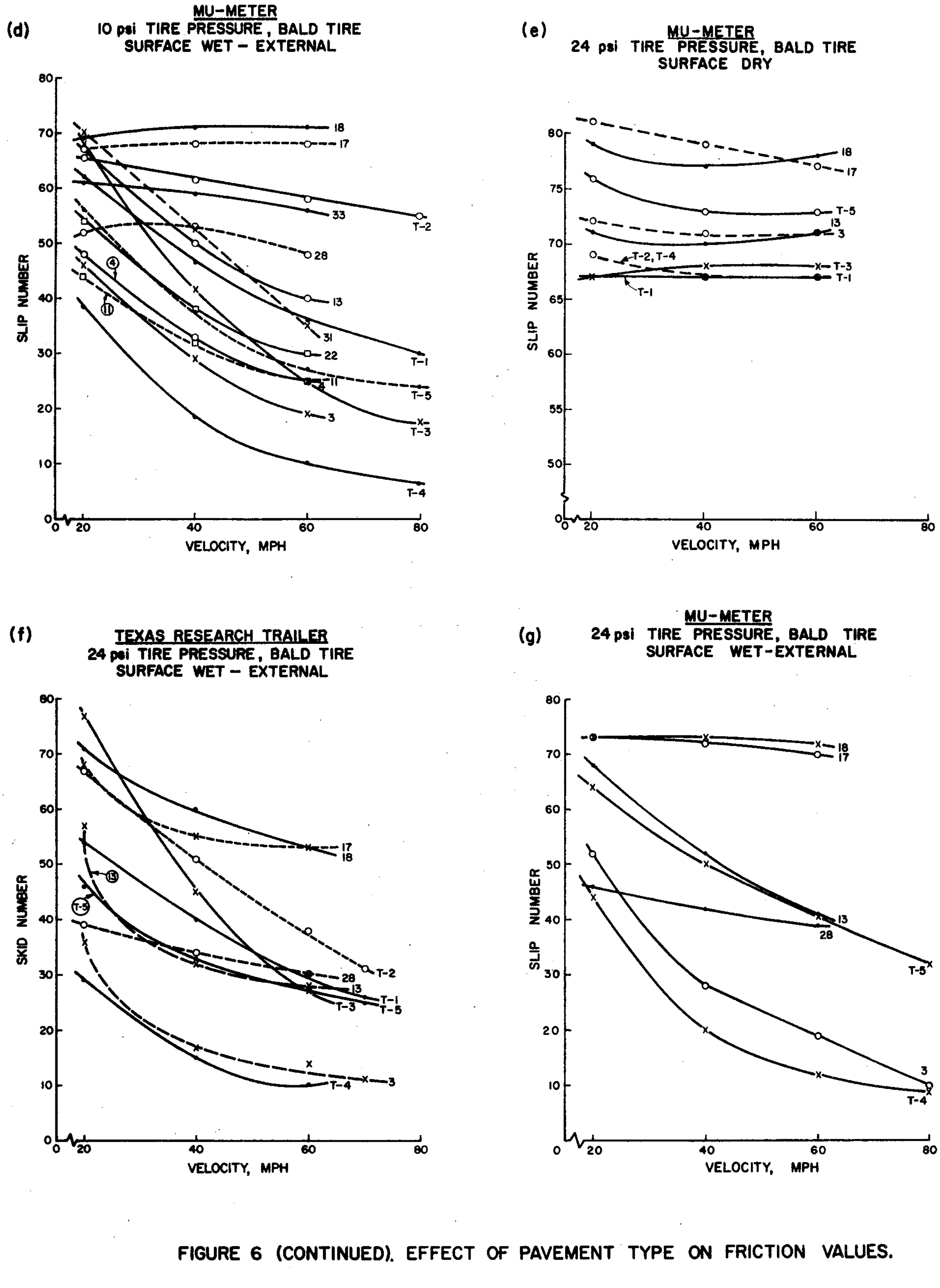

FIGURE 6 (CONTINUED). EFFECT OF PAVEMENT TYPE ON FRICTION VALUES.

APPENDIX B

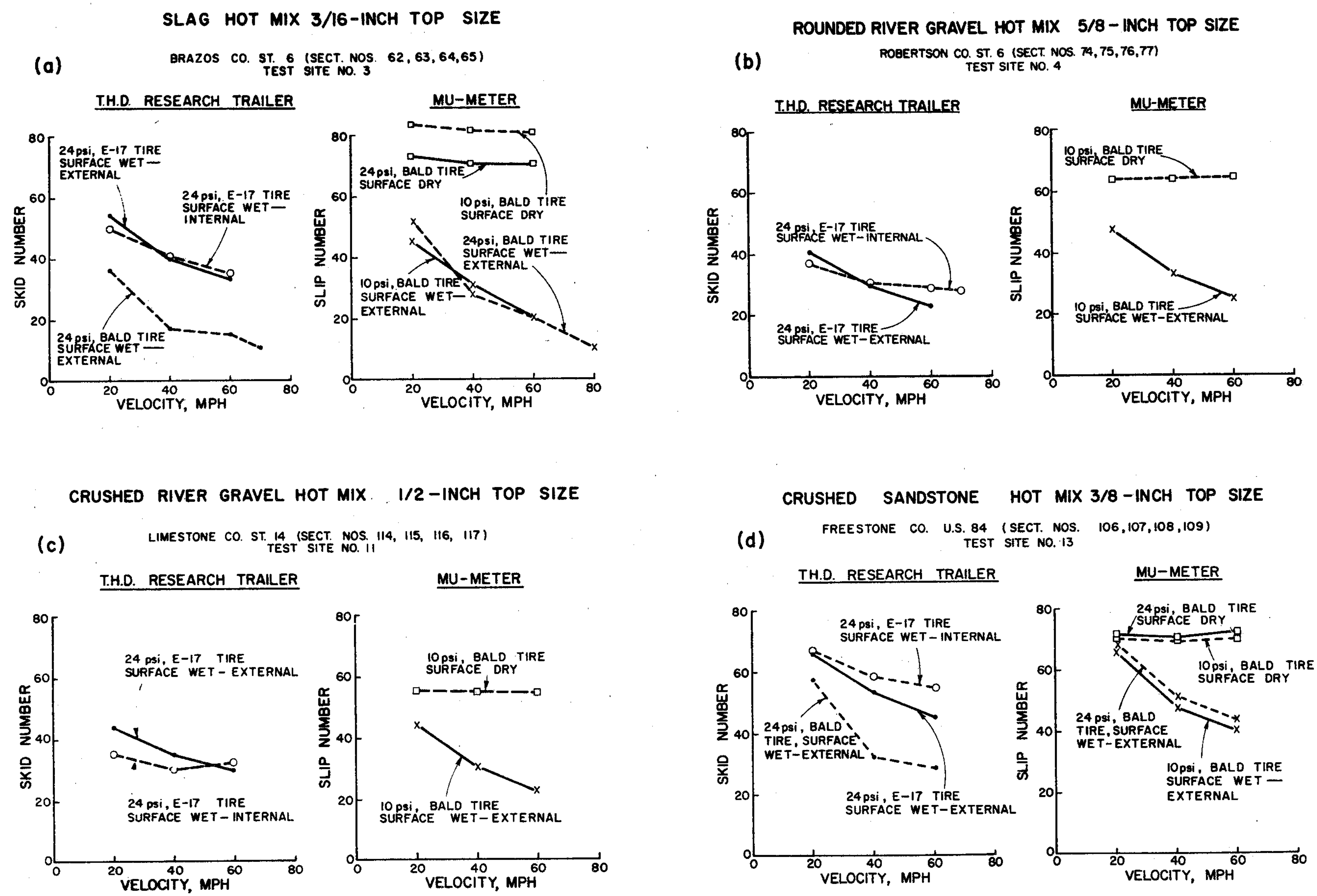

FIGURE 7. TRAILER AND MU-METER FRICTION VALUES.

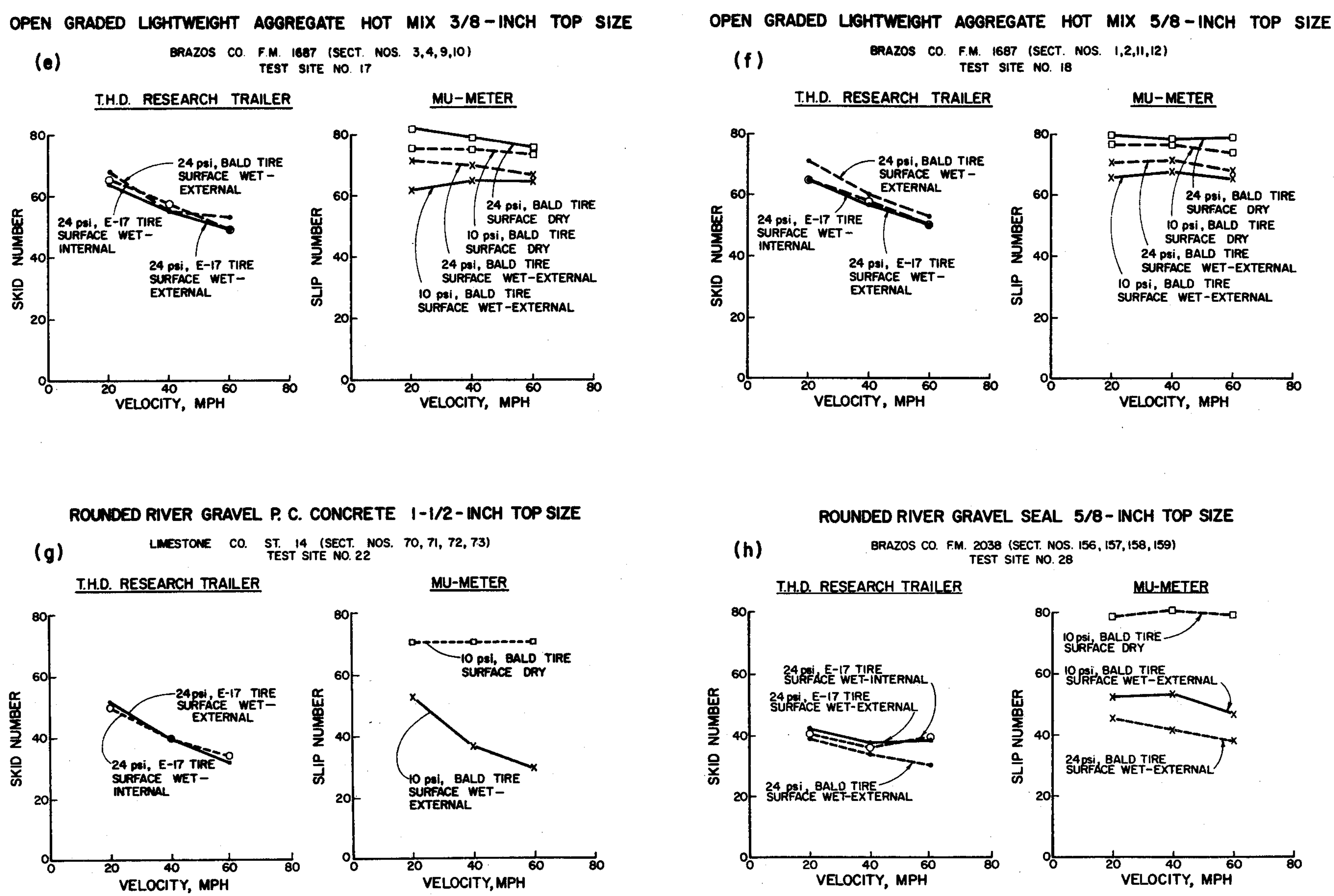

FIGURE 7 (CONTINUED). TRAILER AND MU-METER FRICTION VALUES.

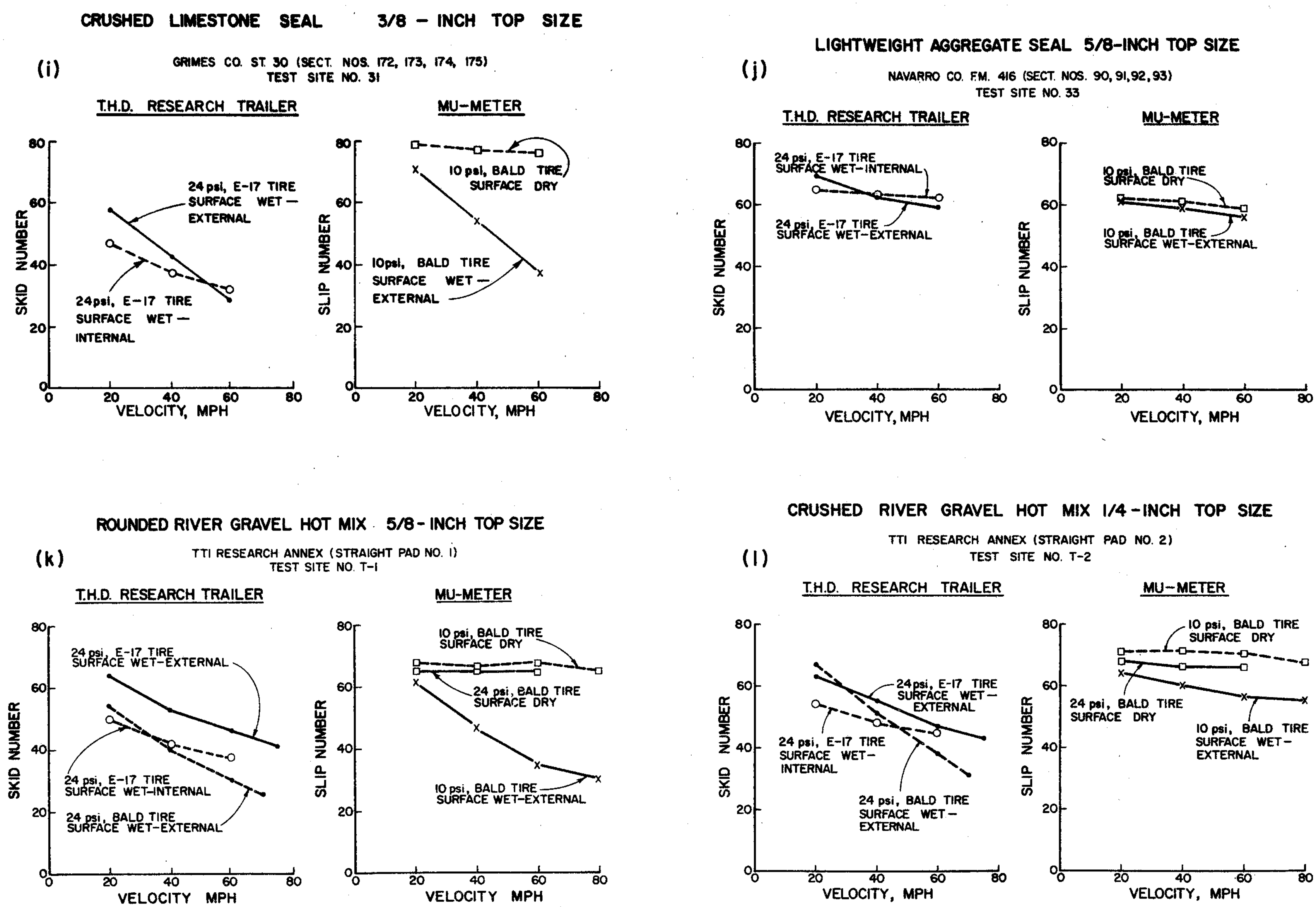

FIGURE 7 (CONTINUED). TRAILER AND MU-METER FRICTION VALUES.

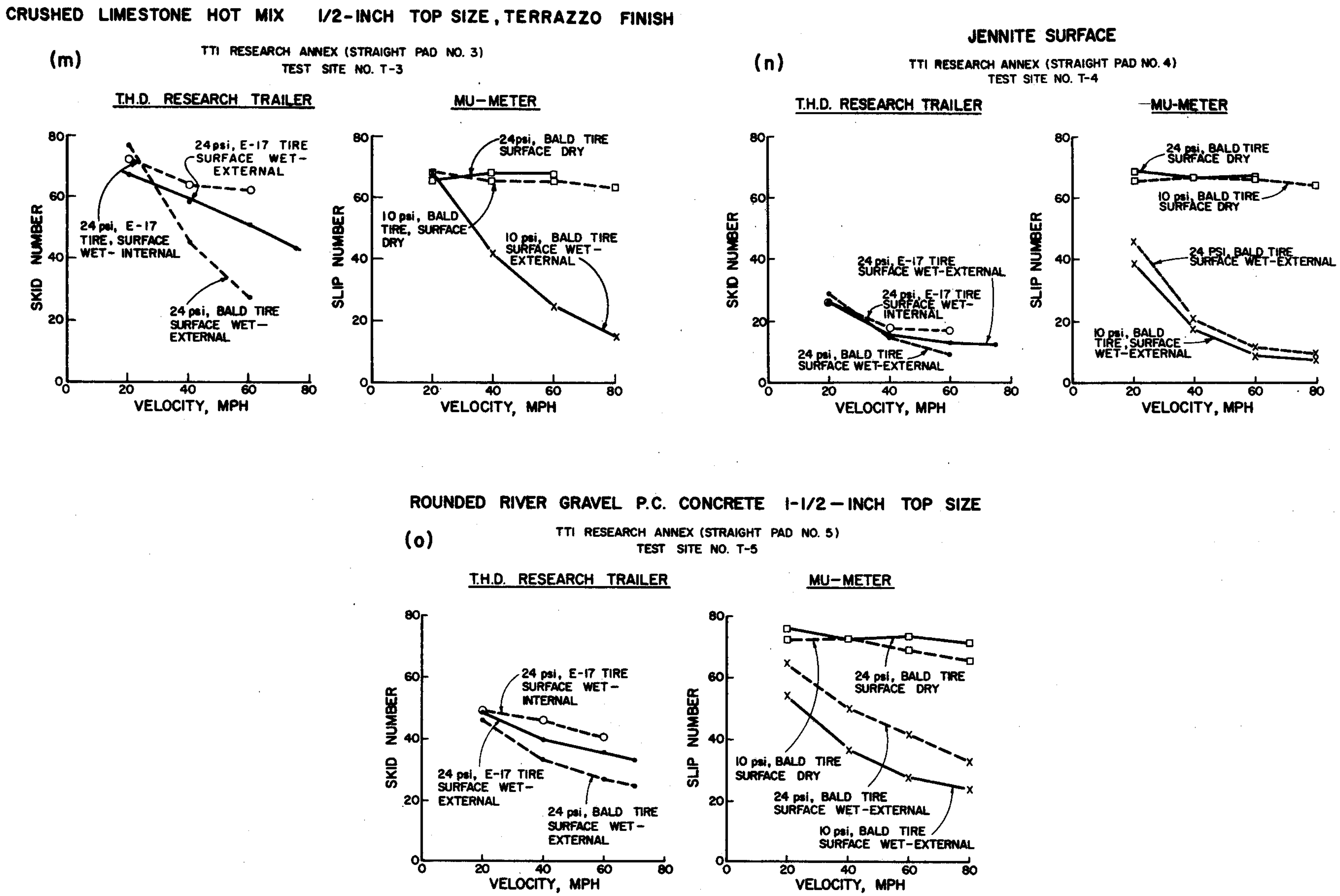

FIGURE 7 (CONTINUED). TRAILER AND MU-METER FRICTION VALUES.

APPENDIX C

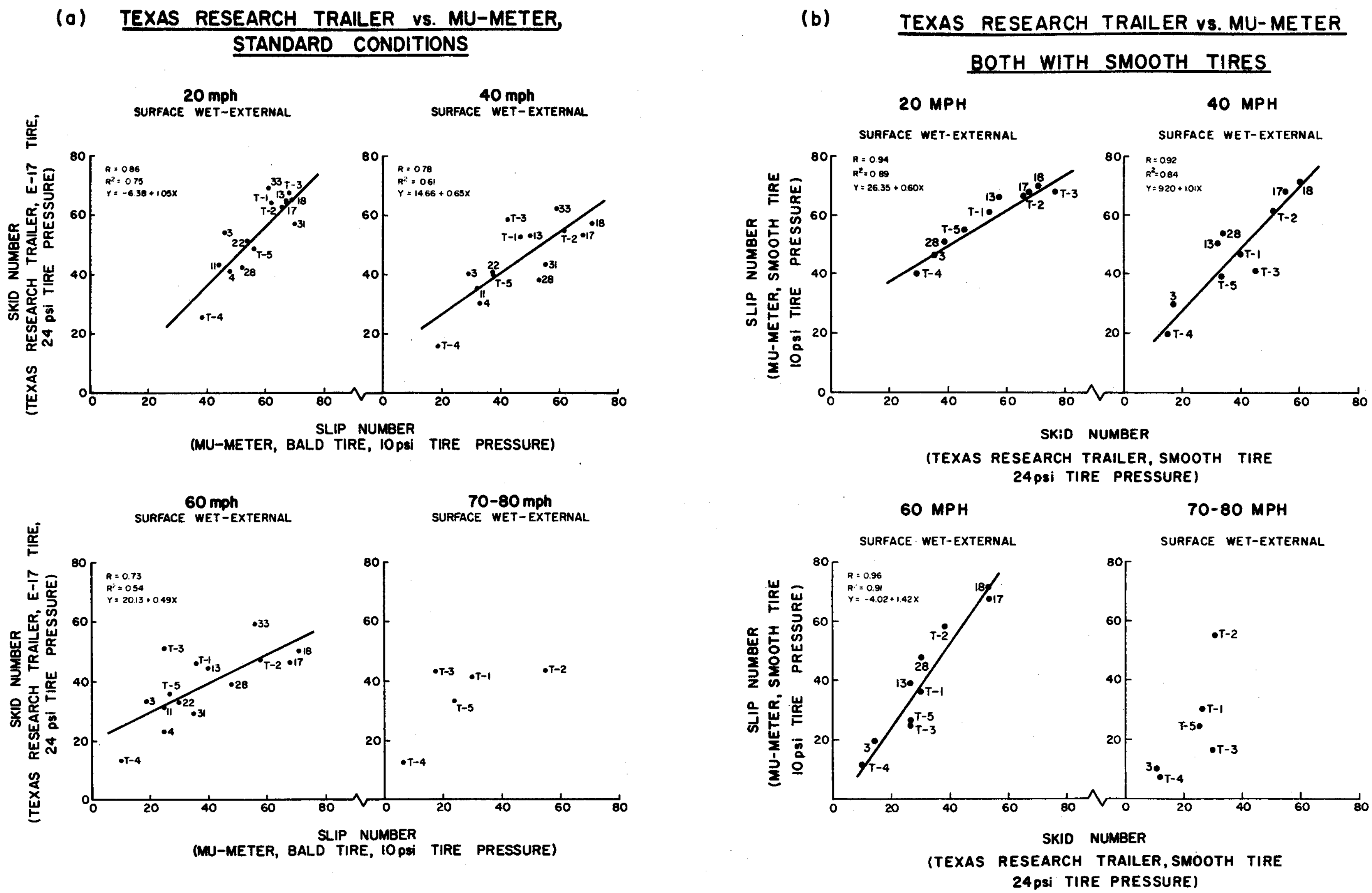

FIGURE 8. FRICTION NUMBER COMPARISONS.

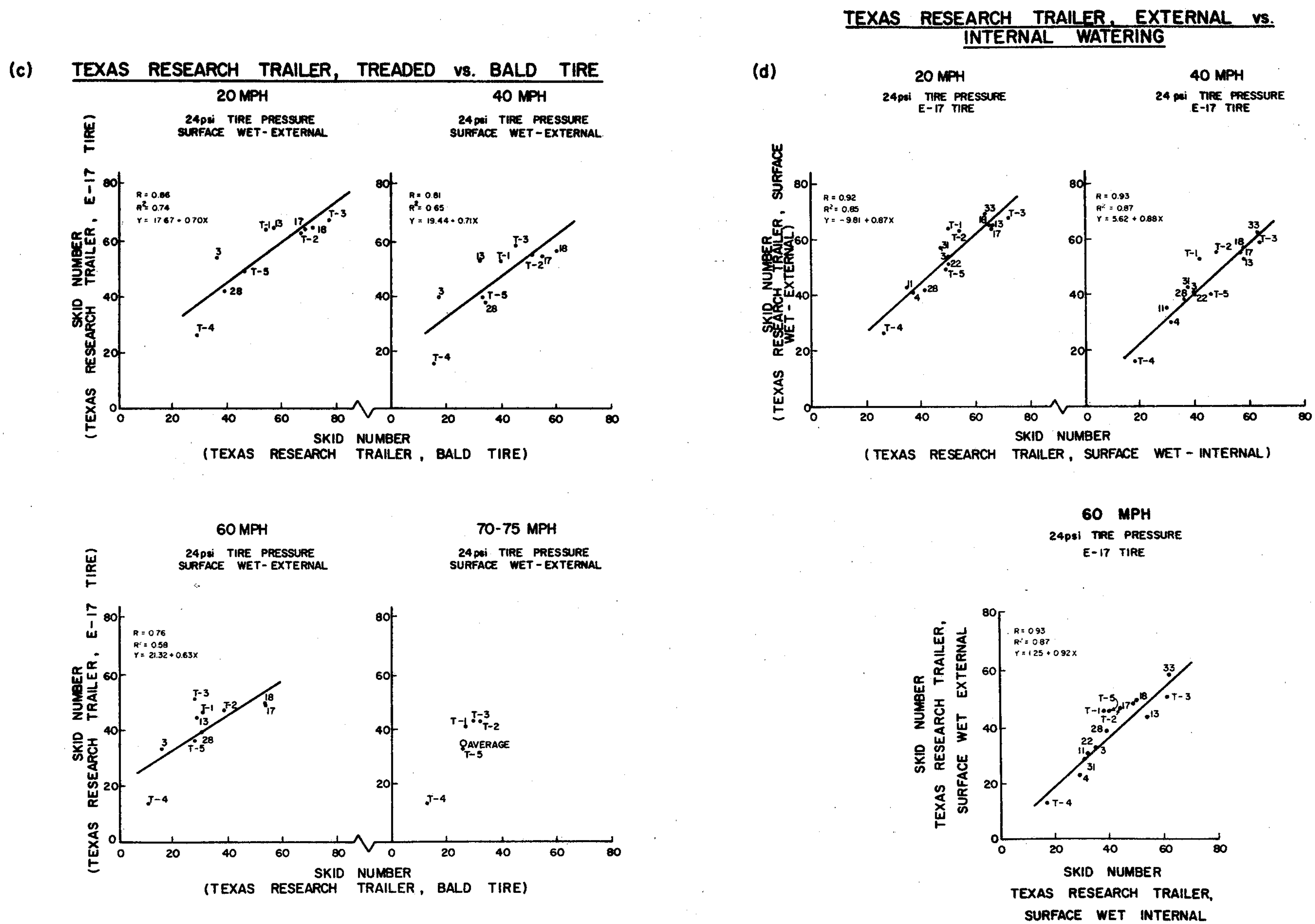

FIGURE 8 (CONTINUED). FRICTION NUMBER COMPARISONS.

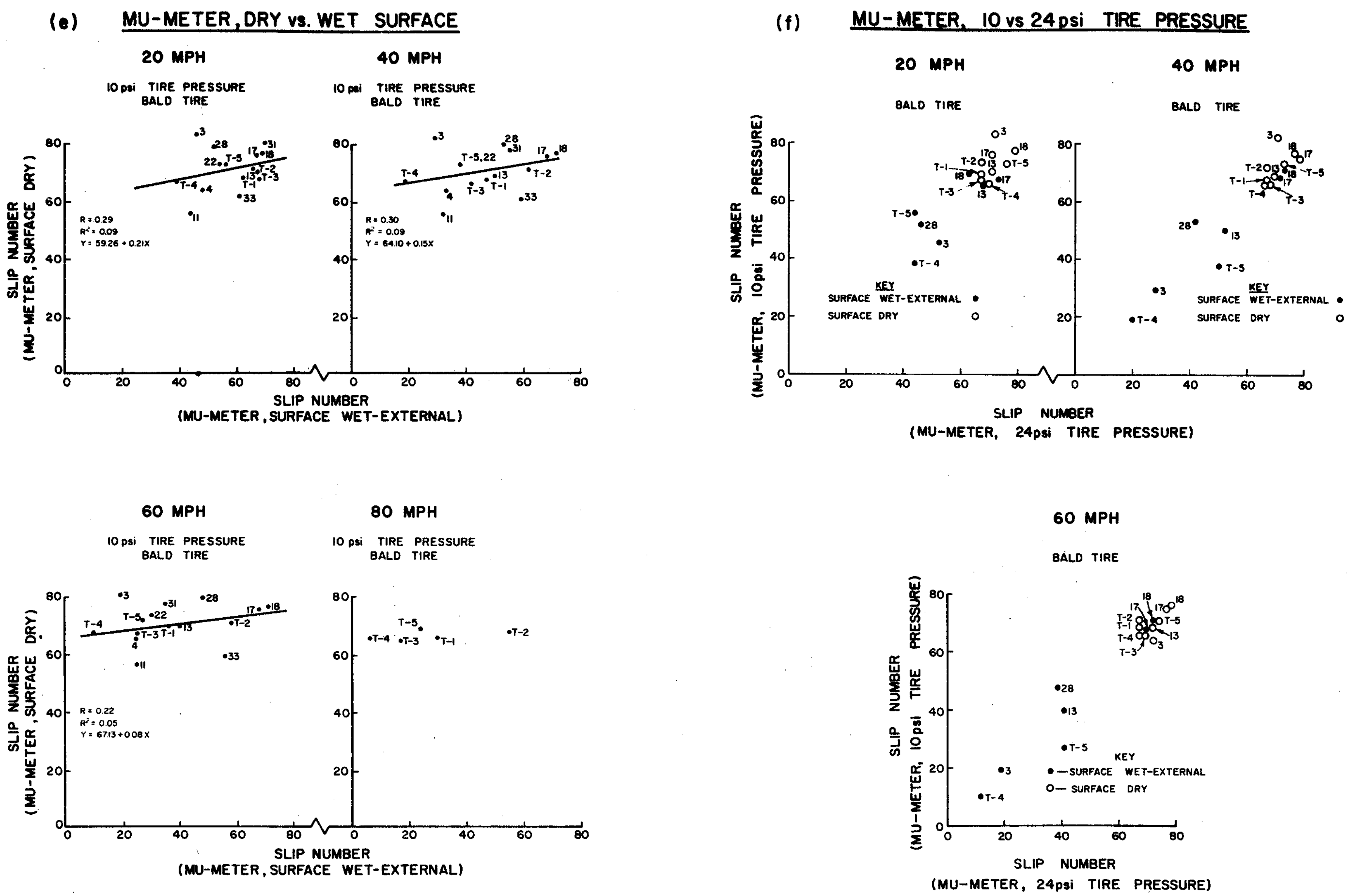

FIGURE 8 (CONTINUED). FRICTION NUMBER COMPARISONS.

TABLE 5. STATISTICAL COMPARISONS OF FRICTION NUMBERS OBTAINED AT VARIOUS SPEEDS AND TEST CONDITIONS

Variables Y	Variables X	Number of Comparisons	Figure Number	Regression Line	Correlation Coefficient	Coefficient of Determination	Standard Deviation
SN_{20}(3)	SN_{20}(4)	15	8a	Y = -6.38 + 1.05X	.86	.75	6.55
SN_{40}(3)	SN_{40}(4)	15	8a	Y = 14.66 + 0.65X	.78	.61	8.20
SN_{60}(3)	SN_{60}(4)	15	8a	Y = 20.13 + 0.49X	.73	.54	8.58
SN_{20}(4)	SN_{20}(6)	10	8b	Y = 26.35 + 0.60X	.94	.89	3.68
SN_{40}(4)	SN_{40}(6)	10	8b	Y = 9.20 + 1.01X	.92	.84	7.05
SN_{60}(4)	SN_{60}(6)	10	8b	Y = -4.02 + 1.42X	.96	.91	6.45
SN_{20}(3)	SN_{20}(6)	10	8c	Y = 17.67 + 0.70X	.86	.74	7.30
SN_{40}(3)	SN_{40}(6)	10	8c	Y = 19.44 + 0.71X	.81	.65	8.29
SN_{60}(3)	SN_{60}(6)	10	8c	Y = 21.32 + 0.63X	.76	.58	7.93
SN_{20}(3)	SN_{20}(2)	15	8d	Y = 9.81 + 0.87X	.92	.85	4.97
SN_{40}(3)	SN_{40}(2)	15	8d	Y = 5.62 + 0.88X	.93	.87	4.68
SN_{60}(3)	SN_{60}(2)	15	8d	Y = 1.25 + 0.92X	.93	.87	4.60
SN_{20}(1)	SN_{20}(4)	15	8e	Y = 59.26 + 0.21X	.29	.09	7.23
SN_{40}(1)	SN_{40}(4)	15	8e	Y = 64.10 + 0.15X	.30	.09	7.19
SN_{60}(1)	SN_{60}(4)	15	8e	Y = 67.13 + 0.08X	.22	.05	6.97
SN_{20}(4)	SN_{20}(7)	7	8f	Y = 4.67 + 0.87X	.93	.86	4.79
SN_{40}(4)	SN_{40}(7)	7	8f	Y = 3.34 + 0.90X	.94	.89	7.17
SN_{60}(4)	SN_{60}(7)	7	8f	Y = -1.06 + 0.99X	.96	.92	7.34
SN_{20}(1)	SN_{20}(5)	9	8f	Y = 30.64 + 0.58X	.59	.34	4.46
SN_{40}(1)	SN_{40}(5)	9	8f	Y = 20.62 + 0.73X	.63	.40	4.31
SN_{60}(1)	SN_{60}(5)	9	8f	Y = 25.47 + 0.65X	.63	.39	3.71

SN = Skid or Slip Number, suffix indicating speed in mph.
() = Numbers in parentheses indicate test conditions as described below:
1 = Mu-Meter, smooth tire, 10 psi, surface dry.
2 = THD Trailer, E-17 tire, 24 psi, surface wet-internal.
3 = THD Trailer, E-17 tire, 24 psi, surface wet-external.
4 = Mu-Meter, smooth tire, 10 psi, surface wet-external.
5 = Mu-Meter, smooth tire, 24 psi, surface dry.
6 = THD Trailer, smooth tire, 24 psi, surface wet-external.
7 = Mu-Meter, smooth tire, 24 psi, surface wet-external.

APPENDIX D

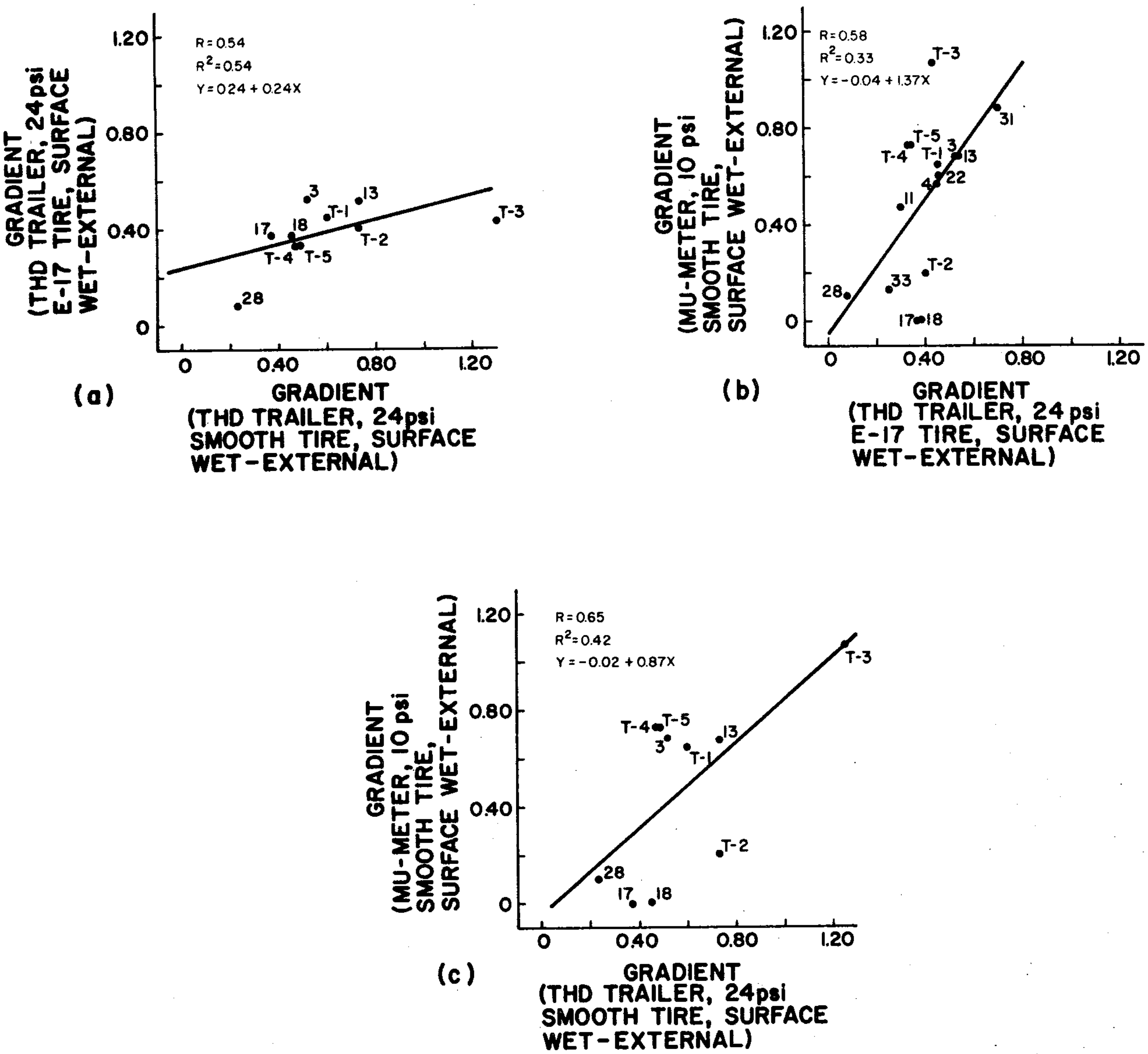

FIGURE 9. COMPARISON OF FRICTION-VELOCITY GRADIENTS TAKEN FROM 20–60 mph.

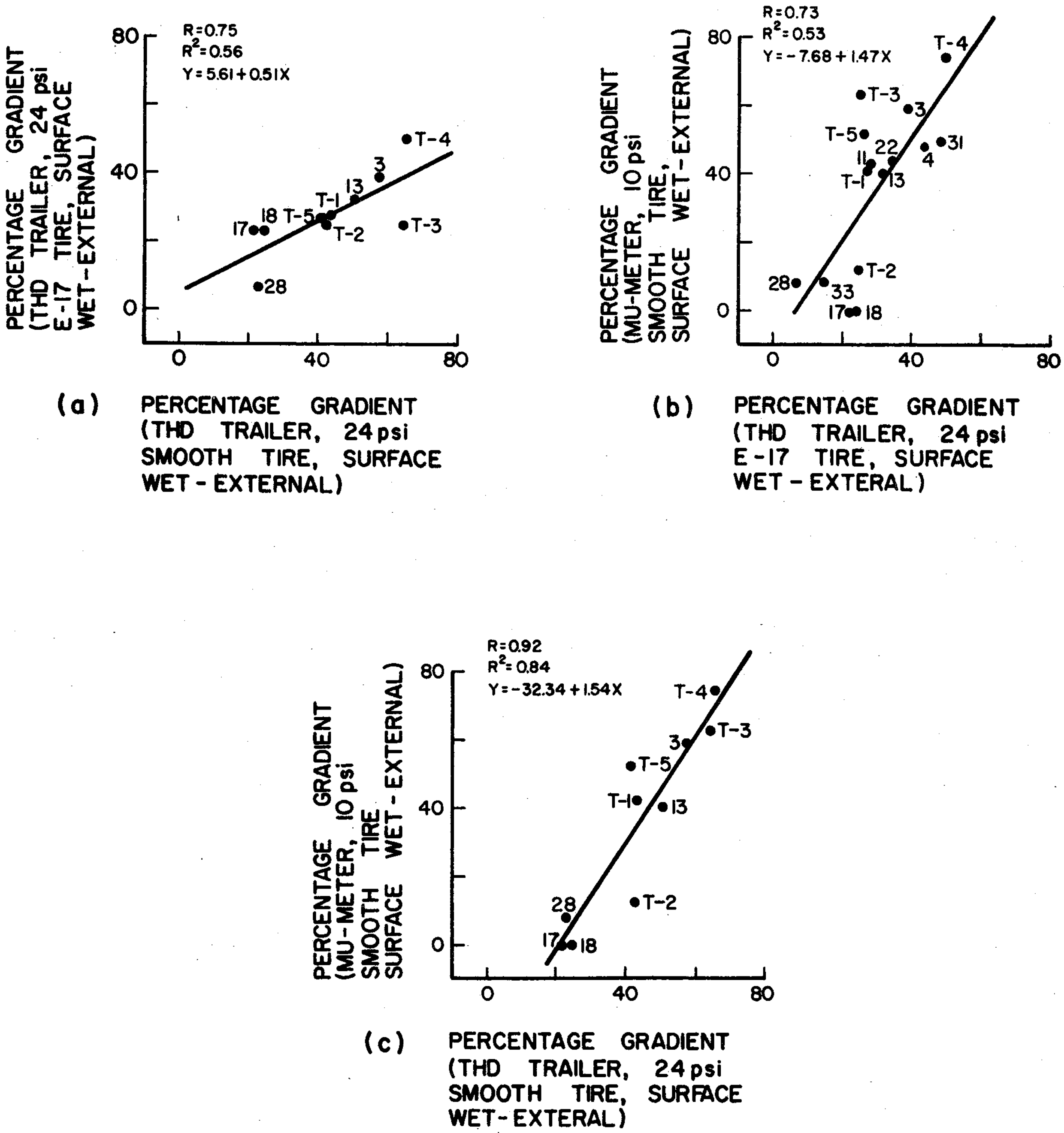

FIGURE 10. COMPARISON OF FRICTION-VELOCITY PERCENTAGE GRADIENTS TAKEN FROM 20-60 mph.

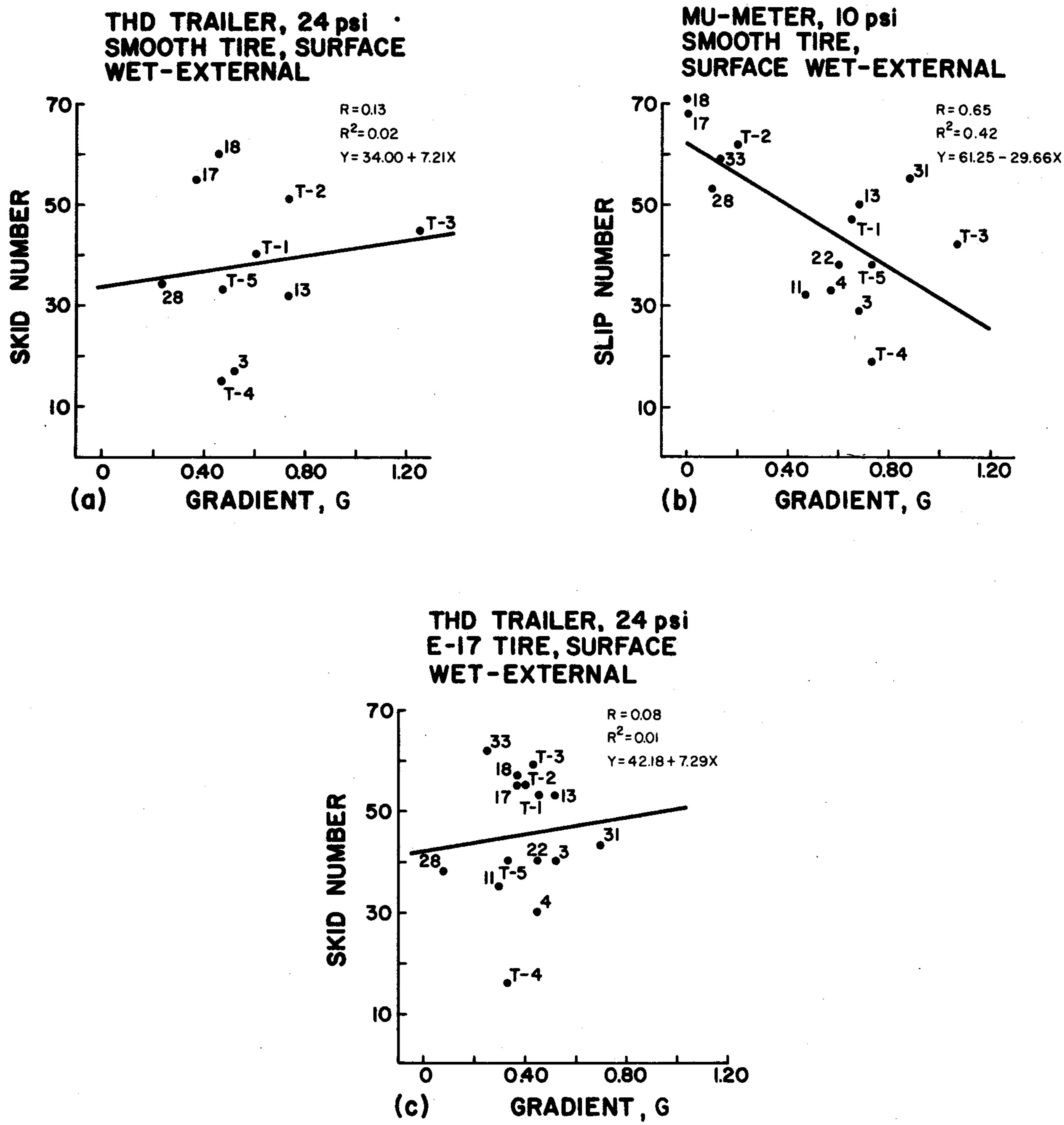

FIGURE 11. COMPARISON OF FRICTION NUMBERS AT 40 mph AND FRICTION-VELOCITY GRADIENTS FROM 20-60 mph.

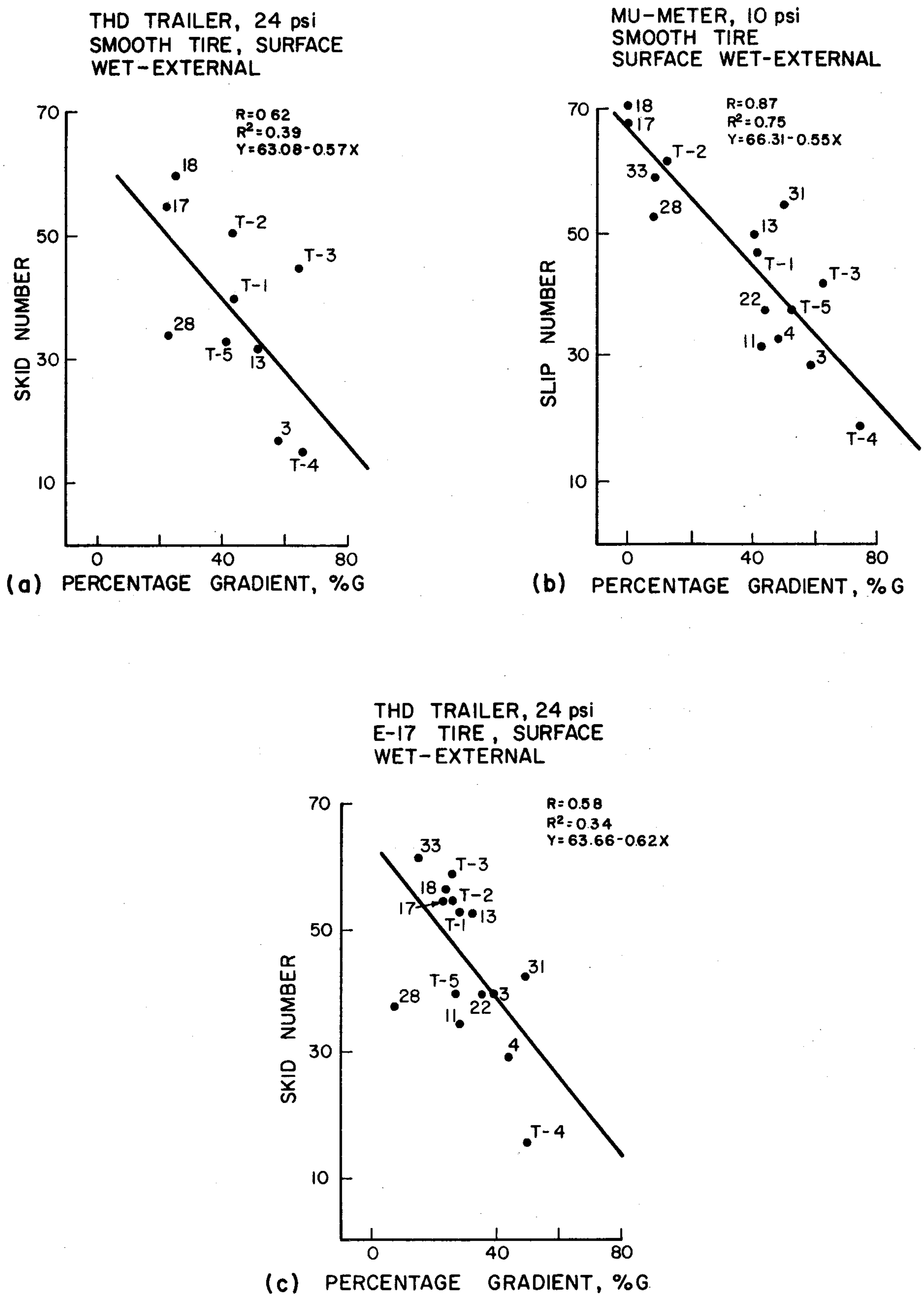

FIGURE 12. COMPARISON OF FRICTION NUMBERS AT 40 mph AND FRICTION-VELOCITY PERCENTAGE GRADIENTS FROM 20-60 mph.

TABLE 6. STATISTICAL COMPARISONS BETWEEN GRADIENTS, PERCENTAGE GRADIENTS AND FRICTION NUMBERS OBTAINED WITH THE VARIOUS TEST CONDITIONS

Variables Y	Variables X	Number of Comparisons	Figure Number	Regression Line	Correlation Coefficient	Coefficient of Determination	Standard Deviation
G (3)	G (6)	10	9a	Y = 0.24 + 0.24X	.54	.29	.11
G (4)	G (3)	15	9b	Y = -0.04 + 1.37X	.58	.33	.28
G (4)	G (6)	10	9c	Y = -0.02 + 0.87X	.65	.42	.30
PG (3)	PG (6)	10	10a	Y = 5.61 + 0.51X	.75	.56	7.84
PG (4)	PG (3)	15	10b	Y = -7.68 + 1.47x	.73	.53	17.05
PG (4)	PG (6)	10	10c	Y =-32.34 + 1.54X	.92	.84	11.84
SN_{40}(6)	G (6)	10	11a	Y = 34.00 + 7.21X	.13	.02	15.83
SN_{40}(6)	lnG(6)	10		Y = 40.23 + 3.20 lnX	.10	.01	15.90
SN_{40}(4)	G (4)	15	11b	Y = 61.25 - 29.66X	.65	.42	11.92
SN_{40}(4)	lnG(4)	15		Y = 37.07 - 7.41 lnX	.74	.56	10.45
SN_{40}(3)	G (3)	15	11c	Y = 42.18 + 7.29X	.08	.01	13.12
SN_{40}(3)	lnG(3)	15		Y = 48.18 + 3.09 lnX	.12	.01	13.06
SN_{40}(6)	PG (6)	10	12a	Y = 63.08 - 0.57X	.62	.39	12.48
SN_{40}(6)	lnPG(6)	10		Y =119.58 - 21.96 lnX	.61	.37	12.65
SN_{40}(4)	PG (4)	15	12b	Y = 66.31 - 0.55X	.87	.75	7.78
SN_{40}(4)	lnPG(4)	15		Y = 72.99 - 8.69lnX	.82	.68	8.90
SN_{40}(3)	PG (3)	15	12c	Y = 63.66 - 0.62X	.58	.34	10.70
SN_{40}(3)	lnPG(3)	15		Y = 77.93 - 9.94 lnX	.38	.15	12.13

G = Gradient (slope) at the friction speed curve between 20-60 mph.
PG = Percentage Gradient of the friction speed curve between 20-60 mph.
SN_{40} = Skid or Slip Number at 40 mph.
ln = lay to the base e.
() = Numbers in parentheses indicate test conditions as described below:
3 = THD Trailer, E-17 tire, 24 psi, surface wet external.
4 = Mu-Meter, smooth tire, 10 psi, surface wet external.
6 = THD Trailer, smooth tire, 24 psi, surface wet external.

APPENDIX E

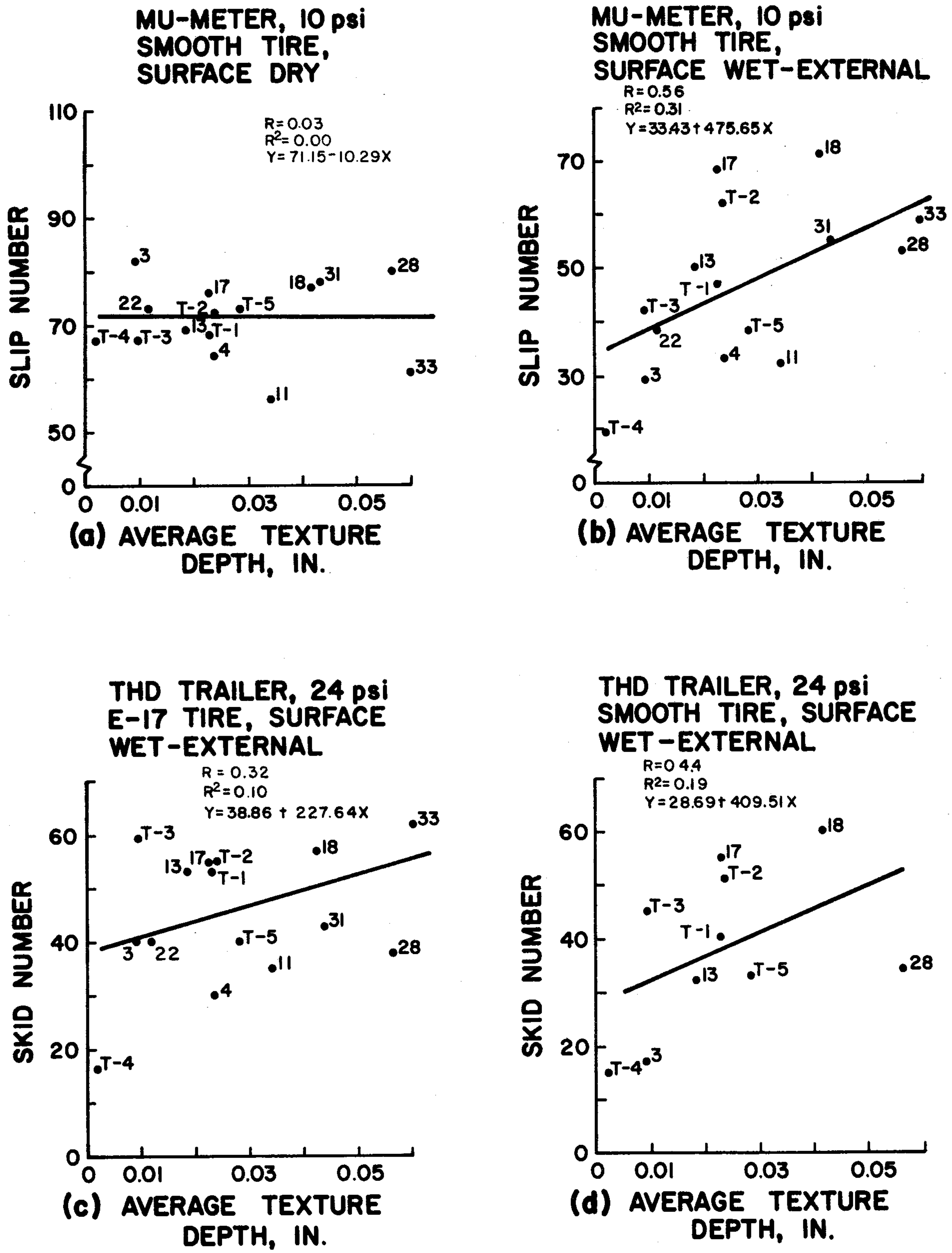

FIGURE 13. FRICTION NUMBERS AT 40 mph VS. MACROTEXTURE BY THE PUTTY IMPRESSION METHOD.

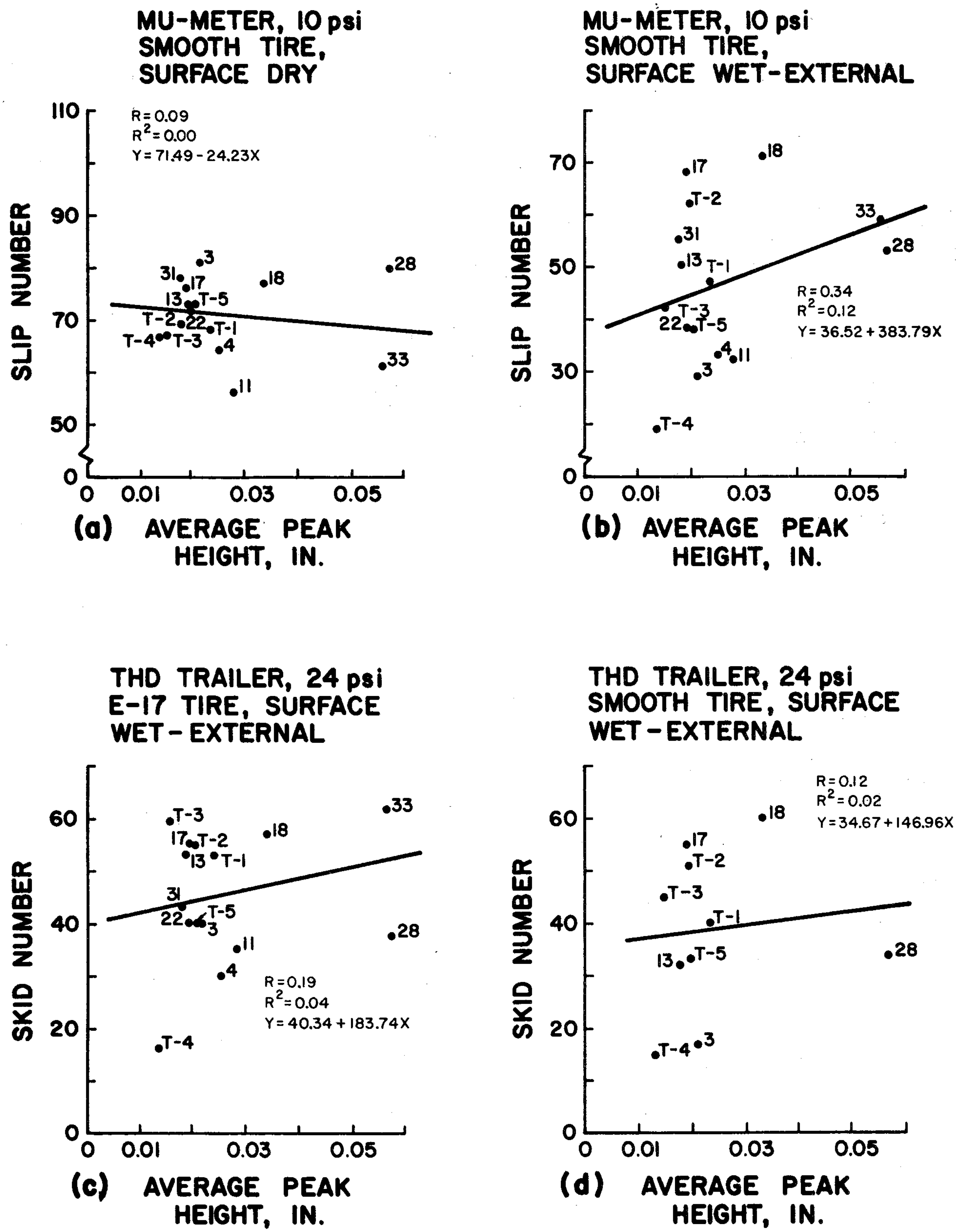

FIGURE 14. FRICTION NUMBERS AT 40 mph VS. MACRO-TEXTURE BY THE PROFILOGRAPH METHOD.

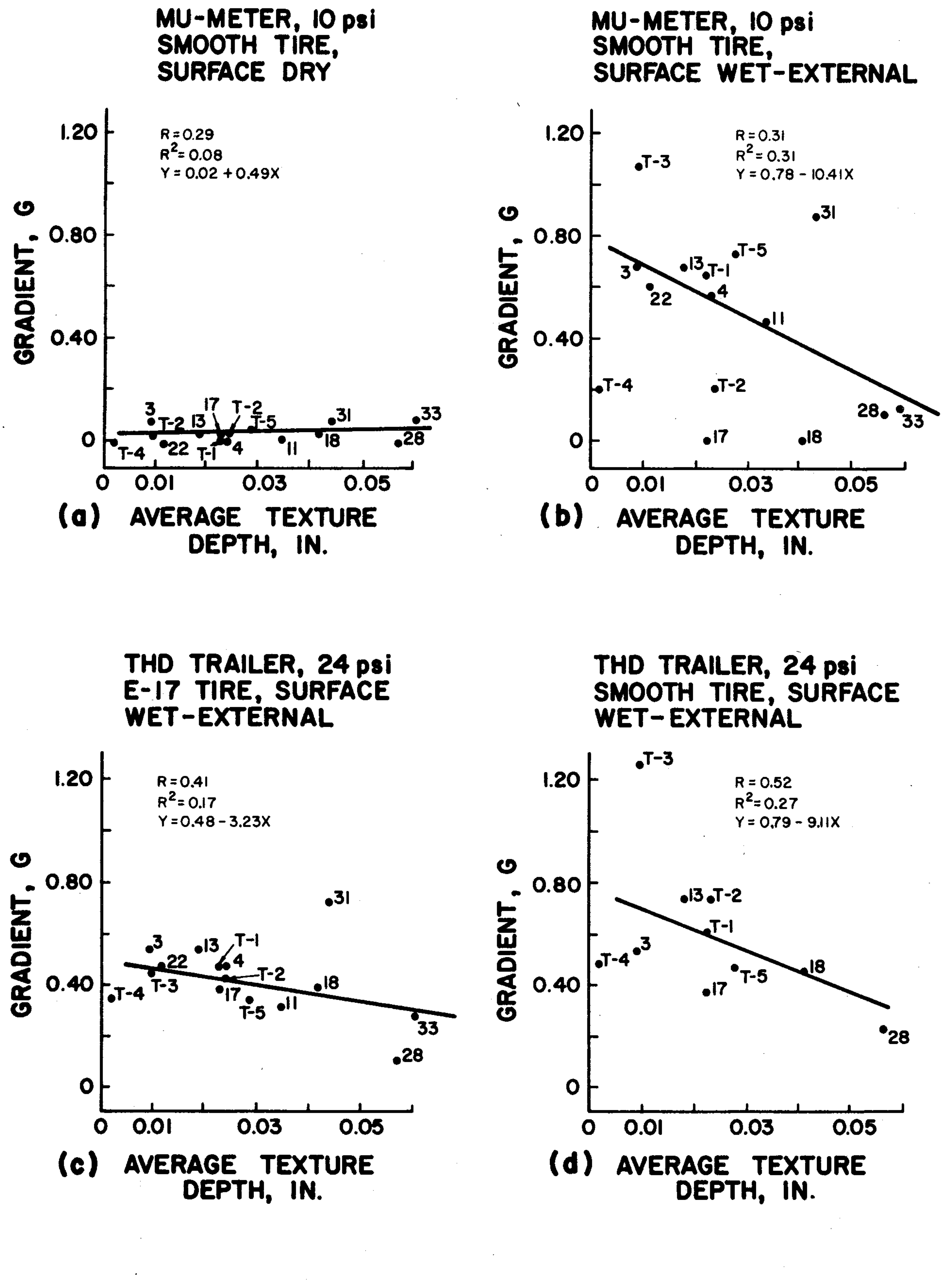

FIGURE 15. FRICTION–VELOCITY GRADIENTS (20-60 mph) VS. MACROTEXTURE BY THE PUTTY IMPRESSION METHOD.

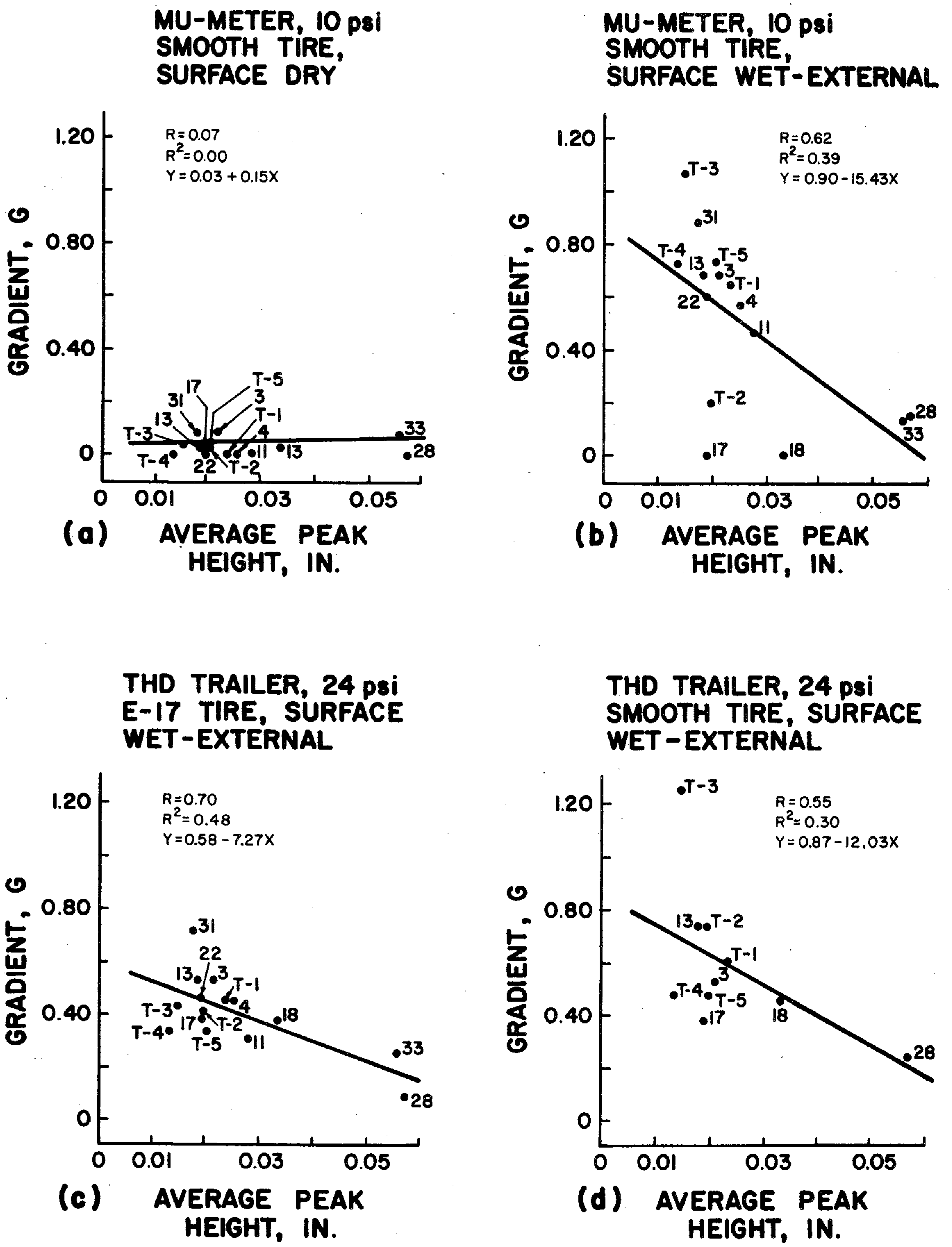

FIGURE 16. FRICTION-VELOCITY GRADIENTS (20-60 mph) VS. MACROTEXTURE BY THE PROFILOGRAPH METHOD.

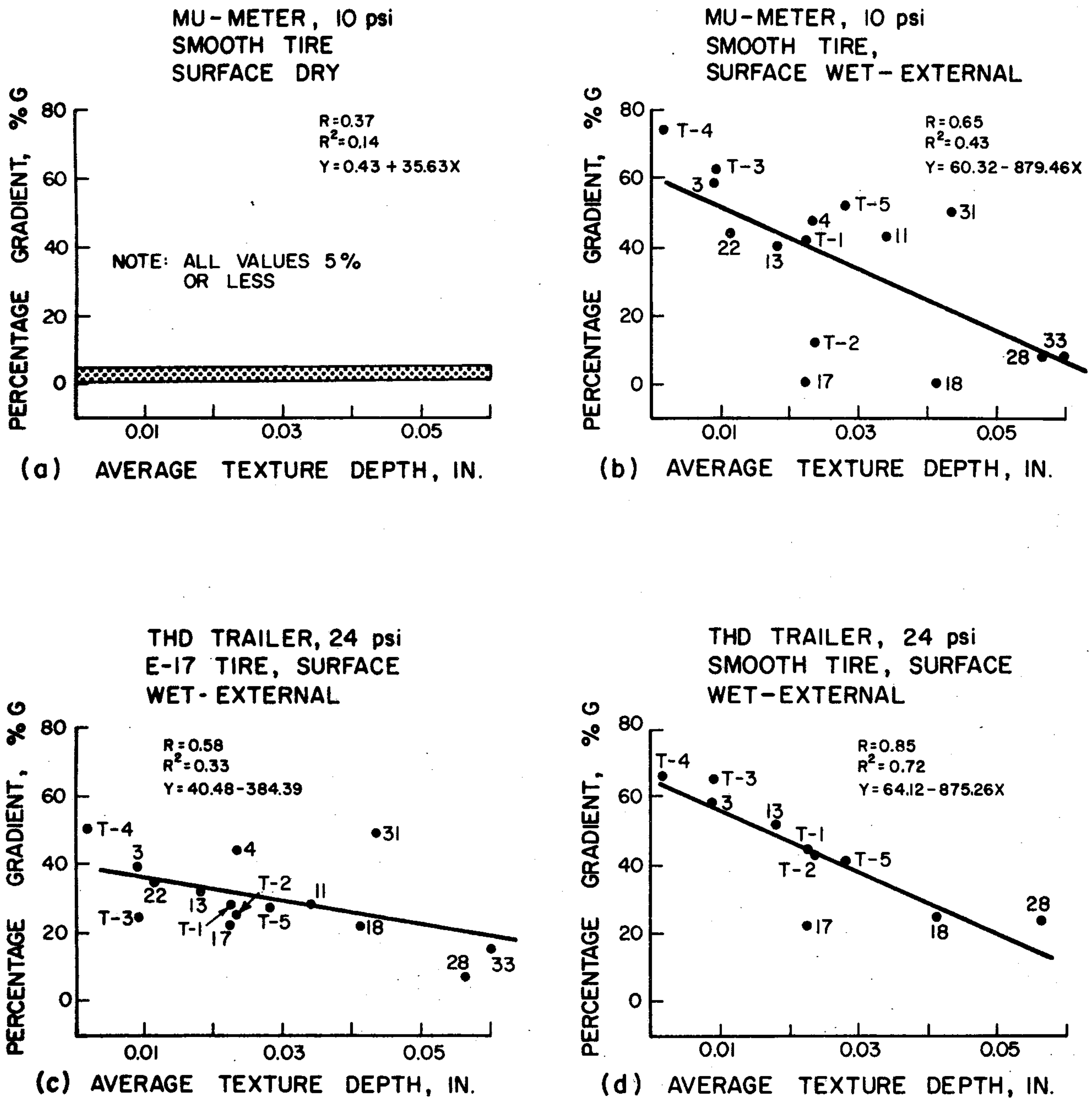

FIGURE 17. FRICTION-VELOCITY PERCENTAGE GRADIENTS (20-60 mph) VS. MACROTEXTURE BY THE PUTTY IMPRESSION METHOD.

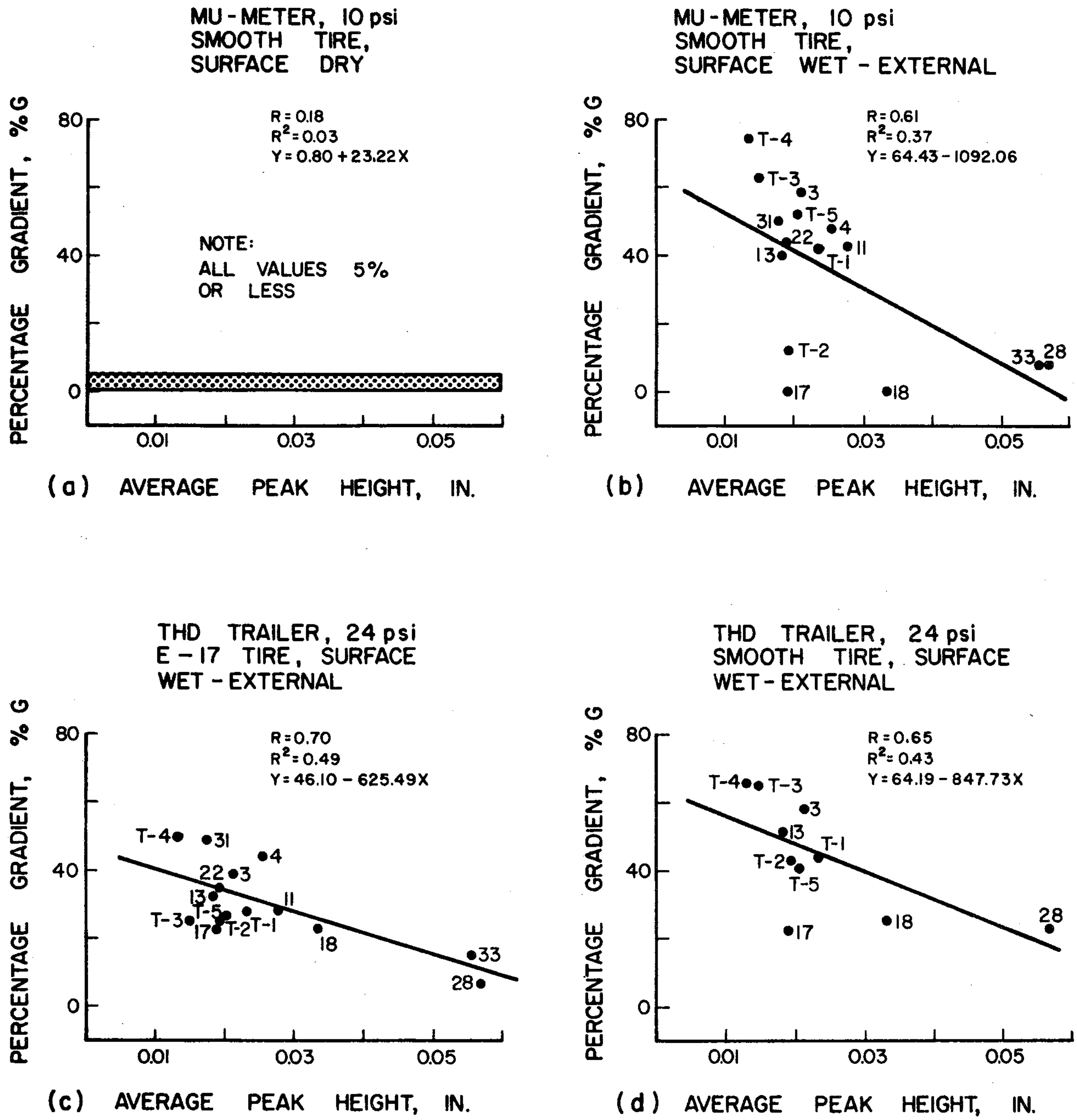

FIGURE 18. FRICTION-VELOCITY PERCENTAGE GRADIENTS (20-60mph) VS. MACROTEXTURE BY THE PROFILOGRAPH METHOD.

TABLE 7. STATISTICAL COMPARISONS OF FRICTION NUMBERS, GRADIENTS, AND PERCENTAGE GRADIENTS WITH MACROTEXTURE AS OBTAINED WITH THE VARIOUS TEST CONDITIONS AND METHODS

Variables Y	Variables X	Number of Comparisons	Figure Number	Regression Line	Correlation Coefficient	Coefficient of Determination	Standard Deviation
SN_{40}(1)	TDP	15	13a	Y = 71.15 - 10.29X	.03	.00	7.54
SN_{40}(4)	TDP	15	13b	Y = 33.43 + 475.65X	.56	.31	13.00
SN_{40}(3)	TDP	15	13c	Y = 38.86 + 227.64X	.32	.10	12.47
SN_{40}(6)	TDP	10	13d	Y = 28.69 + 409.51X	.44	.19	14.37
SN_{40}(1)	PHP	15	14a	Y = 71.49 - 24.23X	.04	.00	7.54
SN_{40}(4)	PHP	15	14b	Y = 36.52 + 383.79X	.34	.12	14.77
SN_{40}(3)	PHP	15	14c	Y = 40.34 + 183.74X	.19	.04	12.91
SN_{40}(6)	PHP	10	14d	Y = 34.67 + 146.96X	.12	.02	15.85
G (1)	TDP	15	15a	Y = 0.02 + 0.49X	.29	.08	.03
G (1)	lnTDP	15		Y = 0.06 + 0.01 lnX	.25	.06	.03
G (4)	TDP	15	15b	Y = 0.78 - 10.41X	.56	.31	.29
G (4)	lnTDP	15		Y = -0.24 - 0.19 lnX	.51	.26	.30
G (3)	TDP	15	15c	Y = 0.48 - 3.23X	.41	.17	.13
G (3)	lnTDP	15		Y = 0.27 - 0.03 lnX	.20	.04	.14
G (6)	TDP	10	15d	Y = 0.79 - 9.11X	.52	.27	.25
G (6)	lnTDP	10		Y = 0.24 - 0.09 lnX	.29	.09	.28
G (1)	PHP	15	16a	Y = 0.03 + 0.15X	.07	.00	.03
G (1)	lnPHP	15		Y = 0.04 + 0.00 lnX	.05	.00	.03
G (4)	PHP	15	16b	Y = 0.90 - 15.43X	.62	.39	.27
G (4)	lnPHP	15		Y = -1.45 - 0.52 lnX	.66	.44	.26
G (3)	PHP	15	16c	Y = 0.58 - 7.27X	.70	.48	.10
G (3)	lnPHP	15		Y = -0.41 - 0.22 lnX	.65	..42	.11
G (6)	PHP	10	16d	Y = 0.87 - 12.03X	.55	.30	.25
G (6)	lnPHP	10		Y = -0.90 - 0.39 lnX	.57	.33	.24
PG (1)	TDP	15	17a	Y = 0.43 + 35.63X	.37	.14	1.66
PG (1)	lnTDP	15		Y = 3.54 + 0.55 lnX	.29	.08	1.71
PG (4)	TDP	15	17b	Y = 60.32 - 879.46X	.65	.43	18.83
PG (4)	lnTDP	15		Y =-35.61 - 18.56 lnX	.69	.47	18.04
PG (3)	TDP	15	17c	Y = 40.48 - 384.39	.58	.33	10.11
PG (3)	lnTDP	15		Y = -0.36 - 7.83 lnX	.59	.34	10.02
PG (6)	TDP	10	17d	Y = 64.12 - 875.26X	.85	.72	9.29
PG (6)	lnTDP	10		Y =-14.57 - 14.36 lnX	.83	.69	9.71
PG (1)	PHP	15	18a	Y = 0.80 + 23.22X	.18	.03	1.76
PG (1)	lnPHP	15		Y = 3.79 + 0.64 lnX	.16	.02	1.76
PG (4)	PHP	15	18b	Y = 64.43 -1092.06X	.61	.37	19.73
PG (4)	lnPHP	15		Y=-101.44 - 36.69 lnX	.65	.42	18.99
PG (3)	PHP	15	18c	Y = 46.10 - 625.49X	.70	.49	8.79
PG (3)	lnPHP	15		Y =-43.72 - 19.63 lnX	.70	.49	8.86
PG (6)	PHP	10	18d	Y = 64.19 - 847.73X	.65	.43	13.28
PG (6)	lnPHP	10		Y =-67.10 - 29.05 lnX	.73	.53	12.05

SN_{40} = Skid or Slip Number at 40 mph.
G = Gradient (slope) of the friction speed curve between 20-60 mph.
PG = Percentage Gradient at the friction speed curve between 20-60 mph.
TDP = Average texture depth (inches) as obtained with the putty impression method, a macrotexture measure.
PHP = Average peak height (inches) as obtained with the profilograph method, a macrotexture measure.
ln = log to the base e.
( ) = Numbers in parentheses indicate test conditions as described below:
1 = Mu-Meter, smooth tire, 10 psi, surface dry.
4 = Mu-Meter, smooth tire, 10 psi, surface wet external.
3 = THD Trailer, E-17 tire, 24 psi, surface wet external.
6 = THD Trailer, smooth tire, 24 psi, surface wet external.