COMPARISON OF STOPPING DISTANCE, TOWED VEHICLE, AND STATIC METHODS FOR MEASURING SKID RESISTANCE

FEB. 1962
NO. 5

by
F. MOAVENZADEH
W. H. GOETZ

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Progress Report

COMPARISON OF STOPPING DISTANCE, TOWED VEHICLE, AND STATIC METHODS FOR MEASURING SKID RESISTANCE

TO: K. B. Woods, Director
Joint Highway Research Project

February 14, 1962

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 9-6-11
Project: C-36-53K

The progress report attached entitled "Comparison of Stopping Distance, Towed Vehicle, and Static Methods for Measuring Skid Resistance" has been authored by Fred Moavenzadeh and W. H. Goetz of our staff.

The subject of the report is a research study on the correlation of three methods of measuring the skidding resistance of highway pavement surfaces. The three methods used were the skid test vehicle, the Tennessee skid test trailer, and the British portable skid tester. Five different sections of pavement with different anti-skid characteristics were used for the correlation and included many of the bituminous mixtures which have been placed in recent years in the research concerned with development of mixtures with good anti-skid characteristics.

The report is presented to the Board as information and for the record.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:lmc

Attachment

Copies:

F. L. Ashbaucher
J. R. Cooper
W. L. Dolch
W. H. Goetz
F. F. Havey
F. S. Hill
G. A. Leonards
J. F. McLaughlin
R. D. Miles
R. E. Mills
M. B. Scott
J. V. Smythe
J. L. Waling
E. J. Yoder

Progress Report

COMPARISON OF STOPPING DISTANCE, TOWED VEHICLE, AND STATIC METHODS FOR MEASURING SKID RESISTANCE

by

Fred Moavenzadeh
Graduate Assistant

and

W. H. Goetz
Research Engineer

Joint Highway Research Project
File No: 9-6-11
Project No: C-36-53K

Purdue University
Lafayette, Indiana

February 14, 1962

Introduction

One of the major problems currently confronting the highway engineer in many areas is to construct highways that will exhibit satisfactory anti-skid characteristics for a reasonable length of time. All pavement surfaces can develop adequate skidding resistance in a dry state but many of them may be critically slippery when wet.

The majority of the highways constructed recently have possessed adequate wet skidding resistance when new. Unfortunately, on many of these surfaces this initial anti-skid resistance has been short-lived. As a result, it has become increasingly important to give some consideration to the change in skidding resistance of pavement surfaces due to the polishing effects of traffic.

Due to the endless list of variables, including factors pertaining to the aggregate, the binder, traffic and age, seasonal variables, and the condition of the surface during testing, the most appropriate means of testing is field investigation.

At present many machines are being used for rating the slipperiness of pavement surfaces, and most of them are serving their intended purpose quite well since individual agencies can make sound judgments on the basis of relative road slipperiness values obtained with their machines. But the exchange of data among these agencies is very difficult, and the need for a standard method is very obvious. Any attempt toward selection of a standard method must be preceded by a correlation between the existing method and analysis of the variables that they measure. Among the most promising devices are:

1. Stopping distance method
2. Towed vehicle technique, and
3. Static machines

In summer 1961, the bituminous laboratory used three pieces of equipment to measure the skid characteristics of several bituminous surfaces. For this purpose the following equipment was utilized:

1. The stopping distance car of the Indiana State Highway Department
2. A towed-vehicle machine identified as the Tennessee Skid Test Trailer from University of Tennessee, and
3. A British Portable Skid Tester owned by Purdue University.

Areas Tested

The sites which were selected for this study included five different areas with contrasting anti-skid characteristics.

Area I included 24 experimental sections of sand mix laid in 1959 on the south-bound lanes of U. S. 52 north of the junction with S.R. 28. The thickness of the layer was about one-half inch and the composition of the mix can be seen in Table I.

Area II included 8 experimental sections of fine sand mix and a section of the old pavement. The 8 sections of the sand mix were laid during the summer of 1960 on the south-bound lanes of U. S. 52 north of Monroe. Their composition is presented in Table I.

Area III included a section of S.R. 28 east of the junction with U. S. 52. This section of S.R. 28 is surfaced with Kentucky Rock Asphalt.

Area IV included a four mile stretch of gravel bituminous concrete with approximately 60% coarse aggregate and 40% fine aggregate on the north-bound lanes of U. S. 52 from four to eight miles south of Lafayette.

Area V included a four mile stretch of gravel bituminous concrete with approximately 45% coarse aggregate and 55% fine aggregate on the north-bound lanes of U. S. 52 from Lafayette to four miles south.

Equipment Used

Skid Test Car

The Skid Test car was a 1956 Ford with vacuum-operated brakes. The only additional equipment on this car was a speedometer which records the speed when the brakes are applied and an odometer attached to a fifth wheel. The car was braked at a speed close to 30 mph and the skidding distance for that speed was measured. A chart was available to correct this distance to 30 mph speed.

Tennessee Skid Test Trailer

The skid trailer consisted of a 4 x 6 ft. concrete slab mounted on the modified front-axle assembly of a passenger car. The slab provides a weight of approximately 835 lbs. on the test wheel. The trailer is connected to the tow truck by an off-set drawbar which is in direct alignment with the center of the left or inside trailer wheel. Through a strain-gauge mechanism any pull exerted on the drawbar caused force to be indicated on a brush recorder through an analyzer. The test trailer was pulled by a two-ton Chevrolet truck which is equipped with a 500 gallon water tank and a sprinkling bar so that a stream of water is directed at the pavement about 2 ft. in front of the skidding wheel. The operation of the machine is fully automatic so that once the control button is pushed and the automatic cycling mechanism is energized, the water valve is opened, and one and one-half seconds later the brake is automatically applied on the trailer and it held for slightly under two seconds. Three such tests are automatically made. The speed and drawbar pull can be read directly from the graph of the Brush recorder. Trailer tests were made at speeds of 10, 20, 30, and 40 mph in most cases, and at 50 mph in a few cases.

British Portable Skid Tester

The British Portable Skid Tester is a device developed in the Road Research Laboratory in Great Britain. It is a pendulum type of machine, in which a slider three-inches long and one-inch wide takes the place of a skidding tire. The machine can be adjusted vertically so that the length of surface that the slider traverses can be controlled. After the proper adjustments are made, the pendulum and a pointer, which acts from the same axis as the pendulum, are cocked in a horizontal position. Upon release, the pendulum carries the pointer through an arc and falls away, leaving the pointer at the furthest point of the arc traversed by the pendulum. At this point, a measurement is recorded from a direct scale. The scale is calibrated directly, the readings given being 100 times the effective coefficient of friction as deduced by equating the work done against friction by the slider to the loss in energy of the pendulum arm. Considerable attention has been given to ensuring that the apparatus will be quick and easy to use on the road. The rubber slider is free to tilt sideways to follow irregularities of the surface and is loaded by an arrangement giving a very low spring rate so that the normal load on the surface stays substantially constant throughout the swing even on very rough surfaces.

Experimental Design

The experiment was designed to provide a possibility of correlation of the three methods of skid testing. For this purpose, at first the trailer tester was used in all five areas at different speeds. At area I and II, the trailer measured the coefficient of friction of each section for both driving lane and passing lane at different speeds and in direction of traffic and opposite the direction of traffic, while in other areas tests were made only in the direction of traffic. After the completion of tests with the trailer, the skid car was used for the same sections with the same directions. Finally the Portable Skid Tester was used in marked areas where the test car had skidded. For each strip on which the car had skidded three positions were tested, two ends and middle, and at each position ten readings were taken. The readings which varied more than 3 points were discarded. At each position the temperature of pavement was recorded. To eliminate the effect of temperature on the results of Portable Skid Tester, all the values of coefficient of friction obtained by this device were corrected according to a method described in Appendix A.

Table 1

Description of Sections Tested

Area I. #17 Sand Sections - U. S. 52 N of S.R. 28

	Composition (Design)			
Sec. No.	#17 Sand	Mineral Filler	Asphalt	Percent Asphalt
1	100	0	AE-60	6.5
2	100	0	AE-60	7.0
3	100	0	AE-60	7.5
4	100	0	AE-60	8.0
5	100	0	AE-60	8.5
6	95	5	AE-60	6.5
7	95	5	AE-60	7.0
8	95	5	AE-60	7.5
9	95	5	AE-60	8.0
10	95	5	AE-60	8.5
11	100	0	AE-90	6.5
12	100	0	AE-90	7.0
13	100	0	AE-90	7.5
14	100	0	AE-90	8.0
15	100	0	AE-90	8.5
16	95	0	AE-90	6.5
17	95	0	AE-90	7.0
18	95	0	AE-90	7.5
19	95	0	AE-90	8.0
20	95	0	AE-90	8.5
21	90	10	AE-90	8.5
22	100	0	AE-150	7.5
23	100	0	AE-200	7.5
25	Ls. Bit. Conc. - Ind. D-3 Spec.			

Table 1 (Continued)

Area II. Fine Sand Sections - U. S. 52 N of Monroe

	Composition - % (Design)				
Sec. No.	#15 Sand	Fine Sand	Mineral Filler	Asphalt	Percent Asphalt
1	100	0	0	AE-90	7
2	95	0	5	AE-90	7
3	75	25	0	AE-90	7
4	70	25	5	AE-90	7
5	50	50	0	AE-90	8
6	45	50	5	AE-90	8
7	25	75	0	AE-90	8
8	20	75	5	AE-90	8
9	Ls. Bit. Conc. - Ind. D-3 Spec.				

Area III. Rock Asphalt. S.R. 28 east of junction with U.S. 52

Natural Kyrock

Gravel Bit. Conc. - Ind. D-4 Spec., U.S. 52 - N.B. lane

Area IV. 8 mi. south of Lafayette -
60% #11 gravel-40% #17 sand

Area V. 4 mi. south of Lafayette -
40% #11 gravel-60% #17 sand

Table 2
Tennessee Skid Test Trailer Results

AREA I

Fine Sand

Series I Driving Lane, South Bound

Section	10	20	30 Run 1	30 Run 2	40	50
1	.68	.66	.62	.48	.47	.31
2	.69	.59	.39	.40	.27	.13
3	.69	.53	.39	.42	.32	.16
4	.63	.53	.37	.34	.25	.13
5	.66	.48	.35	.32	.30	.17
6	.64	.48	.32	.28	.26	.17
7	.61	.42	.34	.30	.24	.23
8	.59	.40	.29	.24	.26	.27
9	.55	.51	.41	.38	.38	.32

Series II* Passing Lane, South Bound

Section	10	30 Run 1	30 Run 2	40
1	.76	.64	.59	.58
2	.72	.58	.52	.37
3	.77	.57	.55	.54
4	.76	.52	.55	.44
5	.79	.52	.55	.44
6	.77	.46	.46	.34
7	.79	.57	.52	.39
8	.82	.50	.51	.38
9	.79	.66	.74	.66

Series III Driving Lane, North Bound

Section	10	20	30	50
	.63	.57	.48	.34
	.57	.48	.38	.16
	.60	.45	.32	.15
	.57	.43	.30	.17
	.63	.44	.32	.21
	.57	.45	.28	.22
	.53	.44	.31	.24
	.57	.40	.25	.24
	.45	.37	.36	.52

Series IV Passing Lane, North Bound

Section	10*	20* Run 1	20* Run 2	30*	40 Run 1*	40 Run 2
1	.65	.63	.65	.55	.48	.48
2	.63	.58	.63	.49	.46	.28
3	.63	.57	.63	.43	.39	.26
4	.68	.59	.62	.50	.32	.20
5	.70	.59	.65	.54	.39	.22
6	.65	.55	.61	.42	.30	.21
7	.68	.58	.66	.42	.41	.21
8	.64	.61	.66	.43	.30	.18
9	.59	.38	.69	.49	.41	.32

* C-M-50

Notes: Run No 1 @ 30 mph in Series II was rerun as water was low

Run No 1 @ 40 mph in Series IV was rerun at a different chart multiplier scale

Table 2 (Continued)
AREA II

No. 17 Sand

Series I Driving Lane, South Bound

Section	10 Run 1	10 Run 2	20	30	40 Run 1	40 Run 2
1	.70	*	.70	.57	*	.52
2	.70	.69	.64	.51	.51	.55
3	.68	.74	.70	.52	.46	.54
4	.70	*	.68	.48	.43	.45
5	.63	.68	.54	.45	.26	.31
6	.70		.64	.49	.42	.41
7	.68		.62	.45	.36	.39
8	.61	.70	.60	.48	.37	.31
9	.59	.60	.45	.30	.22	.25
10	.57	.60	.44	.30	.19	.28
11	.71		.70	.56	.59	
12			.74	.62	.59	
13	.70		.68	.59	.49	
14	.69	.74	.64	.53	.46	
15	.73		.69	.54	.50	
16	.69	.74	.64	.60	.48	
17	.68		.61	.48	.48	
18	.66	.69	.53	.47	.37	
19	.61	.66	.48	.36	.25	
20	.49	.52	.39	.26	.20	
21	.56	.60	.36	.23	.22	
22	.68	.70	.55	.34	.34	
23	.68	.71	.51	.39	.41	
24						
25	.66	.68	.51	.51	.45	

Series II Passing Lane, South Bound

Section	20*	30
1	.71	.65
2	.70	.60
3	.70	.60
4	.70	.61
5	.73	.58
6	.68	.59
7	.70	.58
8	.68	.58
9	.68	.58
10	.69	.59
11	.72	.57
12	.74	.57
13	.72	.60
14	.68	.58
15	.73	.58
16	.70	.59
17	.69	.64
18	.65	.59
19	.68	.45
20	.63	.44
21	.63	.47
22	.68	.58
23	.68	.60
24		
25	.76	.68

* G-M-50

Note: Brake was operating improperly in several of these runs.

Table 2 (Continued)

AREA III
Kentucky Rock

Series I East of U.S. 52, Driving Lanes

TEST NO.	MILES PER HOUR, RUNNING TESTS					
			Away from U.S. 52		Toward U.S. 52	
	10*	20*	30*	40*	30	40
1	.87	.72	.62	.74	.67	.58
2	.86	.73	.65	.66	.65	.61

* C-M-50

AREA IV
Gravel Bituminous Concrete

Series I on U.S. 52, 8 mi S. LaFayette, Driving Lane, North Bound

TEST NO.	MPH Standard Test				Test No.	Miles Per Hour, Running Test
	10	20	30	40		30
1	.58	.42	.28	.22	1	.32
2	.56	.40	.28	.23	2	.34
					3	.36
					4	.38
					5	.31
					6	.35
					7	.31
					8	.34

AREA V

Gravel Bituminous Concrete

Series I, on U.S. 52, 4 mi S. LaFayette, Driving lane, North Bound

TEST NO.	MPH Standard Test				Test No.	Miles Per Hour, Running Test
	10	20	30	40		30
1	.63	.51	.34	.25	1	.34
2	.64	.45	.40	.30	2	.37
					3	.30
					4	.34
					5	.35
					6	.40
					7	.37
					8	.34
					9	.37
					10	.39

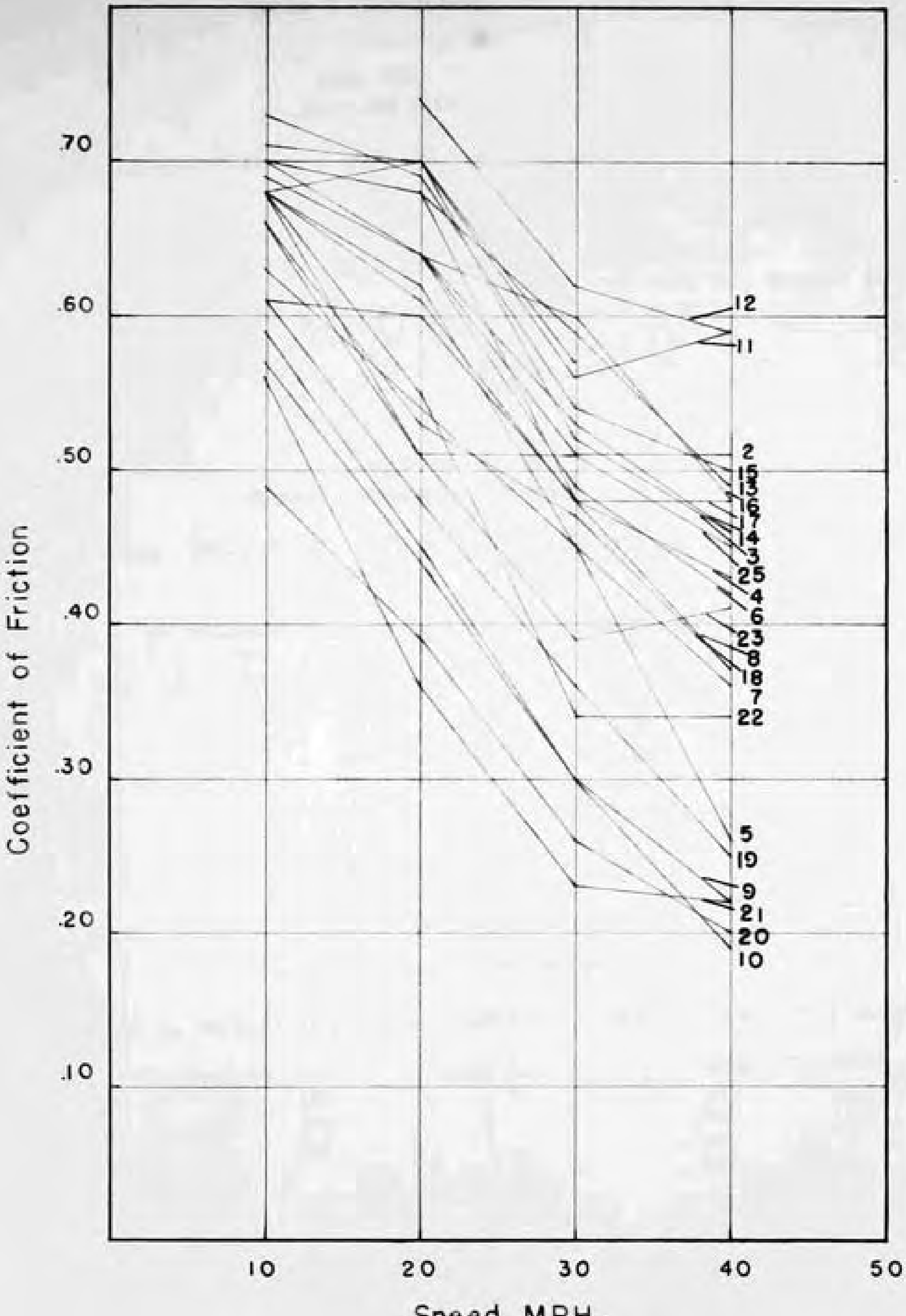


Fig. I
AREA I
No 17. Sand
Series I Driving Lane. South.Bound

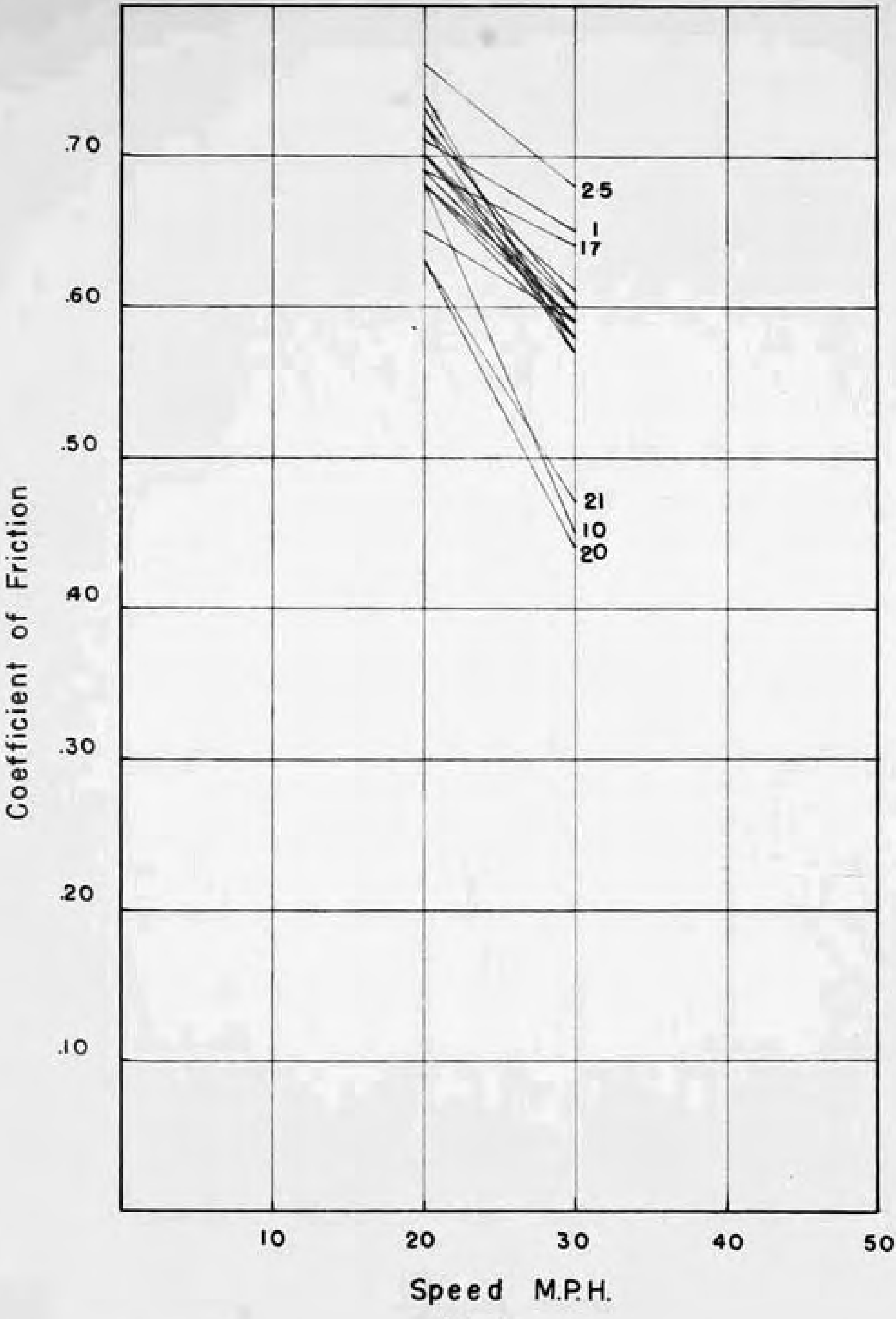


Fig. 2
AREA I
No 17. Sand
Series II Passing Lane South Bound

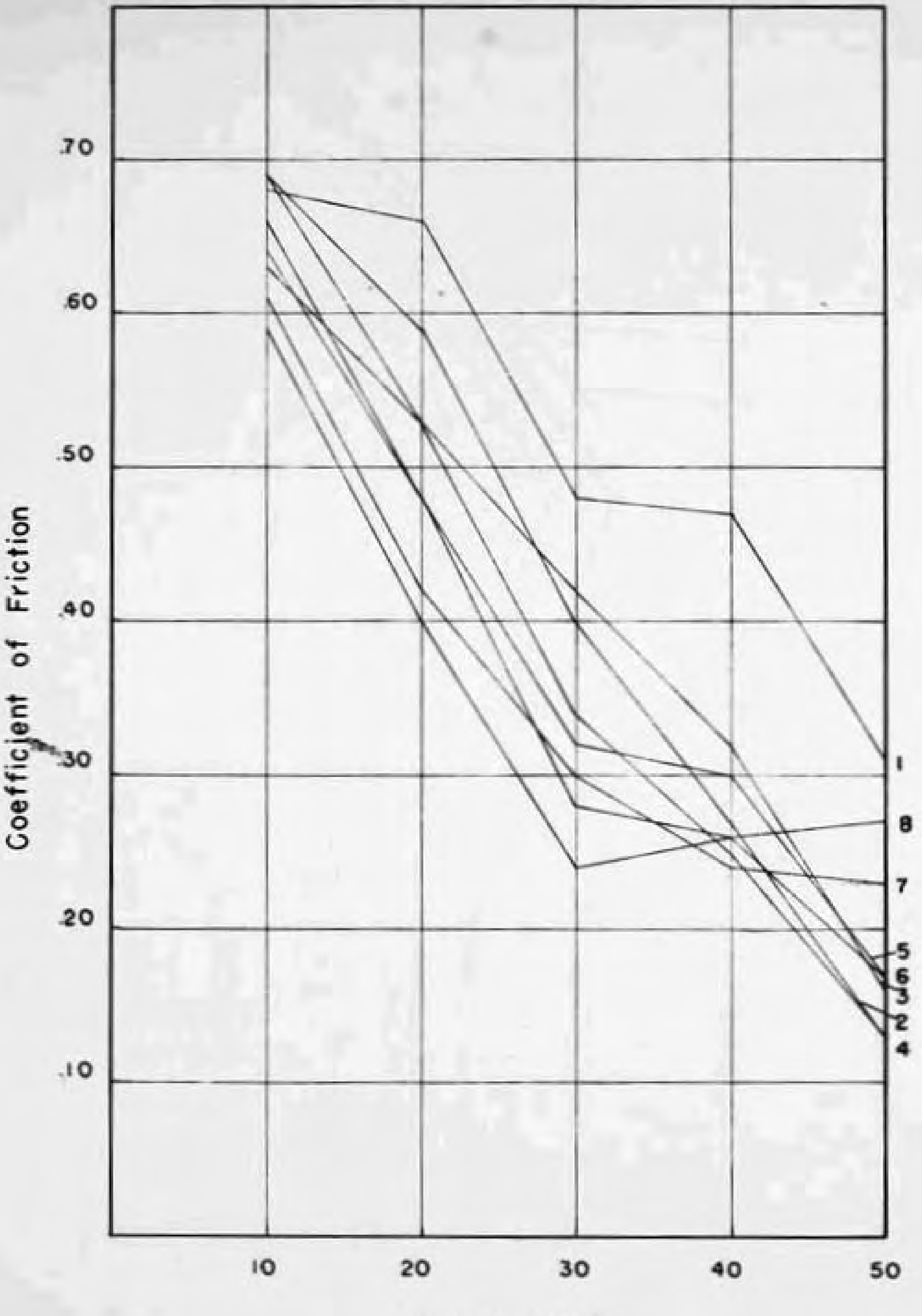


Fig. 3

AREA II

Fine Sand

Series I Driving Lane South Bound

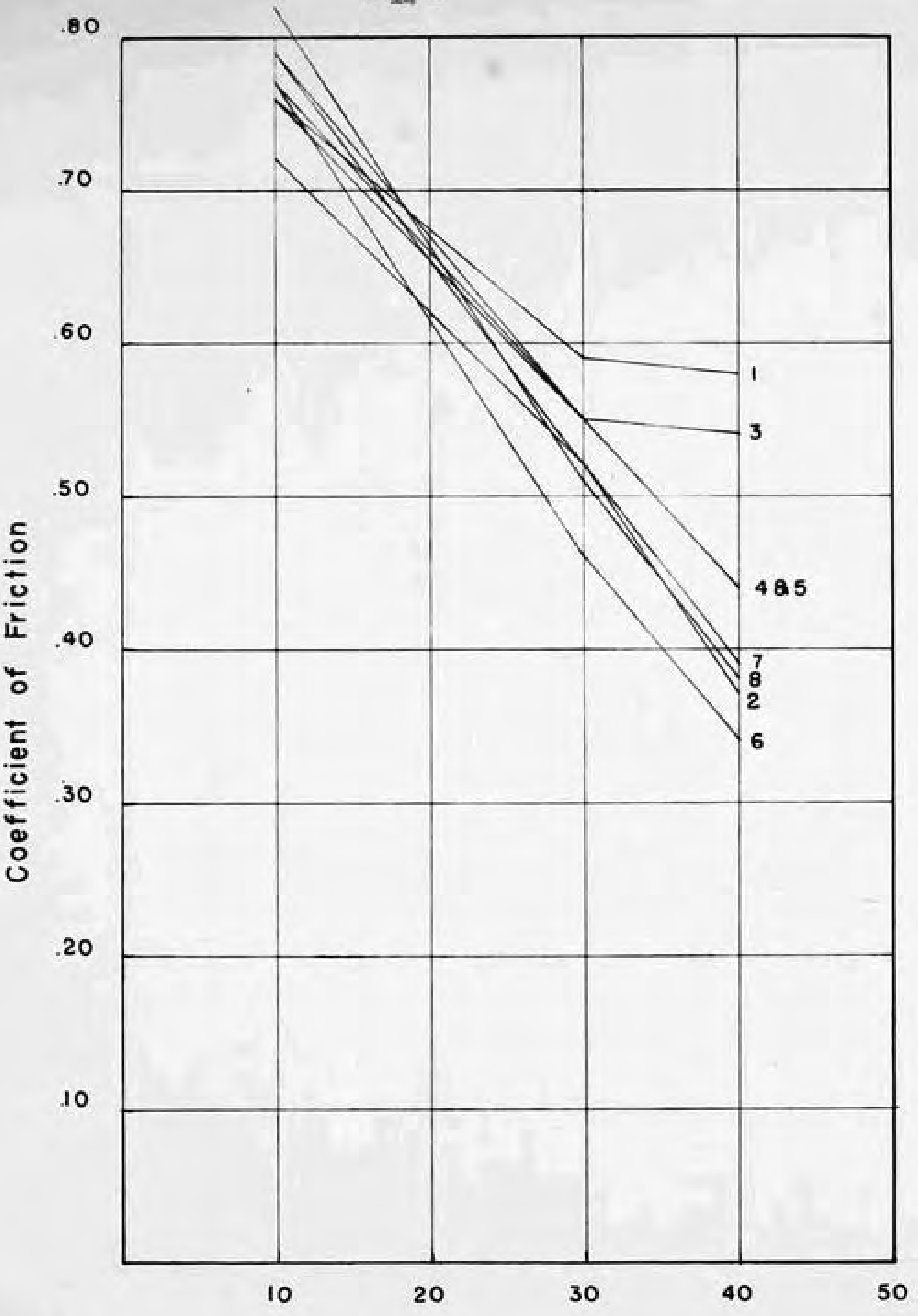


Fig. 4
AREA II
Fine Sand
Series II Passing Lane South Bound

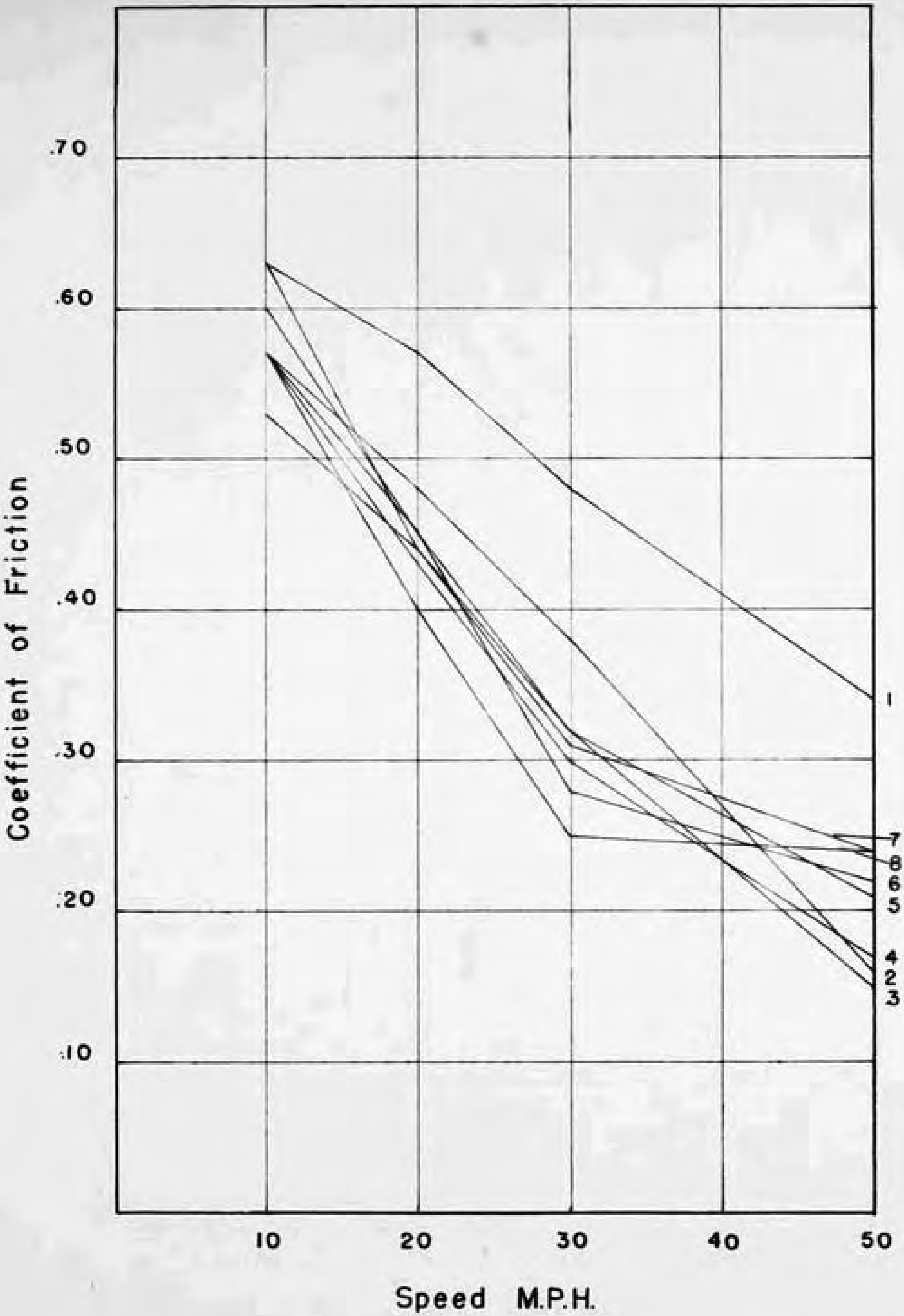


Fig. 5 .
AREA II
Fine Sand
Series III Driving Lane North Bound

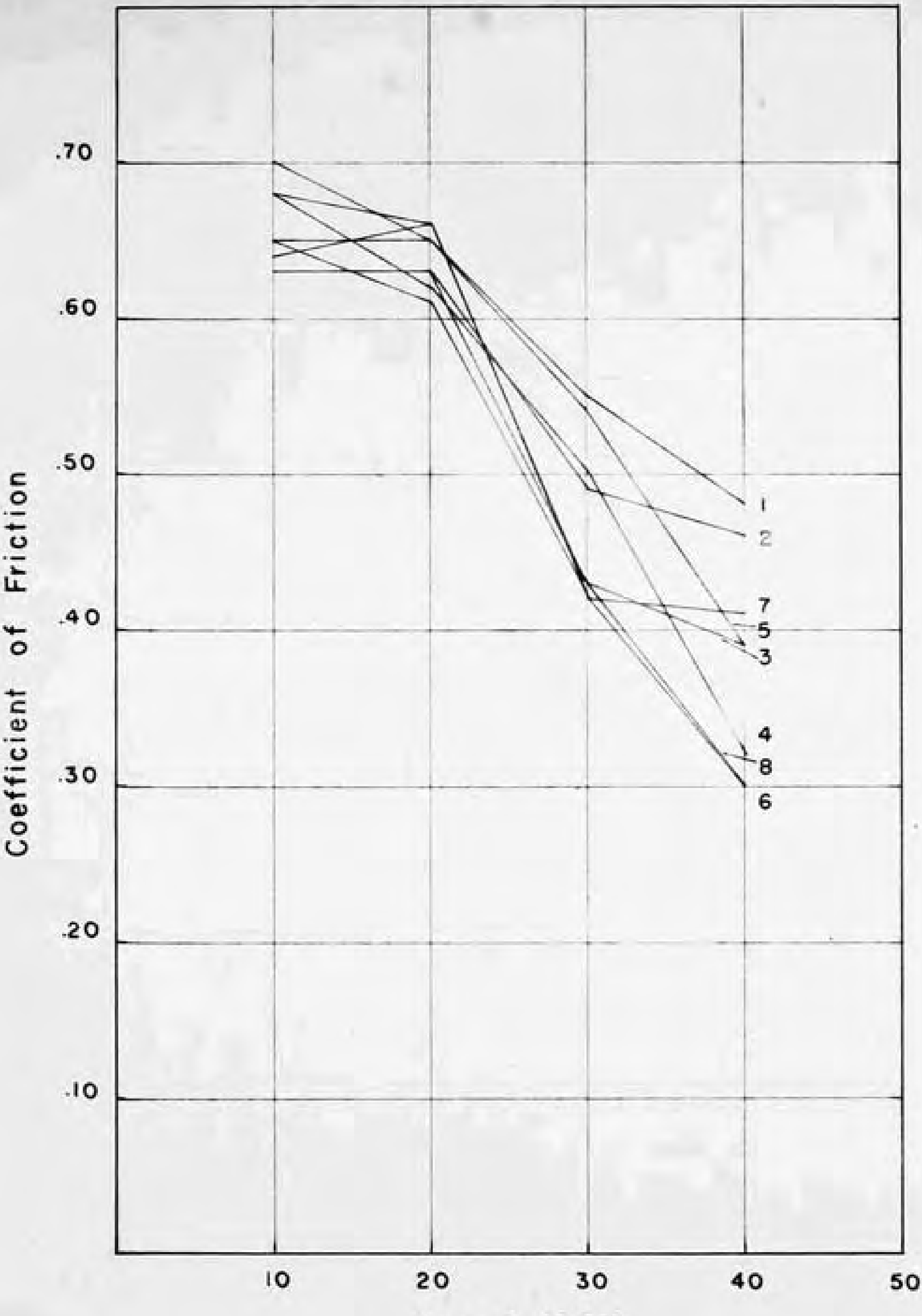
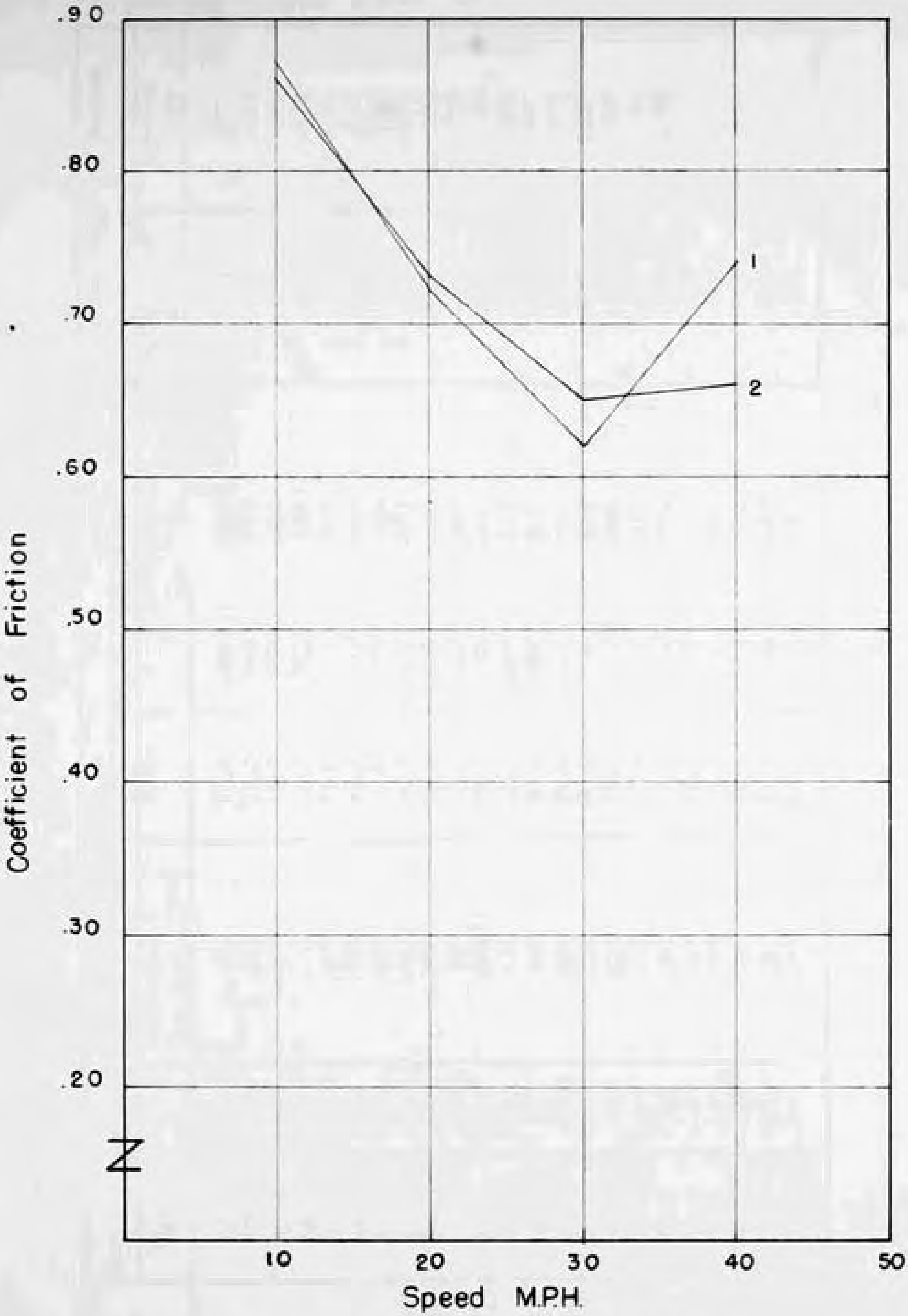


Fig. 6
AREA II
Fine Sand
Series IV Passing Lane North Bound



AREA III (SR-28)

Kentucky Rockasphalt

Series I East Bound Lane

Fig. 7

Area 1

#17 Sand

Section	Portable Skid Tester						Stopping Distance Method	
	Travelling Lane			Passing Lane				
	Temp. °C	f	Corrected f for Temp. 20°C	Temp.	f	Corrected f for Temp. 20°C	Travelling Lane	Passing Lane
1	42.0	.502	.612	33.0	.571	.636	.542	.571
2	43.0	.503	.668	33.0	.562	.627	.505	.569
3	43.0	.502	.617	33.0	.569	.634	.535	.579
4	41.0	.529	.634	34.0	.571	.641	.532	.571
5	41.0	.482	.587	33.0	.561	.626	.470	.584
6	41.0	.502	.607	33.0	.559	.624	.509	.559
7	41.5	.499	.605	32.0	.570	.630	.495	.575
8	42.0	.500	.610	34.5	.608	.680	.467	.571
9	38.5	.499	.596	30.0	.606	.656	.420	.569
10	39.0	.497	.592	33.0	.580	.645	.430	.548
11	37.5	.538	.625	30.0	.550	.600	.537	.538
12	29.0	.573	.618	31.0	.565	.620	.545	.540
13	30.0	.558	.608	30.0	.569	.619	.532	.575
14	30.0	.550	.600	30.0	.575	.625	.559	.571
15	28.0	.586	.626	28.0	.596	.636	.503	.563
16	35.0	.553	.638	31.0	.587	.642	.536	.598
17	35.0	.533	.618	32.5	.568	.630	.520	.591
18	34.0	.517	.587	32.0	.572	.632	.518	.569
19	34.0	.498	.568	33.5	.608	.675	.450	.575
20	34.0	.497	.567	33.5	.600	.667	.442	.566
21	34.0	.499	.569	35.5	.595	.672	.478	.589
22	32.0	.533	.593	33.0	.600	.665	.548	.601
23	32.0	.530	.590	33.0	.595	.660	.579	.610

Table 3 (Continued)

Area II
Fine Sand

Section	Portable Skid Tester						Stopping Distance Method	
	Travelling Lane			Passing Lane				
	Temp.	Coeff. of Friction	Corrected for Temp. @ 20°C	Temp.	f	Corrected for Temp. @ 20°C	f Travelling Lane	f Passing Lane
1	32.0	.548	.608	26.0	.583	.613	.530	.548
2	31.5	.530	.587	25.0	.583	.605	.520	.555
3	31.0	.532	.587	24.5	.608	.630	.501	.547
4	34.0	.543	.613	23.5	.638	.655	.525	.564
5	33.5	.545	.610	22.0	.652	.662	.500	.598
6	34.0	.558	.628	22.0	.627	.637	.509	.564
7	34.0	.514	.584	21.5	.676	.684	.487	.566
8	33.0	.540	.605	21.0	.662	.667	.480	.572

Table 3 (Continued)

Area III Rock Asphalt S.R. 28

Section		°C Temp.	P.S.T.	Average	Corrected for Temp.	Average	Stopping Distance Method	Average
East Bound								
	1A	37.5	.669		.756		.630	
1				.678		.766		.637
	1B	37.5	.688		.775		.645	
	2A	37.0	.673		.758		.625	
2				.671		.762		.628
	2B	39.5	.669		.766		.632	
	3A	40.3	.624		.726		.645	
3				.635		.751		.632
	3B	42.5	.666		.776		.620	
West Bound								
	1A	40.5	.644		.745		.640	
1				.624		.742		.630
	1B	43.0	.623		.740		.620	
	2A	38.5	.649		.750		.632	
2				.651		.754		.629
	2B	41.0	.653		.758		.623	
	3A	42.0	.651		.761		.652	
3				.663		.773		.637
	3B	42.0	.676		.786		.622	

Table 3 (Continued)

Area IV

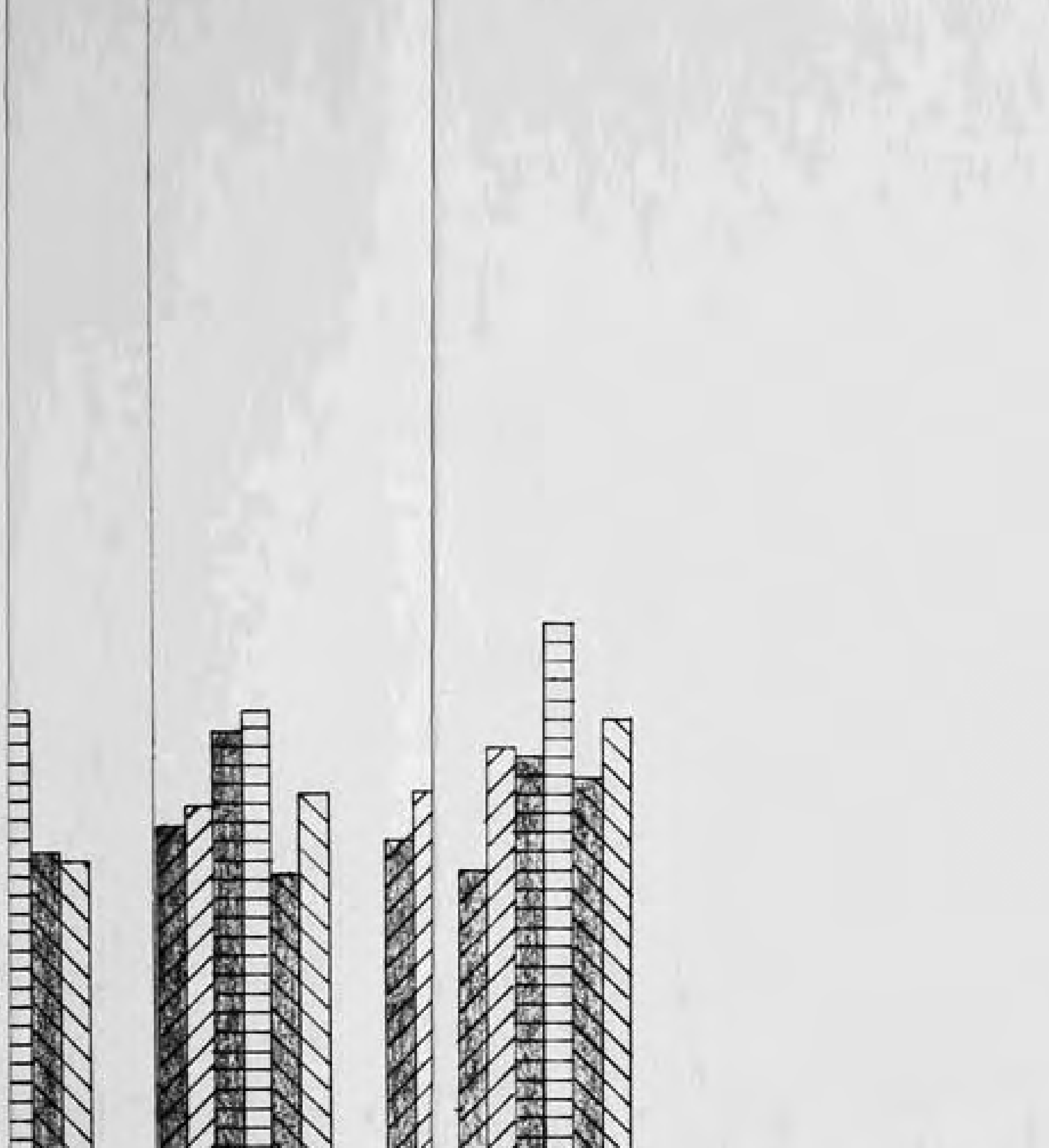
Gravel Bituminous Concrete
U.S. 52 - North Bound Lane

Section		Temp. °C	P.S.T.	Average	Corrected for Temp.	Stopping Distance Method
Trav. Lane						
1	1A	37.5	.458	.450	.540	.390
	1B	38.5	.443			
2	2A	37.5	.438	.445	.520	.376
	2B	37.0	.452			
Pass. Lane						
1	1A	38.5	.499	.492	.585	.494
	1B	38.7	.486			
2	2A	39.2	.451	.450	.542	.470
	2B	39.5	.449			

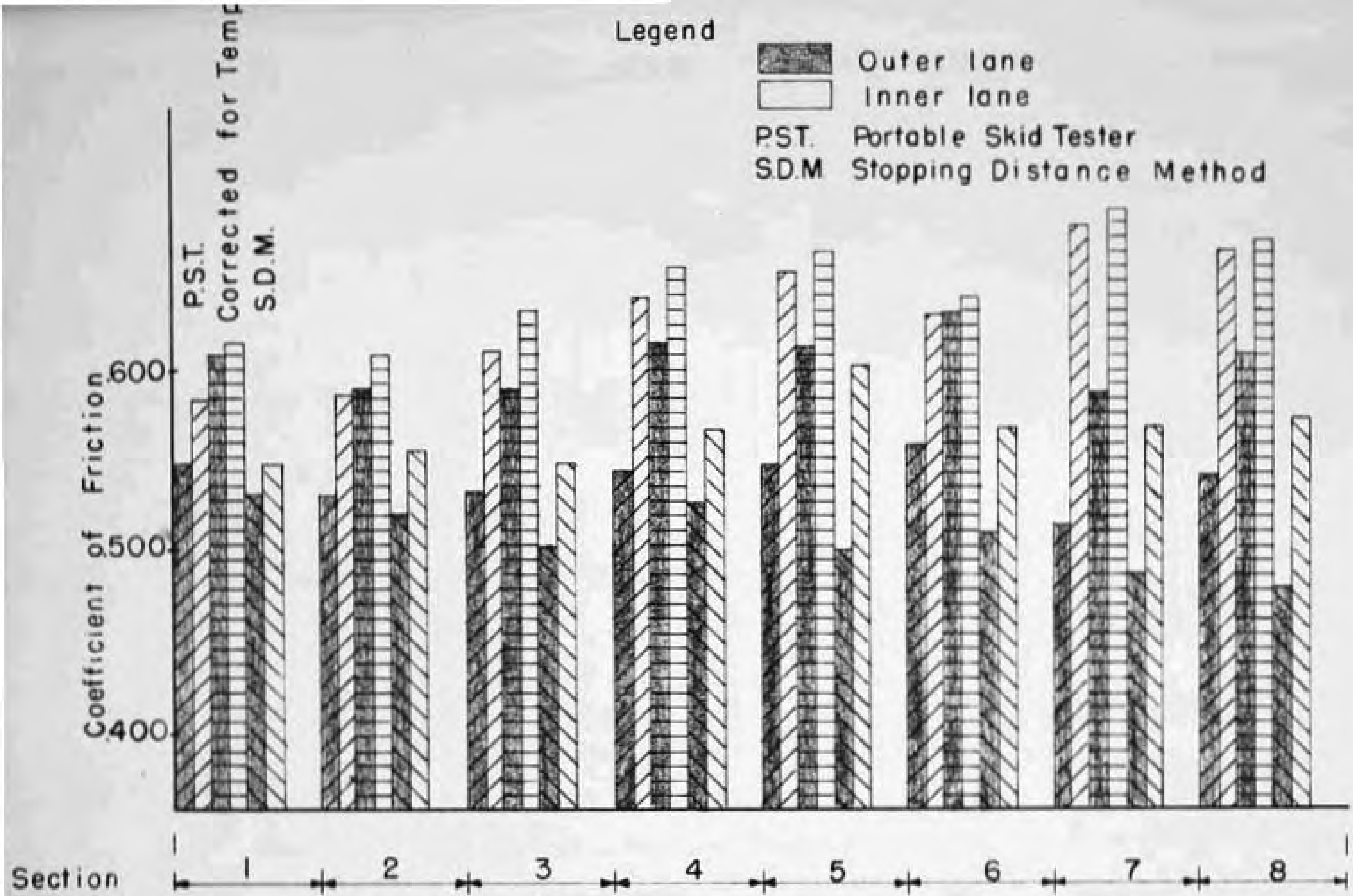
Area V

Gravel Bituminous Concrete
U.S. 52, North Bound Lane

Section		Temp. °C	P.S.T.	Average	Corrected for Temp.	Stopping Distance Method
Trav. Lane						
1	1A	36.2	.478	.467	.552	.465
	1B	37.7	.456			
2	2A	38.3	.507	.507	.597	.478
Pass. Lane						
1	1A	37.5	.499	.501	.590	.494
	1B	38.0	.502			
2	2A	38.1	.525	.510	.600	.487
	2B	38.1	.495			

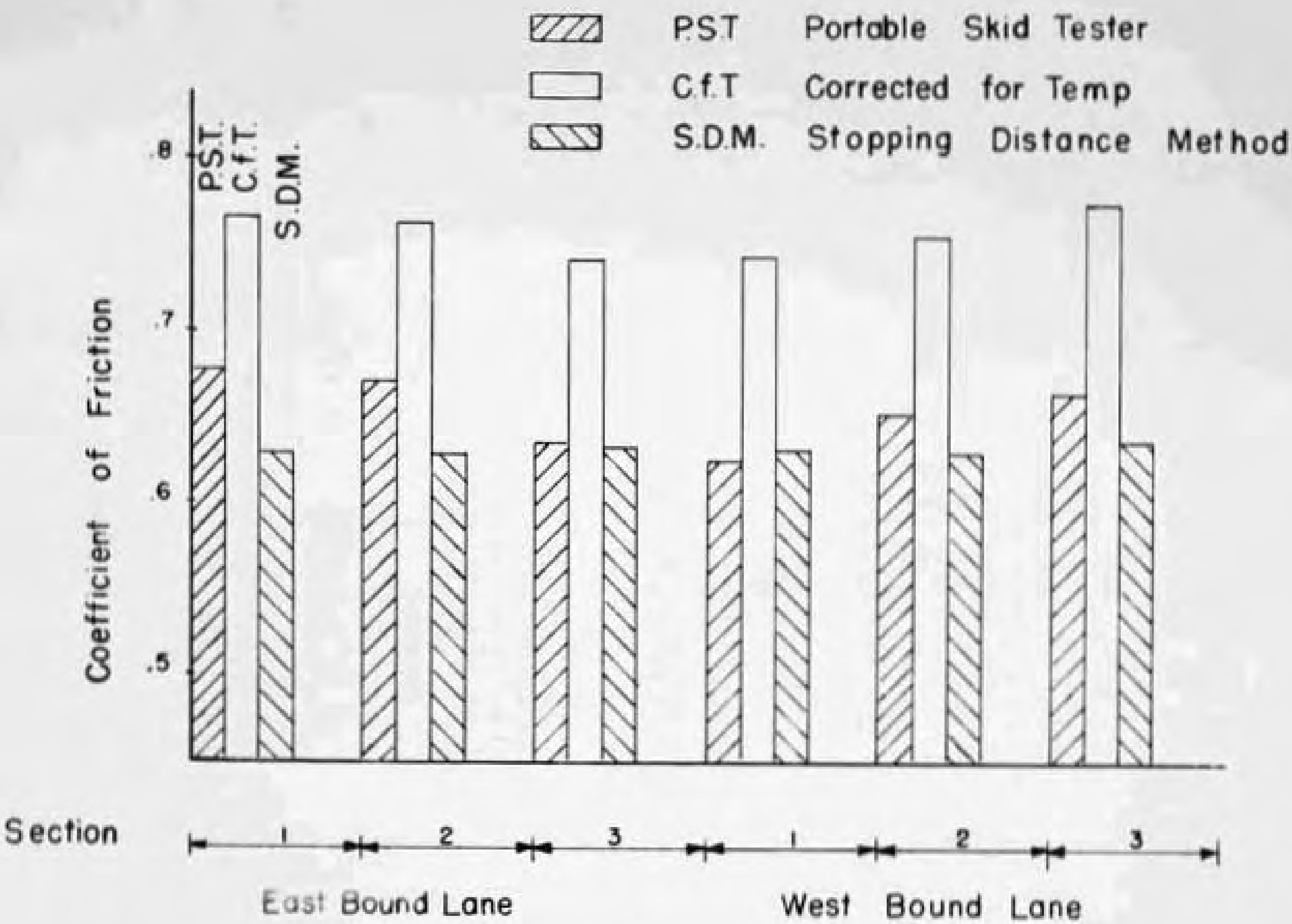


12
13
23



Fine Sand
South Bound Lanes

Fig. 9

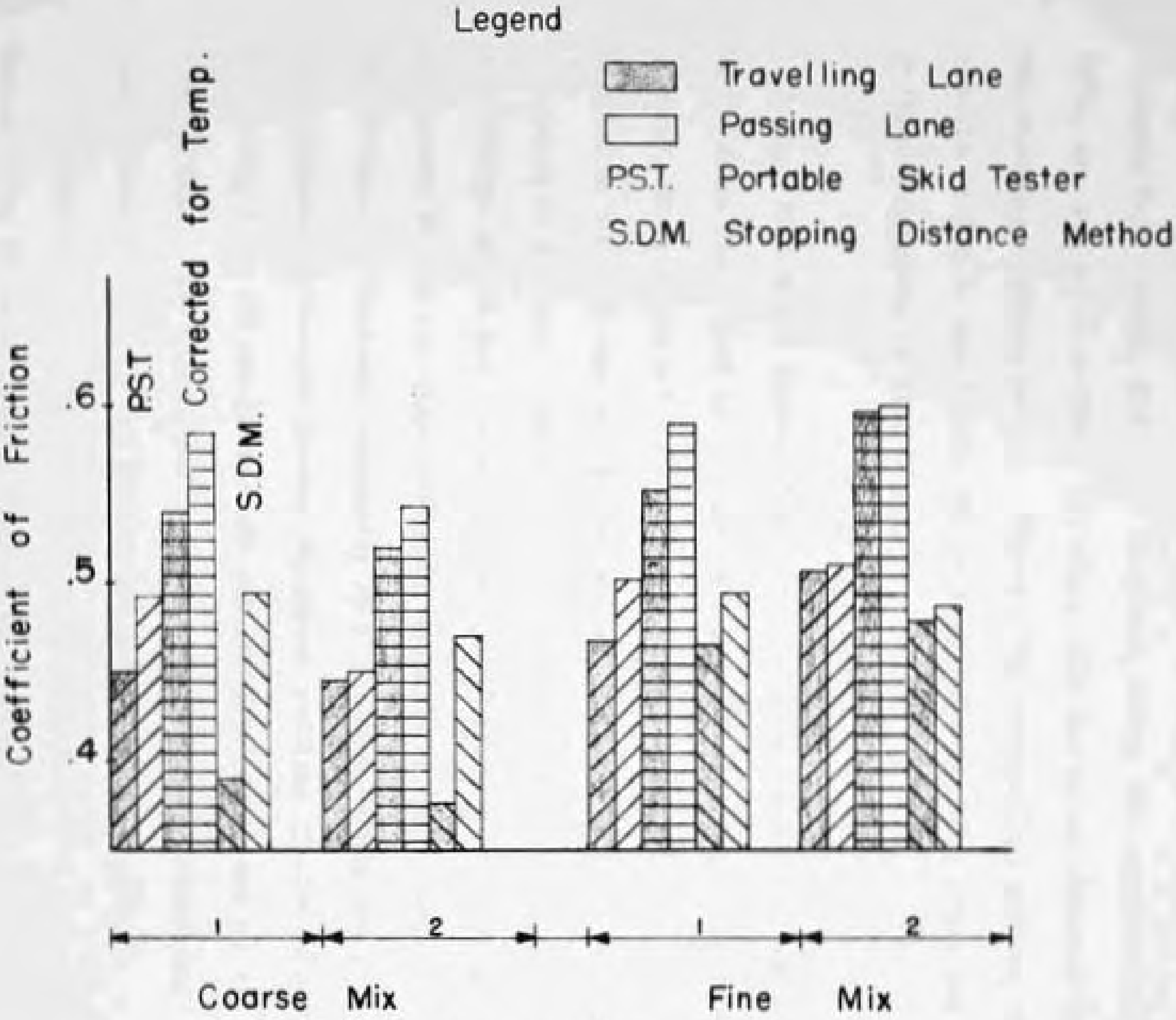


Kentucky Rock Asphalt

SR 28

East of Junction with U.S. 52

Fig. 10



Skid Test Data
U.S. 52
North Bound Lanes South of Lafayette

Fig. 11

Results

The results obtained from the trailer tests are presented in tabular form in Table (2). For each area coefficient of friction is plotted versus the speed in Figure (1) through Figure (7).

The actual measured values of coefficient of friction by the Portable Skid Tester, and their corrected values for temperature at 20°C, are presented in Table (3) along with the values obtained from the Stopping Distance method. Figures (8) through (10) present the results of P.S.T. and S.D.M. for passing and travelling lanes for different sections of five areas.

Conclusions

From Figure (1) through Figure (7) it is obvious that coefficient of friction for almost all of the sections decreases as speed increases. However, there could not be established a correlation between the trailer method and others. A statistical analysis of variances is presented in Appendix B which shows at area II the values obtained by the trailer method are not significantly different within 95% of confidence limits for eight different sections in that area. In other words the trailer, especially at high speed, could not detect a significant difference between different sections of area II. This analysis could not be carried out for other areas due to the lack of data. The excess heat produced at the brakes caused discontinuance of tests by the trailer at area I for high speeds.

Comparing the results obtained by the Portable Skid Tester and the stopping distance method, Figures (8) through (11) show that although the values for coefficient of friction for each section are different by each method, they both produce results with the same trend. In other words, for sections on which high values of friction have been indicated by the Portable Skid Tester the stopping distance method gave high values also.

APPENDIX A

EFFECT OF TEMPERATURE ON COEFFICIENT OF FRICTION OBTAINED BY PORTABLE SKID TESTER

During the tests with the Portable Skid Tester it was noticed that at different temperatures different values were obtained for coefficient of friction of the same section. Therefore, it was felt necessary to obtain a correction factor for this variation. Because most of the change was caused by change in resilience (hysteresis losses) of the rubber with change in temperature and with some change of surface properties, it was decided to make test samples from a few types of pavement and under controlled conditions measure the effect of temperature. For this purpose three specimens 8 x 8" were made from representative samples of three sections. Then all the specimens and the Portable Skid Tester were set in a constant temperature room and the temperature changed about 5°C every 24 hours. Table (4) shows the results of this test. Coefficient of friction values obtained at different temperature for different samples are plotted against the temperature in Figure (12). It was found that all three curves for temperatures between 10°C to 50°C were very close to a straight line. The equation of this straight portion was obtained as:

$$f = f_1 + \frac{T_1 - T}{200}$$

where

f = is coefficient of friction @ T°C

and

f_1 = is coefficient of friction @ T_1°C

To change all values to a certain temperature, 20°C was selected as a base temperature; the correction formula is then:

$$f_{20^{\circ}C} = f_1 + \frac{T_1 - 20}{200}$$

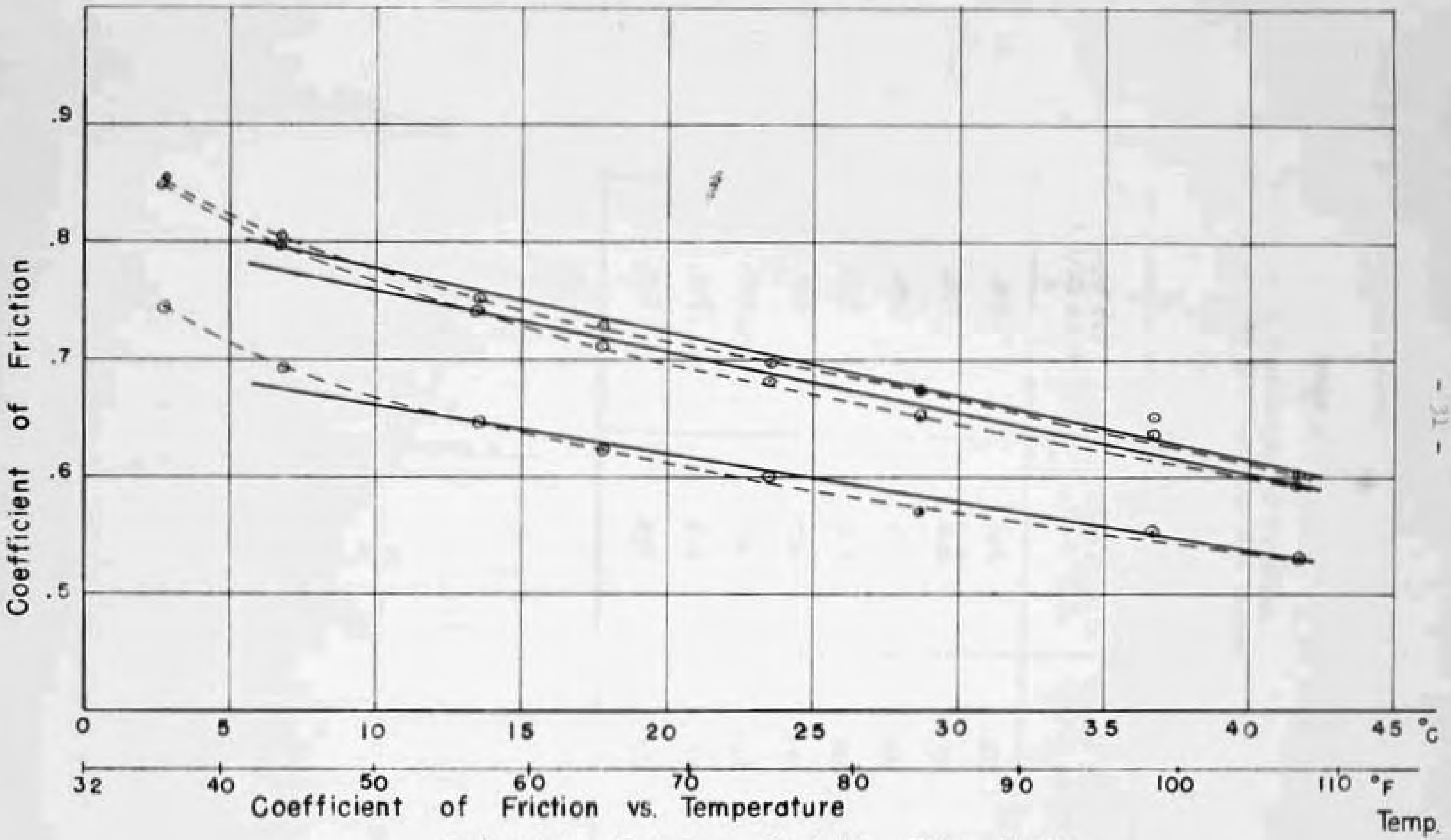
This equation was used to correct all of the Portable Skid Tester values obtained in the field at different temperatures to a common temperature.

Table 4

Variation of Coefficient of Friction
With Temperature for Portable Skid Tester

Temperature °C	Sand #17 7 1/2% AE-60 A	Fine Sand B	Sand #17 7 1/2% AE-90 °C
41.7	.593	.601	.531
36.5	.637	.650	.551
28.5	.652	.670	.570
23.5	.683	.698	.600
17.8	.712	.728	.625
13.5	.742	.750	.648
6.8	.798	.802	.695
2.5	.849	.850	.745

Corrected for Temp. $f = f_1 + \frac{T_1 - 20}{200}$



Coefficient of Friction vs. Temperature

Laboratory Results – Portable Skid Tester

Fig. 12

APPENDIX B

Series I Driving Lane, South Bound

Section / Speed	1	2	3	4	5	6	7	8			
10	.68	.69	.69	.63	.66	.64	.61	.59	5.19	26.936	3.367
20	.66	.59	.53	.53	.48	.48	.42	.40	4.09	16.728	2.091
30 2nd	.48	.40	.42	.34	.32	.28	.30	.24	2.78	7.728	.996
40	.47	.27	.32	.25	.30	.26	.24	.26	2.37	5.617	.702
50	.31	.13	.16	.13	.17	.17	.23	.27	1.57	2.465	.308
	2.60	2.08	2.12	1.88	1.93	1.83	1.80	1.76	16.00	256.00	
	6.76	4.326	4.494	3.534	3.725	3.349	3.240	3.098		6.400	
	1.372	.865	.899	.707	.745	.67	.608	.619			

Column sum of squares = 6.485 - 6.4 = .085
Row sum of squares = 7.434 - 6.4 = 1.034
Total sum of squares = 7.611 - 6.4 = 1.211

Source	d. f.	S. S.	E. M. S.	
Sections	7	.085	.0121	
Speeds	4	1.034	.2585	
Residual	28	1.092	.0033	
Total	39	1.211		

H_0: $\sigma_\beta^2 = 0$

$$F = \frac{.0121}{.0033} = 3.67$$

$$F_{.05}(7, 28) = 2.78$$

3.67 > 2.78 significant

H_0: $\sigma_\alpha^2 = 0$

$$F = \frac{.2585}{.0033} = 78.33$$ not significant

Series II **Passing Lane, South Bound**

ection \ ed	1	2	3	4	5	6	7	8			
0	.76	.72	.77	.76	.79	.77	.79	.82	6.18	38.192	4.774
0 run2	.59	.52	.55	.55	.55	.46	.52	.51	4.25	18.062	2.258
0	.58	.37	.54	.44	.44	.34	.39	.38	3.48	12.110	1.514
	1.93	1.61	1.86	1.75	1.78	1.57	1.70	1.71	13.91		
	3.725	2.592	3.459	3.062	3.168	2.465	2.890	2.924	193.488		
	1.241	.864	1.153	1.020	1.056	.821	.963	.975			

Column sum of squares = 8.093 - 8.062 = .031

Row sum of squares = 8.546 - 8.062 = .484

Total sum of squares = 8.612 - 8.062 = .550

Source	d. f.	S. S.	E. M. S.	
Sections	7	.031	.0044	
Speeds	2	.484	.242	
Residual	14	.035	.0025	
Total	23	.550		

$H_0: \sigma_S^2 = 0$

$F = \frac{.44}{.25} = 1.76$

$F_{(05)}\ (7, 14) = 2.76$

1.76 2.76 not significant

$H_0: \sigma_K^2 = 0$

$F = \frac{.242}{.0025} = 96.8$

$F_{.05}\ (2, 14) = 23.74$

$96.8 > 3.74$ significant

Series III Driving Lane, North Bound

Section / Speed MPH	1	2	3	4	5	6	7	8	Total R_i	$(R_i)^2$	
10	.63	.57	.60	.57	.63	.57	.53	.57	4.67	21.81	2.726
20	.57	.48	.45	.43	.44	.45	.44	.40	3.66	13.39	1.674
30	.48	.38	.32	.30	.32	.28	.31	.25	2.64	6.97	.871
50	.34	.16	.15	.17	.21	.22	.24	.24	1.73	2.99	.374
Total C_j	2.02	1.59	1.52	1.47	1.60	1.52	1.52	1.46	12.7		
$(C_j)^2$	4.08	2.53	2.31	2.16	2.56	2.31	2.31	2.13	161.29		
$\frac{(C_j)^2}{r}$	1.02	.6225	.5775	.54	.64	.5775	.5775	.5257		$\frac{G^2}{N}=5.04$	

$$\text{Column sum of squares} = \sum_j^c \frac{(C_j)^2}{r} - \frac{G^2}{N} = 5.08 - 5.04 = .04$$

$$\text{Row sum of squares} = \sum_i^r \frac{(R_i)^2}{C} - \frac{G^2}{N} = 5.645 - 5.04 = .605$$

$$\text{Residual sum of squares} = \sum_i^r \sum_j^c x_{ij}^2 - \sum_j^c \frac{(C_j)^2}{C} - \frac{(R_i)^2}{C} + \frac{G^2}{N} =$$

$$\text{Total sum of squares} = \sum_i^r \sum_j^c x_{ij}^2 - \frac{G^2}{N} = 5.7336 - 5.04 = .6936$$

Source	d. f.	S. S.	E. M. S.	
Sections	7	.040	.0057	
Speeds	3	.605	.2017	
Residual	21	.049	.0023	
Total	31	.694		

$H_o: \sigma_\alpha^2 = 0$

$F = \frac{57}{27} = 2.47$

$F_{.05\ (7,\ 21)} = 2.49$

$2.47 < 2.49$ Variation not significant

$H_o: \sigma_\alpha^2 = 0$

$F = \frac{.2017}{.0023} = 94.34$

$F_{.05\ (3,\ 21)} = 3.07$

$94.34 > 3.07$ Variation significant

Series IV Passing Lane, South Bound

Section / Speed	1	2	3	4	5	6	7	8			
10	.65	.63	.63	.68	.70	.65	.68	.64	5.26	27.666	3.458
20_2	.65	.63	.63	.62	.65	.61	.66	.66	5.11	26.112	3.264
30	.55	.49	.43	.50	.54	.42	.42	.43	3.78	14.288	1.786
40_1	.46	.46	.39	.32	.39	.30	.41	.30	3.03	9.181	1.148
	2.31	2.21	2.08	2.12	2.28	1.98	2.17	2.03	17.18		
	5.336	4.884	4.326	4.494	5.198	3.920	4.709	4.121	295.152		
	1.334	1.221	1.081	1.123	1.299	.980	1.177	1.030	9.223	$\frac{G^2}{N}$ = 9.223	

Column sum of squares = 9.245 - 9.223 = .022
Row sum of squares = 9.656 - 9.223 = 0.433
Total sum of squares = 9.714 - 9.223 = 0.491

Source	d. f.	S. S.	E. M. S.	
Sections	7	.022	.0031	
Speeds	3	.433	.1443	
Residual	21	.058	.0028	
Total	31	.491		

$\sigma_\beta^2 = 0$

$2 = \quad F_2 = \frac{.0031}{.0028} = 1.107$

$F_{.05}(7, 21) = 2.49 \quad 1.107 < 2.49$ not significant

$\sigma_\alpha^2 = 0$

$F = \frac{.1443}{.0028} = 51.53 \quad 51.53 > 3.07$ significant