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H-2-24

MEMO TO: A. O. Nesier, State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report; "Florida Skid Correlation Study of 1967: Skid Testing with Automobiles"; HPR-1(4), Part II; KYHPR-64-24

Three, cooperative skid-test correlation studies have been sponsored in the past by state agencies. Two were conducted in Virginia, and one was at the University of Tennessee. Heretofore, the degree of correlation among methods of test has not been altogether satisfying. Meanwhile, test devices and instrumentation have been vastly improved; and a standard method of testing with a trailer (ASTM E-274) has been adopted. The automobile method has not been standardized. We were convienced that our study of 1966 (by Rizenbergs and Ward, Feb. 1966--reference 3 in the subject report) provided sufficient basis for standardization of the automobile method of testing. Some expertize(rs) have considered attempts to correlate trailer-type test results with skidding-automobile test results as being somewhat futile. It seems now that perseverance may be rewarded. A discussion, which I prepared some time ago, extending Rizenbergs' and Ward's findings into this realm of correlation is quoted in its entirety:

*Discussion**

J. H. HAVENS, Director of Research, Kentucky Department of Highways—Skid resistance measured with a trailer-type tester reflects the frictional properties of the surface at specific velocities. The problem of relating this information to skid distances of a skidding vehicle, however, is very much with us. We can, for instance, attempt to correlate the trailer test data at 40 mph with skid distances of an automobile at 40 mph or at any other velocity. This approach constitutes an approximation since we have to deal with surfaces of varying textures. Each surface, therefore, exhibits its own skid gradient. Skid distances can be computed quite accurately by utilizing the stopping distance equation:

$$f = \frac{Va^2 - Vb^2}{30S} \quad (1)$$

$$S = \frac{Va^2 - Vb^2}{30f} \quad (2)$$

where f = effective coefficient of friction; S = skid distance, in feet; V_a = initial velocity under consideration, in mph; and V_b = final velocity under consideration, in mph—provided the steady-state skid resistance is measured at closely spaced intervals of velocity. In that case, we can summate the resultant skid distances for the small intervals of velocity:

$$S_t = \Sigma\, S_{(V_a - V_b)} + S_{(V_b - V_c)} + S_{(V_c - V_d)} \cdots + S_{(V_n - 0)} \qquad (3)$$

where V_a, V_b, etc., are initial and final velocities of small velocity increments.

Eq. 2 then becomes:

$$S_t = \Sigma \frac{V_a^2 - V_b^2}{30 f_{(V_a - V_b)}} + \frac{V_b^2 - V_c^2}{30 f_{(V_b - V_c)}} + \frac{V_c^2 - V_d^2}{30 f_{(V_c - V_d)}} \cdots + \frac{V_n^2 - V_o^2}{30 f_{(V_n - 0)}} \qquad (4)$$

where $f_{(V_a - V_b)}$, $f_{(V_b - V_c)}$, etc., are the measured coefficients of friction at midpoints between velocities $V_a - V_b$, $V_b - V_c$, etc.

This equation is equally applicable to the coefficients of friction measured over small increments of velocity in the case of a skidding automobile. Here the coefficients $f_{(V_a - V_b)}$, $f_{(V_b - V_c)}$, etc., would represent velocity increments of $V_a - V_b$, $V_b - V_c$, etc.

By using the data found in Rizenbergs' study, a comparison was made between the mean skid distances for Sites 2, 3, 4 and 5 and the distances computed from Eq. 4. The velocity at wheel lock was about 40 mph and the velocity increments were 10 mph, i.e., 40 to 30 mph, 30 to 20 mph, etc. The results are

SKID DISTANCES

Site	Measured	Calculated (Eq. 4)	Percent Error	Avg. Velocity at Wheel Lock
2	126.2	126.8	0.5	39.4
3	95.0	96.3	1.8	39.6
4	85.2	84.5	0.8	38.5
5	70.0	70.0	0.0	38.9

Obviously, the differences between the measured and calculated skid distances are negligible, and the practical implications of such computations are apparent. Quite possibly coefficients of friction for wider velocity separations could be used with equally good results. The skid distance determination could be further simplified by substituting S_x for the computed skid distance in the last 10-mph increment, since skid measurements at low velocities are difficult to conduct. The magnitude of S_x could be based upon coefficients of friction at the higher velocities. We should keep in mind, of course, that the contribution of S_x to the total skid distance S_t is quite small. The equation would then become:

$$S_t = \Sigma S_{(V_a - V_b)} + S_{(V_b - V_c)} \cdots + S_{(V_n - 10)} + S_x \qquad (5)$$

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*This is a discussion of the paper on "Skid Testing With an Automobile," by Rolands L. Rizenbergs and Hugh A. Ward which was published in Highway Research Record 189, pages 115-136.

The Florida correlation study issued from discussions in ASTM Committee E-17. Florida sponsored the study through their HPR research program. Our participation was also authorized under our HPR-study, KYHPR-64-24. R. L. Rizenbergs was largely responsible for the automobile-type tests and for the analyses and reporting. The report submitted herewith fulfills his assignment--except for presentation at a meeting of ASTM Committee E-17 in Atlanta on October 1. The paper in styled in the format of a manuscript submission--for publication by ASTM. It is also an interim report of progress creditable to KYHPR-64-24 and is hereby entered into the Department's research records.

Respectfully submitted,

Jas. H. Havens

Jas. H. Havens
Director of Research

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Research Report

Florida Skid Correlation Study of 1967
SKID TESTING WITH AUTOMOBILES

KYHPR-64-24, HPR-1(4), Part II

by
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Division of Research
DEPARTMENT OF HIGHWAYS
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in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
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The opinions, findings, and conclusions in this report are not necessarily those of the Department of Highways or the Bureau of Public Roads.

August 1968

Florida Skid Correlation Study of 1967

SKID TESTING WITH AUTOMOBILES

By Rizenbergs, R. L.[1]

REFERENCE - Rizenbergs, R. L., "Florida Skid Correlation Study of 1967 - Skid Testing with Automobiles"

ABSTRACT - The inclusion of automobiles in the Florida skid correlation study was promoted by the recognition of the following needs: 1) to compare stopping-distance measurements obtained with different instrumentation, 2) to suggest a standard method of stopping-distance testing, 3) to relate skid-resistance measurements of trailer-type testers with stopping distances of automobiles, and 4) to explore other skid-resistance measurements techniques using an automobile.

The vehicles were all full-size automobiles. Each vehicle was instrumented to measure a distance from a predetermined pressure in the brake hydraulic system to where the vehicle came to rest. Stopping distance in most of the automobiles was read directly from summating counters. Two of the automobiles were equipped with strip-chart recorders to measure distance, velocity and deceleration during the skid.

The measured stopping distances displayed minor differences between automobiles regardless of the instrumentation. The primary cause of variation in the test results was attributed to the ability of the driver to apply brakes at the prescribed test velocity. Lag between brake application and wheel lock and errors in the distance-measurement instrumentation were of secondary concern.

The stopping-distance data were correlated with the trailer-measured skid resistances for several velocities. Approximate stopping distance, therefore, can be predicted from trailer tests, or vice versa.

The results of the stopping-distance tests were sufficiently encouraging to consider standarization. Adoption of a standard method of test would serve several useful purposes. The principal benefits would be derived from having a reliable, alternate method of skid testing and references to "stopping distance" of automobiles would acquire a uniform understanding of the measurement and, therefore, common usage of the term.

KEY WORDS - testing, stopping distance, skid resistance, friction, skid, automobiles, trailers, correlation, pavements, highways.

INTRODUCTION

The automobile has been used to measure friction of highway surfaces for many years and predates any of the skid-testing devices now in common use. In retrospect, the measurement of stopping distances or skid distances of automobiles has been regarded as a semi-official standard method of test not only by the highway engineer but also by law enforcement agencies. The highway engineer has utilized the automobile to measure stopping distances, skid distances and other parameters associated with a decelerating or accelerating vehicle as a means of assessing pavement friction from the standpoint of mix design and maintenance requirements. Law enforcement agencies, on the other hand, have conducted skid tests and measured skid distances of vehicles involved in accidents for the purpose of ascertaining vehicle speeds and affixing causes contributing to the accidents. However, the inherent hazards and limitations imposed by the automobile as a skid-testing device has enhanced the development of other devices primarily as substitutes for the automobile. The advent of the trailer method of test in particular has practically eliminated the automobile as a skid-testing device. Yet, the question of what any particular skid-resistance measurement obtained with these devices means in terms of stopping distance and coefficient of friction at a specific velocity of an automobile remains unresolved.

The skid correlation study, sponsored by the Florida State Road Department and the Bureau of Public Roads, provided an opportunity to reexamine the automobile as a device for conducting skid tests with the ultimate aim of suggesting a standard method of test. The primary investigation centered on comparing stopping-distance measurements which were obtained with different automobiles, drivers and instrumentations. The "stopping distance" was predefined in the context of a panic-stop situation, i.e. distance required to stop from the moment of brake application. The study also afforded an opportunity to relate skid-resistance measurements obtained with the trailer to stopping distances of automobiles.

TEST VEHICLES AND INSTRUMENTATION

The vehicles used in the study were all full-size automobiles -- three sedans and two station wagons. The participating agencies and their automobiles were:

1. Virginia Highway Research Council - sedan (1964 Plymouth)
2. Florida State Road Department - sedan (1963 Ford)
3. Kentucky Department of Highways - sedan (1962 Ford)
4. Tennessee Highway Research Program - station wagon (1966 Chevrolet)
5. University of Wisconsin - station wagon (1961 Chevrolet)

Each vehicle was equipped with the following:

1. ASTM E-17 skid-test tires
2. Pretested pressure sensitive (75 to 83 psi) switch in the brake hydraulic system
3. Fifth wheel with a tachometer generator and a distance transducer (exception - Virginia used direct-drive mechanical speedometer and distance counter)
4. Speed-indicating meter - 1/4 mph resolution
5. Distance counter or recorder - one count per foot.

Kentucky and Wisconsin utilized strip-chart recorders to measure stopping distances and to record velocities of the vehicles during the skid. Additional information pertaining to the equipment used by several of the participants is listed in Appendix I.

PROCEDURES

Instrument Calibration

The velocity and distance measurement instrumentation was carefully calibrated each day prior to skid testing. One of the automobiles (Kentucky) was driven at least twice on an accurately surveyed two-mile section of Interstate 75 at 40 mph. The time of traverse was obtained with a stop watch. The correct speed was computed from the known distance and the measured time. The speed indicating meter was then corrected accordingly. Distance calibration was achieved on the same test course at 25 mph by driving one-mile sections and counting distance traversed at one count per foot with a magnetic distance counter. The inflation pressure in the tire of the fifth wheel was maintained at 24 psi.

At the test site equipment in each automobile was referenced for velocity and distance calibration to the previously calibrated instruments in the Kentucky vehicle. Speed checks were performed at least once daily by driving two vehicles at a time, side by side, at 40 mph and at 20 mph until proper verification or meter adjustments were performed. Distance calibration was conducted similarly by driving at least 1000 feet from a set starting point.

Skid Test

Testing with automobiles was initiated on November 1 and, except for Wisconsin, completed in three days as shown below:

Nov. 1 - Site I, Section A, B and C
Nov. 2 - Site II, Section A, C and E
Nov. 6 - Site I, Section C and E
Site II, Section B and D

On every section, automobiles followed the trailer tests.

The test sections were subdivided into six zones. Detailed descriptions of the test sites as well as other pertinent information concerning design, conduct and trailer data of the correlation study may be found in the companion report prepared by Smith and Fuller[2]. Location of the sprinkler system next to Zones 1 and 2 necessitated omission of these zones on some sections in order to protect the sprinkler system from the skidding automobiles. In the case of Site II, Section D, the trailers had worn two distinct tracks. The separation of the tracks conincided with the tread width of the cars and, therefore, testing was confined to the tracks.

The test procedure required the automobiles to accelerate above test speed and coast onto the proper zone. As the decreasing velocity reached test speed, the brakes were promptly and firmly applied to facilitate quick lock-up of the wheels and to skid to a stop. The stopping distance indicated on a counter, or recorded on a strip-cart recorder for later determination, was noted. If the velocity at the moment of brake application deviated perceptably from the desired test speed or if the skidding excursion took place on an improper zone, the test was repeated. Some tests were repeated if the driver felt that he did not properly apply brakes. In all, six acceptable tests were performed on each section per test speed as follows:

Site	Sections	Zones	No. of Tests
I	A, B & C	3 & 4	3
I	A, B & C	5 & 6	3
I	D & E	1 thru 6	1 per zone
II	A & C	3 & 4	3
II	A & C	5 & 6	3
II	B	1 & 2	3

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[2] Smith, L. L. and Fuller, S. L., "Florida Skid Correlation Study of 1967 - Skid Testing with Trailers".

Site	Sections	Zones	No. of Tests
II	B	5 & 6	3
II	D	3 & 4	3 per zone
II	E	1 thru 6	1 per zone

A fixed order of sequence in testing was followed on all surfaces. Every section was tested at 20 mph and then at 40 mph. Section C on Site I proved to be impossible to test at 40 mph. Differential lock-up of the automobile wheel caused the vehicles to spin around.

Inflation pressure in tires was monitored with a calibrated pressure gauge and was maintained at 24 psi.

TEST RESULTS AND DISCUSSION

Automobiles

The stopping distances measured at the correlation study represent a panic-stop situation as defined earlier and no consideration was given to perception and reaction time that would be involved when a driver was confronted with an impending hazard on the highway. The measurement was in fact made from the moment pressure in the brake hydraulic system was sufficient to close a pressure sensitive switch and not from the instant of brake application. The test speed conincided with the brake application but not with the beginning of the distance measurement. Therefore, between brake application and closing of the switch, a loss in vehicle speed was involved. To determine if this speed loss was sufficiently great to be of any particular concern, determination of the actual velocity at the start of distance counting was made from velocity recordings obtained with the Kentucky vehicle. When compared with the 40 mph test velocities, the average loss in velocity on a given section did not exceed 0.5 mph and in most cases was much less. Since no effort was made to record the moment of brake application, it is not possible to ascertain whether the loss in velocity was primarily due to the lag time involved or due to other factors, such as any bias of the test driver in reading the speed meter. In all probability, the test driver was the most dominant influence. A previous study by Rizenbergs and Ward[3] supports this assumption.

Data -- Test data for all automobiles are summarized in Table I in terms of stopping distances and in Table II in terms of coefficients of friction, as computed using the stopping-distance equation $f = \frac{V^2}{30\ S}$. Average values shown are for four of the participating vehicles. The data are also exhibited graphically in Figs. 1 and 2. Wisconsin data, while presented, were not considered in the analysis since it was incomplete and quite likely erroneous on some surfaces due to improper instrument calibration or malfunctions. No further reference will be made to it in this discussion.

The automobile data were subjected to various statistical analysis in an effort to evaluate each vehicle and to relate data of one vehicle to another. The complete mathematical procedure used in the statistical analysis is presented in Appendix II.

Repeatability -- Standard deviations were calculated for the six stopping-distance tests conducted on each surface at the two test speeds. The results of this analysis as well as the arithmetical mean for each section and vehicle are presented in Table III.

The magnitude of the standard deviation is influenced by the friction level of surfaces and by all the other variables associated with the test. The principal influences were the driver who controls the velocity at which brakes

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[3] Rizenbergs, R. L. and Ward, H. A., "Skid Testing With an Automobile", <u>Record No. 187</u>, Highway Research Board, pp 115-137, 1967.

TABLE I -- AUTOMOBILE STOPPING DISTANCES
(in feet)

Site I

20 mph

Section	Ky.	Tenn.	Va.	Fla.	Wis.	Avg.[a]
A	22	23	22	25	22	23
B	50	52	50	54	50	52
C	43	46	37	-	-	42
D	20	20	21	24	21	21
E	19	19	20	20	-	20

40 mph

A	104	103	99	105	82	103
B	288	307	285	301	-	295
C	-	-	-	-	-	-
D	87	88	81	88	83	86
E	79	78	78	82	-	79

Site II

20 mph

Section	Ky.	Tenn.	Va.	Fla.	Wis.	Avg.[a]
A	20	20	19	19	21	20
B	18	20	20	-	23	19
C	23	22	21	22	-	22
D	24	23	24	-	14	24
E	24	24	25	26	-	25

40 mph

A	80	78	77	77	80	78
B	80	78	80	-	-	79
C	88	82	90	86	-	87
D	95	89	95	-	77	93
E	115	113	111	114	-	113

a. Wisconsin data not included.

TABLE II -- AUTOMOBILE STOPPING DISTANCE COEFFICIENTS

Site I

20 mph

Section	Ky.	Tenn.	Va.	Fla.	Wis.	Avg.[a]
A	0.60	0.58	0.60	0.53	0.61	0.58
B	0.27	0.26	0.27	0.24	0.27	0.26
C	0.31	0.29	0.37	–	–	0.32
D	0.66	0.65	0.64	0.56	0.64	0.63
E	0.61	0.71	0.72	0.66	–	0.70
40 mph						
A	0.51	0.52	0.54	0.51	0.65	0.52
B	0.18	0.17	0.19	0.18	–	0.18
C	–	–	–	–	–	–
D	0.61	0.61	0.66	0.60	0.64	0.62
E	0.68	0.68	0.68	0.65	–	0.67

Site II

20 mph

Section	Ky.	Tenn.	Va.	Fla.	Wis.	Avg.[a]
A	0.66	0.66	0.71	0.71	0.64	0.68
B	0.72	0.67	0.68	–	0.58	0.69
C	0.58	0.62	0.61	0.62	–	0.61
D	0.55	0.57	0.57	–	0.95	0.56
E	0.55	0.56	0.52	0.52	–	0.54
40 mph						
A	0.67	0.69	0.69	0.69	0.67	0.69
B	0.67	0.69	0.67	–	–	0.68
C	0.61	0.65	0.60	0.62	–	0.62
D	0.56	0.60	0.54	–	0.70	0.57
E	0.46	0.47	0.48	0.47	–	0.47

[a] Wisconsin data not included.

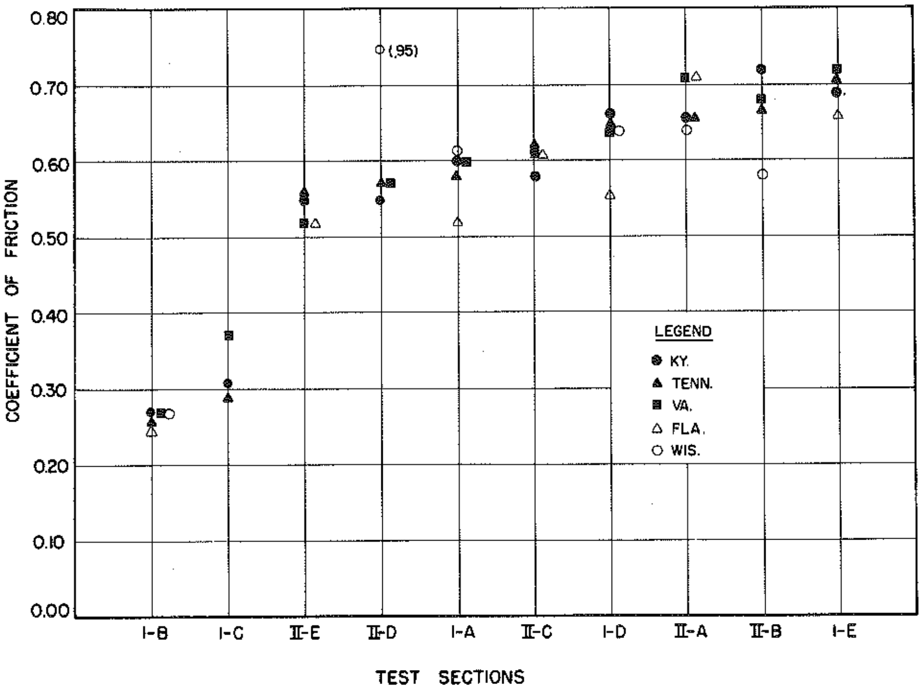

Fig. 1. Coefficient of friction of each automobile (20-mph test speed).

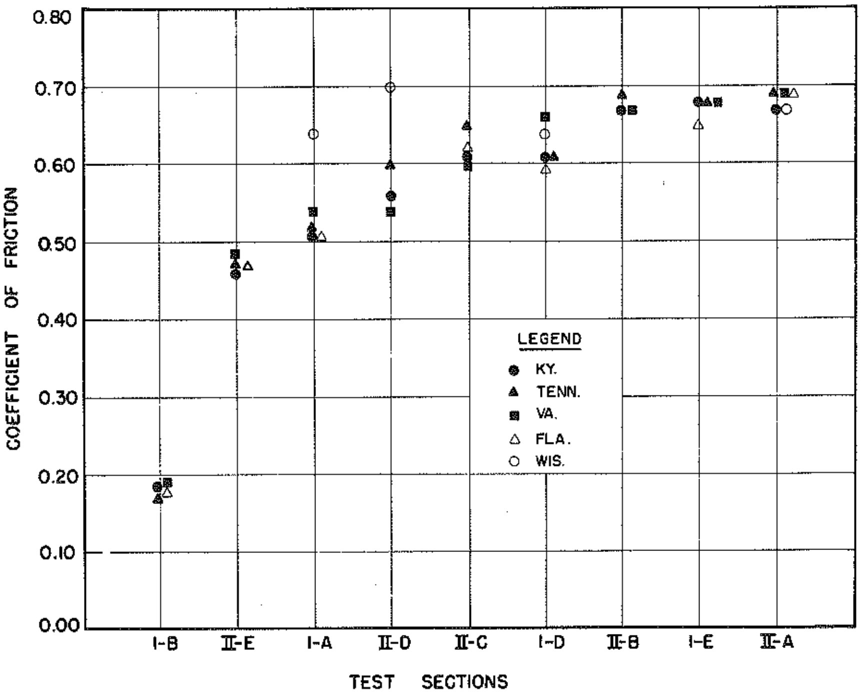

Fig. 2. Coefficient of friction of each automobile (40-mph test speed).

TABLE III -- STANDARD DEVIATIONS

Site	Section	Ky.	Tenn.	Va.	Fla.	Mean
			20 mph			
I	A	0.023	0.015	0.023	0.067	0.032
I	B	0.013	0.015	0.020	0.014	0.016
I	C	0.026	0.031	0.040	---	0.032
I	D	0.022	0.024	0.034	0.079	0.040
I	E	0.033	0.015	0.018	0.101	0.042
	Avg.	0.023	0.020	0.027	0.065	0.032
			40 mph			
I	A	0.027	0.016	0.012	0.022	0.019
I	B	0.010	0.015	0.014	0.007	0.012
I	D	0.046	0.012	0.018	0.036	0.028
I	E	0.031	0.021	0.018	0.023	0.023
	Avg.	0.028	0.016	0.016	0.022	0.020
			20 mph			
II	A	0.036	0.032	0.034	0.082	0.046
II	B	0.022	0.031	0.027	---	0.027
II	C	0.019	0.009	0.025	0.070	0.031
II	D	0.025	0.034	0.039	---	0.033
II	E	0.050	0.033	0.027	0.084	0.048
	Avg.	0.030	0.028	0.030	0.079	0.038
			40 mph			
II	A	0.025	0.035	0.011	0.018	0.022
II	B	0.027	0.009	0.012	---	0.016
II	C	0.007	0.018	0.033	0.015	0.018
II	D	0.037	0.011	0.019	---	0.022
II	E	0.020	0.015	0.015	0.016	0.016
	Avg.	0.023	0.018	0.018	0.016	0.019
σ for 20 mph		0.026	0.024	0.028	0.072	0.035
σ for 40 mph		0.025	0.017	0.017	0.019	0.020

were applied and how firmly they were applied, the performance of the brake system, and the accuracy and performance of the measuring equipment. Influence of the surface was well noted in the increased standard deviations for the more skid-resistant surfaces. Zone averages for each surface were calculated and no significant variation in friction was noted.

Good repeatability of test data for both 20 mph and 40 mph was evidenced for all vehicles except for Florida's at the 20 mph tests. Florida was experiencing brake malfunctions, which apparently caused prolonged lags between brake application and wheel lock. Difficulties with the brakes necessitated Florida to abstain from testing several sections. The most repeatable results were obtained by Tennessee. More repeatable results for all vehicles were obtained at 40-mph test speeds than at 20 mph. At 40 mph the stopping distances were four to five times longer, and therefore, a greater proportion of each pavement was sampled. Also, the variations in the lag time -- between brake application and wheel lock -- and errors in velocity reading by the driver were less significant.

Judged on a group basis, the automobiles yielded more repeatable test results than the trailers. At 40 mph the trailers sampled about 60 feet of pavement for each test while the automobiles usually skidded further with all four wheels locked. The automobiles, therefore, had a built-in advantage.

The standard deviations were used to determine the number of tests required to achieve the desired degree of accuracy. The number of required tests for the automobiles are presented in Table IV. At the 95%-confidence level, the automobiles require a total of five tests at a speed of 40 mph.

Least Significant Difference -- The analysis for least significant difference (LSD) was conducted to determine whether the differences in the means (six measurements each) of two vehicles are truly different or are due to

TABLE IV -- NUMBER OF TESTS REQUIRED FOR 5 PERCENT ERROR OR LESS

Site I

Section	Ky.	Tenn.	Va.	Fla.	Mean
			20 mph		
A	5	4	5	Very large	5[a]
B	4	5	6	5	5
C	9	11	18	---	13[a]
D	5	5	7	Very large	6[a]
E	6	3	4	Very large	4[a]
Avg.	6	6	8		7
			40 mph		
A	7	4	4	6	5
B	4	5	5	3	4
D	11	3	4	8	6
E	6	4	4	5	5
Avg.	7	4	4	5	5

[a] Fla. not included.

TABLE V -- LEAST SIGNIFICANT DIFFERENCE

	Site I		Site II	
Section	20 mph	40 mph	20 mph	40 mph
A	0.06	0.03	0.08	0.04
B	0.03	0.02	0.04	0.03
C	0.05	-	0.06	0.07
D	0.08	0.05	0.05	0.04
E	0.09	0.04	0.09	0.03

chance variations. The standard deviations of the data for each automobile within a section-speed combination were used to compute a LSD. The results are presented in Table V. If the means of two cars differ in excess of the LSD value for a given section and speed, significant difference was found; otherwise the difference was due to chance variation. These data are summarized in Table VI and Table VII.

Significant differences were found between Florida and the other vehicles on several surfaces. The performance of the Florida automobile was discussed earlier.

Relative Precision -- The precision of a particular automobile as a testing device was judged on the basis of group averages for each section-speed combination in the absence of an "absolute" friction reference. The difference between the group mean and each automobile was determined for every section-speed combination. The results of this analysis are displayed in Table VIII and graphed in Fig. 3.

The best accuracy and precision for the group as a whole were realized at the 40-mph test speed. A brief statement regarding each automobile follows:

1. Kentucky - good precision at 40 mph, somewhat erratic results at 20 mph.
2. Tennessee - good precision on Site I, data biased upward on Site II at 40 mph.
3. Virginia - an upward bias on Site I, good accuracy on Site II.
4. Florida - a downward bias on Site I, especially on 20-mph tests; good precision on Site II.

Correlation Equations -- In a further effort to relate the data of one vehicle to another or to the average of all vehicles, linear regression equations were calculated along with the statistical parameters of coefficients of correlation (R) and standard error (E_s). The correlation equations for Site I

TABLE VI -- STATISTICAL DIFFERENCE BETWEEN AUTOMOBILES

Site I

		20 mph															40 mph														
		Ky.					Tenn.					Va.					Ky.					Tenn.					Va.				
	Sec.	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Fla.	A	Y[b]					N					Y					N					N					N				
Fla.	B		N[a]					N					N					N					N					N			
Fla.	C			-					-					-					-					-					-		
Fla.	D				Y					Y					N					N					N					Y	
Fla.	E					N					N					N					N					N					N
Ky.	A						N					N										N					N				
Ky.	B							N					N										N					N			
Ky.	C								N					Y										-					-		
Ky.	D									N					N										N					N	
Ky.	E										N					N										N					N
Tenn.	A											N															N				
Tenn.	B												N															N			
Tenn.	C													Y															-		
Tenn.	D														N															N	
Tenn.	E															N															N

[a] N means no significant difference was found.
[b] Y means significant difference was found.

TABLE VII -- STATISTICAL DIFFERENCE BETWEEN AUTOMOBILES

Site II

		20 mph														
		Ky.					Tenn.					Va.				
	Sec.	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Fla.	A	N[a]					N					N				
Fla.	B		–					–					–			
Fla.	C			N					N					N		
Fla.	D				–					–					–	
Fla.	E					N					N					N
Ky.	A						N					N				
Ky.	B							Y[b]					N			
Ky.	C								N					N		
Ky.	D									N					N	
Ky.	E										N					N
Tenn.	A											N				
Tenn.	B												N			
Tenn.	C													N		
Tenn.	D														N	
Tenn.	E															N

		40 mph														
		Ky.					Tenn.					Va.				
	Sec.	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Fla.	A	N					N					N				
Fla.	B		–					–					–			
Fla.	C			N					N					N		
Fla.	D				–					–					–	
Fla.	E					N					N					N
Ky.	A						N					N				
Ky.	B							N					N			
Ky.	C								N					N		
Ky.	D									N					N	
Ky.	E										N					N
Tenn.	A											N				
Tenn.	B												N			
Tenn.	C													N		
Tenn.	D														Y	
Tenn.	E															N

[a] N means no significant difference was found.
[b] Y means significant difference was found.

TABLE VIII -- DEVIATION FROM GROUP AVERAGES

Participant	Site I A	Site I B	Site I C	Site I D	Site I E	Site II A	Site II B	Site II C	Site II D	Site II E
					20 mph					
Ky.	+.02[a]	+.01	-.01	+.03	-.01	-.02	+.03	-.03	-.01	+.01
Tenn.	0	0	-.03	+.02	+.01	-.02	-.02	+.01	+.01	+.02
Va.	+.02	+.01	+.05	+.01	+.02	+.03	-.01	0	+.01	-.02
Fla.	-.05	-.02	-	-.07	-.04	+.03	-	+.01	-	-.02
					40 mph					
Ky.	+.01	0	-	+.01	+.01	-.02	-.01	-.01	-.01	-.01
Tenn.	0	-.01	-	-.01	+.01	0	+.01	+.03	+.03	0
Va.	+.02	+.01	-	+.04	+.01	0	-.01	-.02	-.03	+.01
Fla.	-.01	0	-	-.02	-.02	0	-	0	-	0

[a] Date in terms of coefficient of friction.

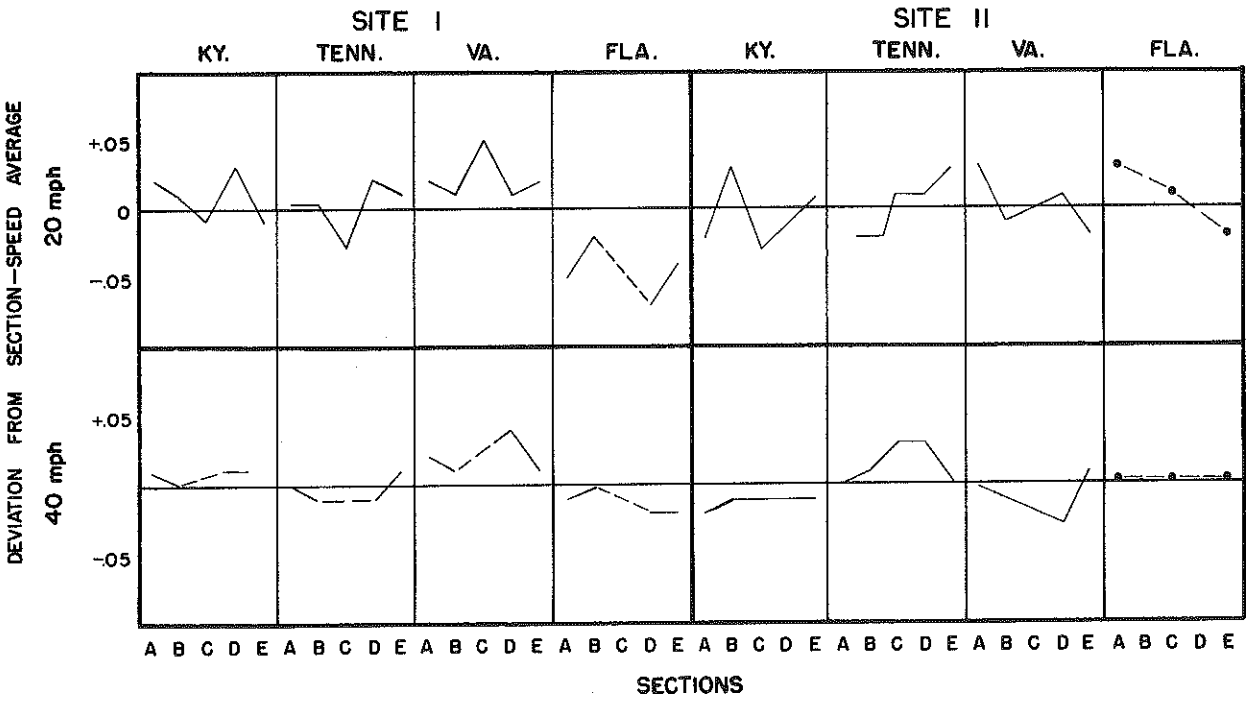

Fig. 3. Deviations of the coefficient of friction of each automobile from the automobile group average of each section-speed combination.

are presented in Table IX and for Site II in Table X. These equations are applicable in relating one vehicle to another only for the same set of conditions and test influences prevailing at the Florida study. Somewhat different test data are likely to result if, for instance, the drivers were interchanged. So, the equations really express the performance relationship between specific functioning systems which include the driver, vehicle, instrumentation, tires, etc.

Automobiles Versus Trailers

Data -- The test data for the automobiles and trailers are compared graphically in Figs. 4, 5 and 6. The best agreement between the two methods of test was obtained at the test speed of 40 mph on the smooth-textured surfaces. On the same sections at 20 mph, the data did not compare well at all, especially on Section E (Kentucky Rock Asphalt). Curiously, on Site II the best relationship was found at 20 mph. It should be remembered at this point that the automobiles followed the trailers and it would be proper to assume that most of the test surfaces experienced some reduction of friction. Friction characteristics on several of the sections on Site II undoubtedly changed quite significantly. For example, on Section D the trailers measured higher friction with increase in speed, whereas, the automobiles did not.

Limited wear tests were conducted with trailers at 40 mph before and after the trailer tests. Several sections exhibited significant reduction in skid resistance. Unfortunately, the initial wear tests were performed in the mornings at lower surface temperatures than the after-trailer tests in the afternoons. It would be erroneous to assume that the differences between A.M. and P.M. measurements were entirely due to wear. Influence due to changes in surface temperature must also be recognized. If the temperature influences were ignored and the trailer data corrected to reflect the surface condition

TABLE IX -- CORRELATION EQUATIONS OF AUTOMOBILES

Site I

X	Y	EQUATION	R	E_s
		20 mph		
Ky.	Tenn.	$Y = 1.041 X - 0.029$	0.998	0.016
Ky.	Va.	$Y = 0.942 X + 0.043$	0.988	0.034
Ky.	Fla.	$Y = 0.919 X - 0.012$	0.986	0.037
Ky.	Avg.	$Y = 0.973 X + 0.005$	0.996	0.020
Tenn.	Va.	$Y = 0.904 X + 0.020$	0.989	0.032
Tenn.	Fla.	$Y = 0.895 X + 0.005$	0.994	0.024
Tenn.	Avg.	$Y = 0.935 X + 0.032$	0.998	0.015
Va.	Fla.	$Y = 0.909 X - 0.009$	0.998	0.015
Va.	Avg.	$Y = 1.022 X - 0.033$	0.997	0.018
Fla.	Avg.	$Y = 1.075 X + 0.008$	0.998	0.019
		40 mph		
Ky.	Tenn.	$Y = 1.022 X - 0.011$	0.999	0.008
Ky.	Va.	$Y = 0.991 X + 0.012$	0.995	0.027
Ky.	Fla.	$Y = 0.954 X + 0.013$	0.999	0.012
Ky.	Avg.	$Y = 0.996 X + 0.004$	0.999	0.012
Tenn.	Va.	$Y = 0.998 X + 0.023$	0.996	0.025
Tenn.	Fla.	$Y = 0.934 X + 0.023$	0.999	0.008
Tenn.	Avg.	$Y = 0.999 X + 0.015$	0.999	0.009
Va.	Fla	$Y = 0.930 X + 0.004$	0.998	0.016
Va.	Avg.	$Y = 0.997 X - 0.005$	0.998	0.015
Fla.	Avg.	$Y = 1.044 X - 0.009$	1.000	0.003

TABLE X -- CORRELATION EQUATIONS OF AUTOMOBILES

Site II

X	Y	EQUATION	R	E_s
		20 mph		
Ky.	Tenn.	$Y = 0.623 X + 0.234$	0.933	0.021
Ky.	Va.	$Y = 0.900 X + 0.067$	0.870	0.044
Ky.	Fla.	$Y = 1.603 X - 0.340$	0.959	0.022
Ky.	Avg.	$Y = 0.857 X + 0.091$	0.948	0.025
Tenn.	Va.	$Y = 1.488 X - 0.299$	0.961	0.025
Tenn.	Fla.	$Y = 1.881 X - 0.537$	0.996	0.006
Tenn.	Avg.	$Y = 1.346 X - 0.213$	0.995	0.008
Va.	Fla.	$Y = 0.998 X + 0.005$	0.998	0.006
Va.	Avg.	$Y = 0.851 X + 0.090$	0.974	0.018
Fla.	Avg.	$Y = 0.736 X + 0.156$	1.000	0.000
		40 mph		
Ky.	Tenn.	$Y = 1.032 X - 0.007$	0.990	0.010
Ky.	Va.	$Y = 0.979 X + 0.014$	0.979	0.021
Ky.	Fla.	$Y = 1.038 X - 0.009$	0.999	0.000
Ky.	Avg.	$Y = 1.025 X - 0.003$	0.999	0.004
Tenn.	Va.	$Y = 0.789 X + 0.122$	0.959	0.029
Tenn.	Fla.	$Y = 0.949 X + 0.021$	0.989	0.017
Tenn.	Avg.	$Y = 0.970 X + 0.004$	0.987	0.013
Va.	Fla.	$Y = 1.059 X - 0.031$	0.992	0.008
Va.	Avg.	$Y = 1.010 X + 0.004$	0.985	0.014
Fla.	Avg.	$Y = X$	1.000	0.000

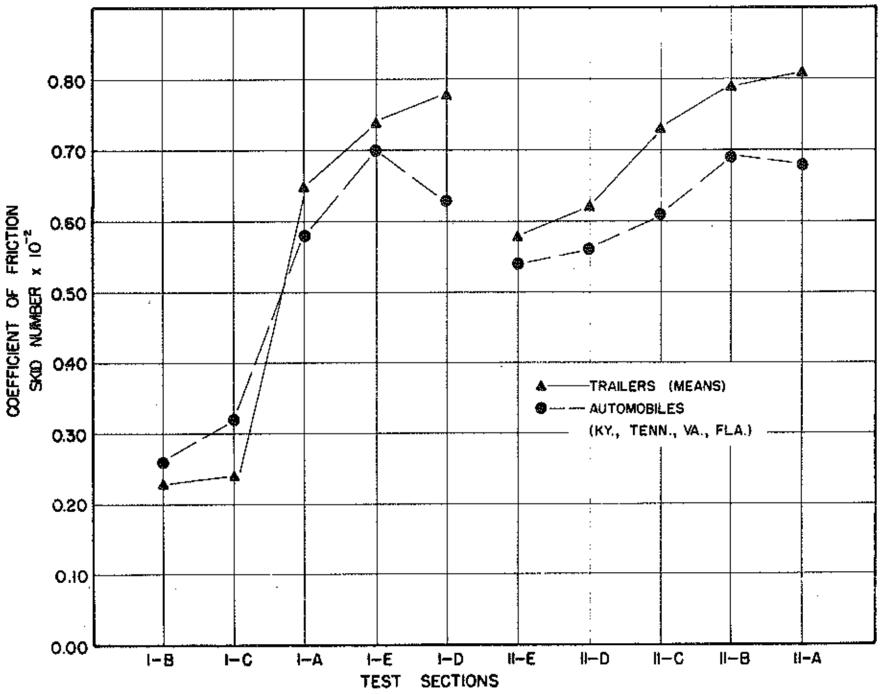

Fig. 4. Coefficients of friction of automobiles compared with skid numbers of trailers for all test sections (20-mph test speed).

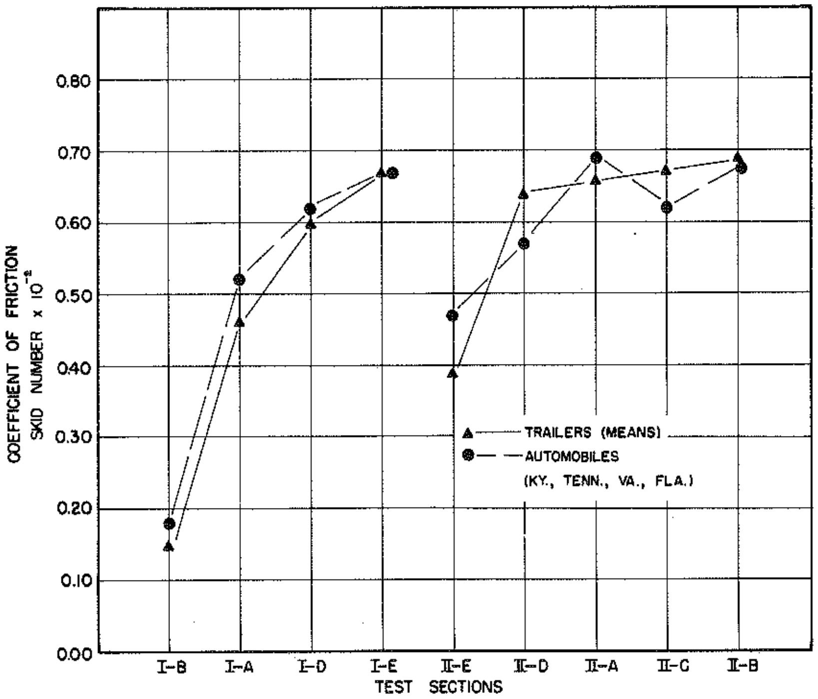

Fig. 5. Coefficients of friction of automobiles compared with skid numbers of trailers for all test sections (40-mph test speed).

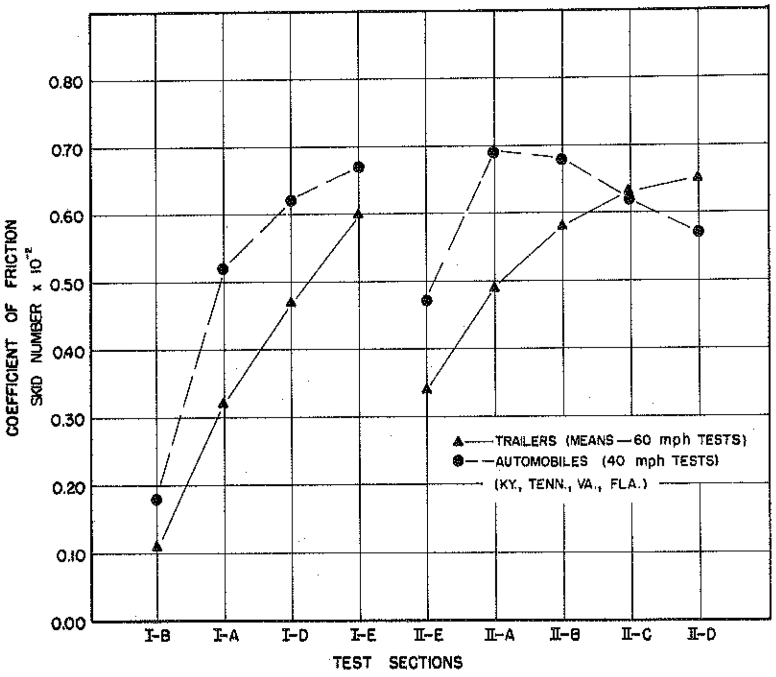

Fig. 6. Coefficients of friction of automobiles (40-mph test speed) compared with skid numbers of trailers (60-mph test speed) for all test sections.

prior to automobile tests, some improvement in relating the automobile and trailer data would be realized, but not on all surfaces.

Correlation -- Statistical analysis of the automobile and trailer data was conducted to find the most suitable regression lines and to assess the degree of correlation between any two sets of data. Between eight and thirteen regression curves (Appendix II) were calculated for each set of data and those lines having the best fit were plotted. Selection of the final equation was made mainly by noting how well the line expresses the general trend of the data. An IBM 360 computer was used for these correlations as well as for most of the statistical analysis presented in this paper. Some reservation must be expressed concerning validity of the regression analysis because of the limited number of data points available. Four, or even five, data points unevenly distributed cannot be regarded to be sufficient for a good correlation. Too much emphasis or weight is given to a single point, such as data on Site I, Section A.

Stopping distances of automobiles were correlated with the trailers for several velocity combinations as shown in Table XI. The 20-mph tests on Site I did not correlate well. On Site II the 40-mph tests did not correlate well and at some of the other speeds the data did not correlate at all. The regression equations for Site I at test velocities of 20 mph and 40 mph are plotted as Fig. 7.

The coefficients of friction of automobiles were correlated with trailers for several speed combinations on Site I only, as shown in Table XII. The 40-mph test results are plotted as Fig. 8.

Correlation equations were also determined to relate the following:

1. Individual trailers versus automobile means for several velocity combinations (Table XIII)
2. Individual automobiles versus trailer means for several velocity combinations (Table XIV).

TABLE XI -- CORRELATION EQUATION OF STOPPING DISTANCE VS TRAILER MEANS

X(Trailer Means) Velocity, mph	Y(Stopping Distance) Velocity, mph	EQUATION	R	E_s
		Site I		
20	20	$Y = 16100\ (1/X^2) + 18$	-0.982	3.20
40	40	$Y = 8150\ (1/X^{1.3}) + 45$	-1.000	1.18
60	40	$Y = 16900\ (1/X^{1.8}) + 70$	-1.000	0.89
60	20	$Y = 2530\ (1/X^{1.8}) + 18$	-1.000	0.27
40	20	$Y = 1960\ (1/X^{1.5}) + 17$	-1.000	0.27
		Site II		
20	20	$Y = -\ 0.242\ X + 39$	-0.970	0.72
40	40	$Y = -\ 0.010\ X^2 + 129$	-0.941	0.57
60	40	No Correlation		
40	20	No Correlation		
40	20	No Correlation		

TABLE XII -- CORRELATION EQUATIONS OF AUTOMOBILE MEANS VS TRAILER MEANS

Site I

X(Trailer Means[a]) Velocity, mph	Y(Automobile Means) Velocity, mph	EQUATION	R	E_s
20	20	$Y = 0.706\ (X) + 0.125$	0.979	0.046
40	40	$Y = -\ 1.394\ (1/e^X) + 1.388$	0.999	0.010
60	40	$Y = 0.294\ (\ln(X)) + 0.836$	0.998	0.019

[a] Skid Numbers x 10^{-2}

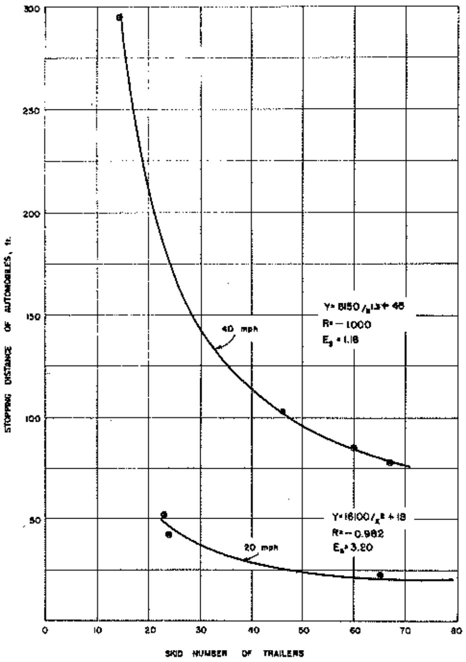

Fig. 7. Graph of stopping distances of automobiles versus skid numbers of trailers for 20-mph and 40-mph test speeds on Site I.

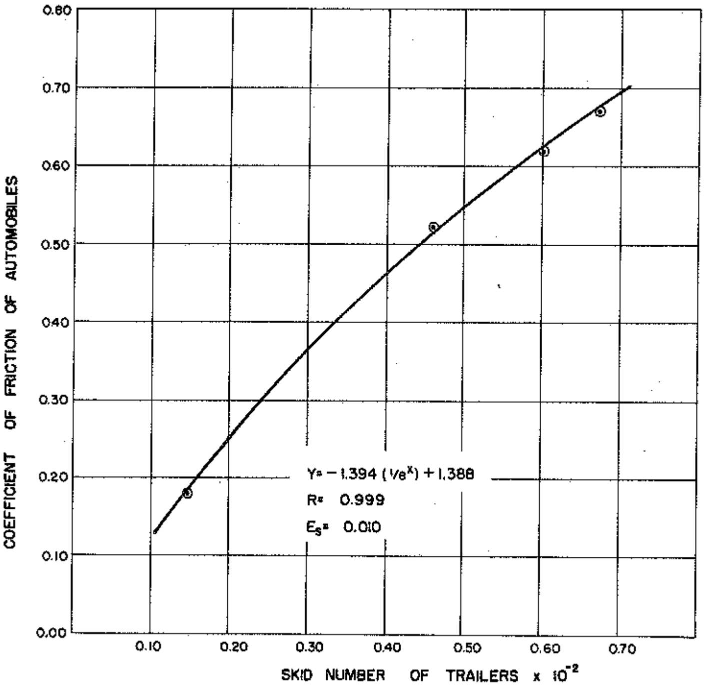

Fig. 8. Graph of coefficient of friction as measured with automobiles versus skid numbers of trailers for 40-mph test speed on Site I.

TABLE XIII -- CORRELATION EQUATIONS OF INDIVIDUAL TRAILERS VS AUTOMOBILE MEANS

Site I

X(Automobiles[a]) Veloctiy, mph	Y(Trailer[b])	Trailer Velocity mph	Equation	R	E_s
20	Tennessee	20	$Y = 1.374\ (X) - 0.149$	0.961	0.089
40		40	$Y = 1.121\ (X^{1.8}) + 0.106$	0.994	0.029
40		60	$Y = 1.476\ (X^3) + 0.074$	0.986	0.040
20	Stevens Inst. (N. J.)	20	$Y = -3.769\ (1/\sqrt{X}) + 3.518$	0.987	0.055
40		40	$Y = -0.294\ (1/\ln(X)) - 0.009$	0.999	0.016
40		60	$Y = -0.253\ (1/\ln(X)) - 0.031$	0.996	0.024
20	Portland Cement Assn.	20	$Y = -3.426\ (1/\sqrt{X}) + 3.185$	0.982	0.058
40		40	$Y = 1.182\ (X^{1.8}) + 0.077$	0.997	0.023
40		60	$Y = -0.247\ (1/\ln(X)) - 0.048$	0.995	0.026
20	Goodyear	20	$Y = 0.527\ (\ln(X)) + 0.931$	0.995	0.030
40		40	$Y = 1.107\ (X^{1.8}) + 0.104$	1.000	0.007
40		60	$Y = 1.640\ (X^3) + 0.090$	0.989	0.038
20	Gen Motors Prov. Gr.	20	$Y = 0.742\ (e^X) - 0.702$	0.970	0.071
40		40	$Y = -0.284\ (1/\ln(X)) - 0.007$	0.998	0.017
40		60	$Y = 1.681\ (X^3) + 0.068$	0.985	0.047
20	Florida (SRD)	20	$Y = -2.381\ (1/e^X) + 2.026$	0.982	0.065
40		40	$Y = 0.805\ (e^X) - 0.839$	1.000	0.010
40		60	$Y = 1.282\ (X^2) + 0.067$	0.996	0.026
20	Bureau of Public Rds.	20	$Y = 1.169\ (X) - 0.014$	0.959	0.082
40		40	$Y = 0.695\ (e^X) - 0.660$	0.999	0.011
40		60	$Y = 1.800\ (X^3) + 0.114$	1.000	0.003
20	Virginia (Right Wheel)	20	$Y = -2.116\ (1/e^X) + 1.840$	0.963	0.084
40		40	$Y = 0.663\ (e^X) - 0.642$	0.989	0.042
40		60	$Y = 1.577\ (X^3) + 0.096$	0.989	0.038

[a] In terms of coefficient of friction. [b] In terms of skid numbers x 10^{-2}.

TABLE XIV -- CORRELATION EQUATIONS OF INDIVIDUAL AUTOMOBILES VS TRAILER MEANS

Site I

X(Trailers[a]) Velocity, mph	Y(Automobiles[b])	Automobile Velocity mph	Equation	R	E_s
20	Tennessee	20	$Y = -1.934\ (1/\sqrt{X}) + 1.995$	0.987	0.038
40		40	$Y = -1.429\ (1/e^X) + 1.408$	0.999	0.014
60		40	$Y = 0.302\ (\ln(X)) + 0.843$	0.998	0.017
20	Virginia	20	$Y = 0.299\ (\ln(X)) + 0.752$	0.968	0.055
40		40	$Y = 0.324\ (\ln(X)) + 0.810$	0.998	0.017
60		40	$Y = 0.301\ (\ln(X)) + 0.865$	0.994	0.031
20	Kentucky	20	$Y = 0.322\ (\ln(X)) + 0.756$	0.994	0.025
40		40	$Y = -1.398\ (1/e^X) + 1.388$	0.999	0.010
60		40	$Y = 0.295\ (\ln(X)) + 0.836$	0.999	0.009
20	Florida	20	$Y = 0.301\ (\ln(X)) + 0.682$	0.961	0.061
40		40	$Y = -1.126\ (1/e^X) + 1.217$	0.987	0.035
60		40	$Y = 0.282\ (\ln(X)) + 0.810$	0.997	0.020

[a] In terms of skid numbers x 10^{-2}.
[b] In terms of coefficient of friction.

The analysis of these data was confined to the fine-textured surfaces (Site I). The coarse-textured surfaces (Site II) would yield different regression curves as evidenced in Table XI and, in fact, would not provide a correlation for many speed combinations.

Predicition of Stopping Distances -- According to the test results of the Florida correlation study, stopping distances of automobiles can be accurately predicted from the trailer tests. For the trailers as a group, Fig. 7 provides the best curve from which to derive equivalent stopping distances at the test velocity of 40 mph. An attempt was also made to manipulate the stopping-distance equation so as to derive a suitable formula for use with the trailer data. Two equation forms provided satisfactory predictions, particularly Equation 2. These and the correlation equation are given below:

$$30S = \frac{40^2 - 20^2}{f_T\ (40)} + \frac{20^2 - 0}{f_T\ (20)} \qquad 1$$

$$30S = \frac{2(40^2 - 20^2)}{f_T(40) + \frac{f_T\ (40) + f_T\ (20)}{2}} + \frac{20^2 - 0}{f_T\ (20)} \qquad 2$$

where, S = Predicted Stopping Distance in feet,

f_T = Skid Number x 10^{-2} at parenthesized velocity, and

40 and 20 = velocities in mph.

$$Y = \frac{8150}{X^{1.3}} + 45 \quad \text{(Correlation equation from Fig. 7)} \qquad 3$$

where, Y = Predicted Stopping Distance in feet and

X = Skid Number.

The resultant stopping distances obtained from these formulas and the actual stopping distances of automobiles on Site I were as follows:

	Prediction Stopping Distances			
		Equation		Automobile
Section	1	2	3	Stopping Distances
A	108	100	102	103
B	332	298	295	295
D	84	79	85	86
E	78	76	80	79

The reliability of predicting stopping distances for any given trailer by using the foregoing formulas depends on how well that trailer relates to the rest of the trailers. Also, it should be remembered that the trailers utilized external watering and not self-watering systems in primary testing. Unfortunately, the study did not yield sufficient data to evaluate the self-watering systems. Another factor that should be considered is that several of the pavement surfaces were "artifical" in the sense that such surfaces are seldom found on highways. Other sections were composed of pavements in common use, but they were in an unpolished or untrafficked condition. Therefore, the skid resistance-velocity gradient of these surfaces may be different from the ordinary bituminous surfaces in service. The automobile stopping distance reflects the frictional characteristics of a surface from test velocity to zero velocity which, in turn, would reflect a difference in the skid resistance-velocity gradients. The trailer testers, however, reflect the frictional characteristics of a surface only at a given test velocity.

Assuming that there is a negligible contribution from the influence mentioned above, the stopping distances measured on most highway surfaces are likely to be shorter for given skid numbers measured by the same trailer. The automobile may initiate a skid in the polished wheel track, but it seldom remains in the wheel track until the end of the skid. As the vehicle skids out of the wheel track, the tires begin to contact higher skid resistance. The degree of the "skid out" will perceptibly change the stopping distance. Most of the surfaces at the correlation study displayed homogeneous friction.

OTHER MEASUREMENTS

The Kentucky automobile was equipped with a two-cahnnel strip-chart recorder to record velocity and distance during the skidding excursions. An event marker was wired to the brake light switch so as to note the moment from which to measure stopping distances. From the resultant recordings, numerous coefficients of friction were determined (Table XV). The coefficients for various velocity increments were calculated using the stopping-distance formula. The coefficients for specific velocities were determined by measuring the slope of the velocity curve.

The most noteworthy observation derived from the data is that the coefficients of friction at specific velocities measured with the automobile were considerably lower, especially at 40 mph, than those obtained with trailers. Figs. 9 and 10 show the test results on two surfaces which were tested at 50 mph with the automobile. The automobile data was not corrected for influences due to air resistance nor errors associated with the coefficient of friction calculations in using the stopping-distance formula. The combined effect would be a reduction in coefficient of friction by approximately 0.01 at 40 mph, mainly due to air resistance since the deceleration of the vehicle was nearly linear. The wear tests on Sections A and B indicated negligible reduction in skid resistance as a result of trailer testing. This suggests that on some surfaces the skid resistance in the non-steady-state skid may be significantly lower than in the steady-state sliding mode. Some of the difference may be atributable to errors in the trailer data as a result of the torque calibration procedure used by several of the participants. According to Goodenow, et al[4], an error of about five percent was found for the ASTM E-17

TABLE XV –– COEFFICIENTS OF FRICTION AT VARIOUS VELOCITIES DURING SKIDDING

(Kentucky Automobile)

Test Sections	Site I					Site II				
Velocity, mph	A	B	C	D	E	A	B	C	D	E
20 mph Tests										
10- 0	0.68	0.36	0.51	0.82	0.83	0.83	0.91	0.70	0.61	0.73
20- 0	0.60	0.27	0.31	0.65	0.70	0.66	0.73	0.59	0.54	0.55
15- 5	0.70	0.30	0.34	0.83	0.87	0.96	0.98	0.76	0.65	0.67
10	0.65	0.30	0.38	0.75	0.80	0.79	0.81	0.61	0.59	0.70
40 mph Tests										
10- 0	0.76	0.41	-	0.95	0.95	0.83	0.83	0.69	0.63	0.75
20- 0	0.68	0.29	-	0.84	0.86	0.82	0.75	0.70	0.63	0.64
30- 0	0.60	0.22	-	0.75	0.78	0.77	0.73	0.67	0.62	0.55
40- 0	0.51	0.18	-	0.60	0.67	0.66	0.67	0.59	0.56	0.47
15- 5	0.70	0.34	-	0.88	0.88	0.83	0.81	0.74	0.63	0.71
25-15	0.61	0.21	-	0.76	0.78	0.84	0.72	0.72	0.63	0.55
35-25	0.49	0.17	-	0.61	0.82	0.71	0.71	0.64	0.59	0.45
20-10	0.65	0.26	-	0.81	0.79	0.70	0.77	0.69	0.63	0.61
30-20	0.55	0.19	-	0.69	0.73	0.75	0.70	0.65	0.62	0.49
40-30	0.43	0.15	-	0.65	0.57	0.56	0.60	0.52	0.52	0.38
30	0.52	0.16	-	0.57	0.64	0.65	0.65	0.61	0.59	0.45
20	0.63	0.23	-	0.72	0.74	0.78	0.69	0.67	0.61	0.55
10	0.72	0.34	-	0.86	0.81	0.86	0.73	0.74	0.62	0.66
50 mph Tests										
10- 0	0.76	-	-	0.89	-	-	-	-	-	-
20- 0	0.68	-	-	0.82	-	-	-	-	-	-
30- 0	0.61	-	-	0.72	-	-	-	-	-	-
40- 0	0.52	-	-	0.60	-	-	-	-	-	-
15- 5	0.74	-	-	0.85	-	-	-	-	-	-
25-15	0.62	-	-	0.73	-	-	-	-	-	-
30-20	0.57	-	-	0.66	-	-	-	-	-	-
35-25	0.51	-	-	0.58	-	-	-	-	-	-
45-35	0.41	-	-	0.47	-	-	-	-	-	-
40	0.39	-	-	0.44	-	-	-	-	-	-
30	0.49	-	-	0.57	-	-	-	-	-	-
20	0.61	-	-	0.72	-	-	-	-	-	-
10	0.74	-	-	0.86	-	-	-	-	-	-

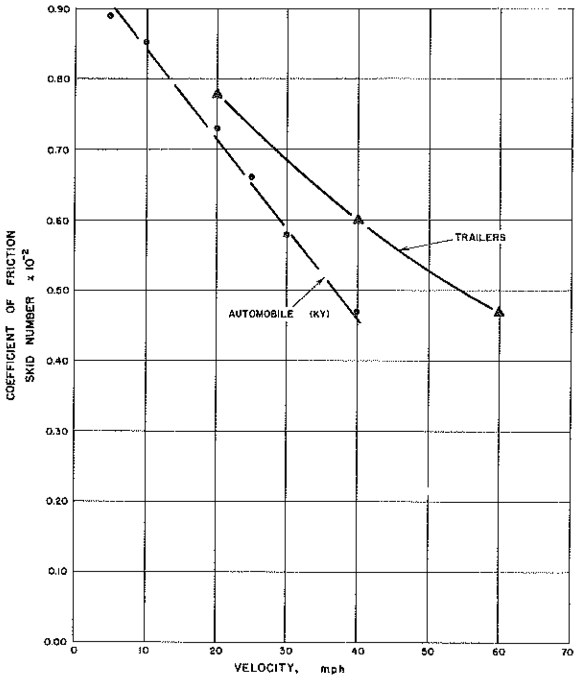

Fig. 9. Coefficients of friction at specific velocities of an automobile compared with skid numbers of trailers (Site I, Section D).

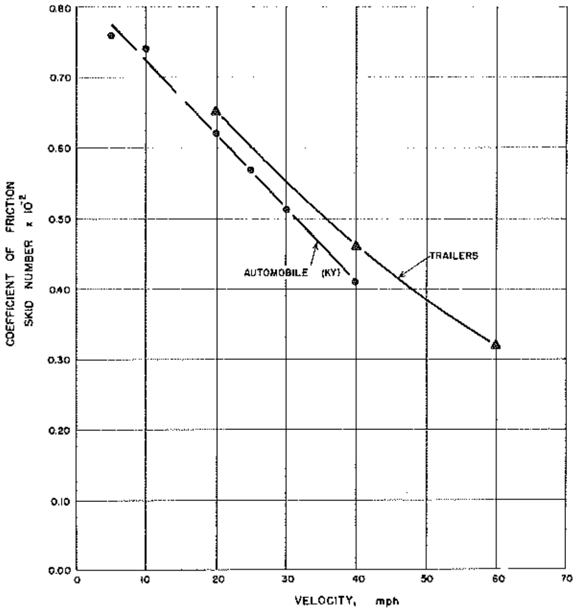

Fig. 10. Coefficients of friction at specific velocities of an automobile compared with skid numbers of trailers (Site I, Section A).

tires due to relocation of the tire patch center of pressure. The magnitude of the difference no doubt is influenced by the velocity at which the automobile initiates the skid.

CONCLUSIONS

The stopping distances of automobiles as measured at the Florida correlation study yielded highly reproducible test results, especially at the test speed of 40 mph. While some differences in test results were noted, no particular trends were evident due to varied instrumentation, drivers or vehicles. The procedures employed for instrument calibration and for skid testing proved to be quite adequate. Further refinement of techniques are not likely to materially improve the stopping-distance test, and for that reason standardization of the test method should be undertaken.

Skid numbers of trailers can be used to predict stopping distances of automobiles, or vice versa, and several alternate procedures are suggested. The degree of success, however, is contingent upon the relationship between measurements under external and self-watering conditions, between the particular trailer and other trailers, and between test surfaces and trafficked pavements. Additional work in this area is warranted on trafficked highway surfaces and using self-watering systems for trailers.

Skid resistance encountered by a skidding automobile found to be significantly lower than those measured with trailers. The difference could not be accounted for by assuming possible errors in the torque measurement due to tire patch relocation. The tests associated with this aspect of the investigation, however, were quite limited, and therefore the results cannot be re-

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[4] Goodenow, G. L., Kolhoff, T. R. and Smithson, F. D., "Tire-Road Friction Measuring System - A Second Generation", Society of Automotive Engineers, No. 680137, Jan. 1968.

garded as conclusive. Further testing for skid resistance with automobiles at velocities of 50 mph and higher in conjunction with trailers is recommended.

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APPENDIX I

EQUIPMENT AND MANUFACTURERS

1. Florida State Road Department
    - G. M. Proving Ground
        - Pousemeter (fifth wheel assembly, tachometer generator, distance transducer)
        - Electronic Counter
    - Weston Model 901 Speed Indicating Meter

2. Kentucky Department of Highways
    - Laboratory Equipment Corporation
        - Model 5101 Fifth Wheel Assembly
        - Model C-5280 Eight-lobe Contactor (1 contact per foot)
        - Model E-160 Magnetic Counter
        - Model G-750 Weston 750 Type J-2 Tachometer Generator
        - Model M-901 Weston Model 901 Speed Indicating Meter
    - Brush Mark 280 Recorder (2-channel strip-chart)

3. Tennessee Highway Research Program
    - Performance Measurements Company
        - Model MP 1625 Fifth Wheel Assembly
        - Model MP 1772 Contactor (1 pulse per foot)
        - Model MP 1625TC Tachometer Generator
        - Model MP 1000 Electronic Counter
        - Model MP 1625M Speed Indicating Meter

APPENDIX II

STATISTICAL CALCULATIONS

REGRESSION LINES

All regression lines were of the form

$$Y = a + bZ$$

where $b = \frac{n(\Sigma ZY) - (\Sigma Z)(\Sigma Y)}{n(\Sigma Z^2) - (\Sigma Z)^2}$,

$a = \frac{\Sigma Y - b(\ Z)}{n}$,

n = number of observations,

Z = selected functions of X, and

X and Y = observed values of data.

For interrelation of automobile data, Z = X. For relationships of automobile data with trailer data, analysis was performed using the following Z's:

$$X,\ \ln(X),\ e^x,\ 1/\ln(X),\ 1/e^x,\ X^2,\ 1/X^2,\ \sqrt{X},\ 1/\sqrt{X}.$$

For those relationships where results indicated that the regression lines obtained for the above Z's were not satisfactory, additional analyses was performed using the following Z's:

$$X^{1.3},\ X^{1.5},\ X^{1.8},\ X^3,\ 1/X^{1.3},\ 1/X^{1.5},\ 1/X^{1.8},\ 1/X^3.$$

COEFFICIENT OF CORRELATION

$$R = \frac{n(\Sigma ZY) - (\Sigma Z)\ (\Sigma Y)}{\sqrt{n(\Sigma Z^2) - (\Sigma Z)^2}\ \sqrt{n(\Sigma Y^2) - (\Sigma Y)^2}}$$

STANDARD ERROR OF ESTIMATE

$$E_s = \frac{\Sigma(Y - Y_1)^2}{n}$$

where Y_1 = calculated values of Y for observed values of X.

STANDARD DEVIATION

$$\sigma = \frac{\Sigma(X - \overline{X})^2}{n}$$

where $\overline{X}$ = mean of n number X's.

REQUIRED NUMBER OF TESTS

$$N = (t \frac{\sigma}{E})^2$$

where t = distribution constant for 95% confidence and N-1 degrees of freedom,

σ = standard deviation of the sample, and

E = percent allowable error.

LEAST SIGNIFICANT DIFFERENCE

$$LSD = t\sigma_D$$

where $^{\sigma}D = \frac{\sigma_1}{n_1}^2 + \frac{\sigma_1}{n_2}^2 + \ldots$

σ_1 and σ_2 = standard deviation of each automobile,

n_1 and n_2 = number of tests made for each automobile, and

t = distribution constant for 95%-confidence level and n-1 degrees of freedom.

FOOTNOTES

[1] Principal Research Engineer, Division of Research, Kentucky Department of Highways, Lexington, Kentucky.

[2] Smith, L. L. and Fuller, S. L., "Florida Skid Correlation Study of 1967 - Skid Testing with Trailers".

[3] Rizenbergs, R. L. and Ward, H. A., "Skid Testing with an Automobile," Record No. 187, Highway Research Board, pp 115-137, 1967.

[4] Goodenow, G. L., Kolhoff, T. R. and Smithson, F. D., "Tire-Road Friction Measuring System - A Second Generation," Society of Automotive Engineers, No. 680137, Jan. 1968.