Comparison of Several Methods of Measuring Road Surface Friction

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●DURING THE PLANNING of the First International Skid Prevention Conference, September 8-12, 1958, at the University of Virginia, it was recognized that the lack of data on the relationship of the various machines that measure coefficient of friction was a serious handicap in attacking skid resistance problems. Therefore, the authors conceived an approach to a correlation of several machines and proposed an experiment. With the endorsement of Subcommittee E and the Steering Committee, planning of the experiment began and during the week of August 25-29, 1958, two weeks prior to the conference, the experiment was conducted.

The need for such a correlation had become apparent in recent years. Concurrent with recognition of the problem of pavement slipperiness in the 1920's and 1930's came the need to make measurements, a need resulting in development by many people of techniques and equipment for measuring road surface slipperiness. Because some engineers were seeking economy, some convenience, and some proximity to theoretical concepts, the equipment differs considerably. The total result of the innovations is that many beneficial ideas are represented in the several dozen machines used in the United States to measure road surface slipperiness, but also that the existing methods differ appreciably in their designs and the results they obtain. These differences make difficult the pooling of data collected by various agencies throughout the country and in general hamper progress toward safe, anti-skid roads.

PURPOSES OF STUDY

Specifically, the purposes of the correlation study were as follows:

1. To compare the test results obtained by the various machines equipped as they are normally used by the respective agencies (Series X).
2. To compare the test results when the tire variable was minimized by using the same kind of tire on each vehicle (Series Y).
3. To obtain information on as many other important aspects of measurement as could be worked into the experiment (Series Z). These include:
    (a) To compare the results from a stopping distance method and a decelerometer.
    (b) To compare the sliding, incipient, and sideway force coefficients.
    (c) To determine the influence of speed on the locked-wheel and incipient friction coefficients.
    (d) To compare a portable laboratory and field method with a stopping distance method.

DESIGN OF THE EXPERIMENT

The experiment was carefully designed so that a sound statistical analysis of results was possible. Insofar as possible all factors affecting results were controlled either experimentally or statistically.

Four test sites, each having a different level of friction, ranging from dangerously low to very high with two intermediate levels approximately uniformly spaced within this range, were selected. The designations of the levels, and their approximate coefficients of friction as obtained from the means of all measurements on the section were as follows: poor 0.25, fair 0.37, good 0.51, and excellent 0.62. These values were obtained at 40 mph when the pavements were wet.

In the main portion of the experiment (Series X and Series Y) each machine tested

each pavement with its regular tires (those normally used on the equipment) and with the standard (specially prepared) tires. For adequate precision, more than one test run was required for each combination of machine, tires, and pavement. Available data indicated that successive measurements by the stopping distance method had a standard deviation of the order of 0.02. In order to be 95 percent confident of an ac-

TABLE 1

SUMMARY OF CHARACTERISTICS OF MACHINES PARTICIPATING IN STUDY

| Machine No.	Agency	Type	Braking Conditions	Tire Size	Normal Static Load per Wheel (lb)	Force Measuring System
1	Bureau of Public Roads	1-wheel trailer	1 wheel locked	6.70-15	1,110	Drawbar force
2	Portland Cement Association	2-wheel trailer	2 wheels locked	6.70-15	925	Beam deflection
3	Cornell Aero Laboratory	1-wheel trailer	1 wheel locked	6.70-15	970	Brake torque
4	General Motors Proving Grounds	2-wheel trailer	2 wheels locked	7.60-15	967	Torque tube deflection
5	National Aeronautics and Space Administration, Langley Field	2-wheel trailer	2 wheels slipping	6.70-15	932	Gear box torque
6	Joint Highway Research Project, Purdue Univ.	Skid car	4 wheels locked	6.70-15	905 approx.	Length of skid
7	Tennessee Highway Research Project	2-wheel trailer	Inside wheel locked	6.70-15	871	Drawbar force
8	Virginia Council of Highway Investigation and Research, Univ. of Va.	Skid car	4 wheels locked	7.40-14	1,015	Length of skid
9	Virginia Council of Highway Investigation and Research, Univ. of Va.	Tapley decelerometer mounted in No. 8				
10	Bureau of Public Roads	An alteration of No. 1 to measure sideway force coefficient				
11	Cornell Aero Laboratory	An alteration of No. 3 to measure sideway force coefficient				
12	National Crushed Stone Association	Bicycle wheel apparatus				
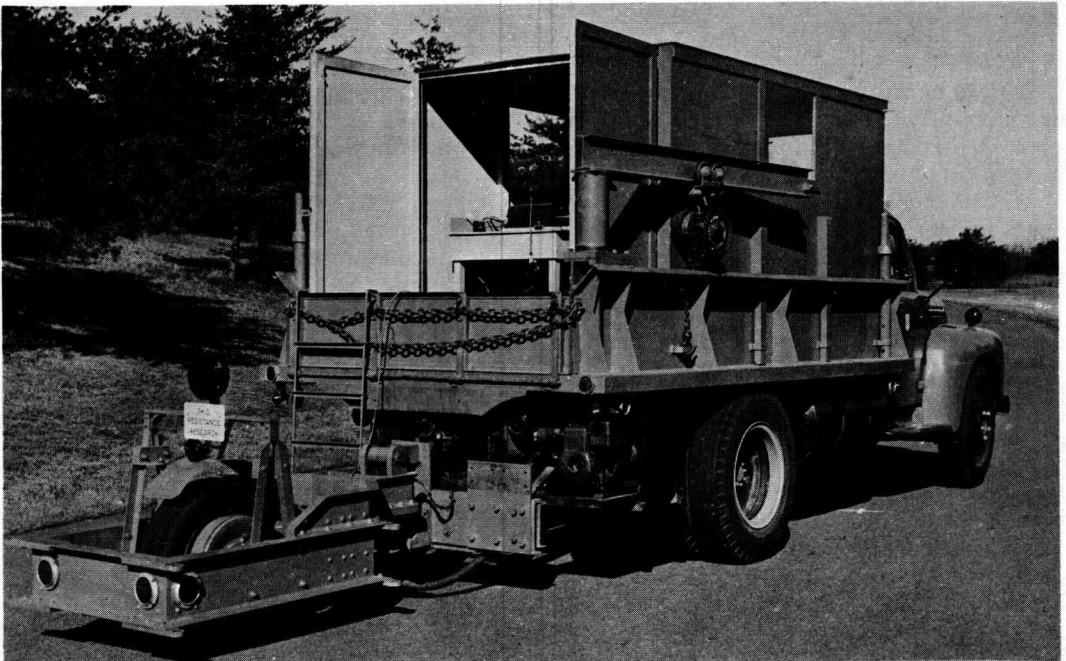
Figure 1. In the Bureau of Public Roads equipment the drawbar force is measured by electrical strain gages for locked-wheel conditions. The trailer can be converted to measure sideway force by fixing the wheel at a predetermined angle to the direction of travel (see Appendix).

curacy of ± 0.02, it was calculated that six repeat measurements would be sufficient. Each machine made six measurements on each of the four pavements for each set of tires, resulting in a total of 48 measurements for each machine.

All machines tested the same pavement with both sets of tires the same day, then moved to the next test site together. All factors such as water film thickness and surface condition were held as constant as possible. The experiment was designed so that all consistent differences between machines were due primarily to the machines themselves and not to uncontrolled factors.

EQUIPMENT PARTICIPATING

Test Machines

The equipment has been described in detail elsewhere (1, 2, 3, 4, 5, 6), therefore only brief descriptions are given here. For those machines not described in the literature (Portland Cement Association and Bureau of Public Roads machines) more detailed descriptions are given in the Appendix. Table 1 summarizes the characteristics of the equipment that participated in the correlation study. This equipment also is described briefly in Figures 1-9. As can be seen, the study encompassed most of the broad categories of road surface friction measuring machines.

Tire Pressure Controls

The tire pressures were controlled in the standard tires, but with the regular tires the equipment operated as it normally does. In the standard tires, pressures of 26 psi were maintained (measured when tire was cold) for the 15-in. wheels and 24 psi for the 14-in. wheels.

Description of Standard Tires

The standard tires (Fig. 10) were made from an oil-extended polymer styrene butadiene rubber (OEP-SBR). Specially prepared stock (experimental No. DZ 219A676) was used and care was exerted to minimize non-uniformity.

For wheels of 14-in. rim diameter the mold code is BSR-3 and for the 15-in. wheel it is BSR-2. Wade Johnson, Manager of the Tire Test Division, Goodyear Tire and Rubber Company, has indicated that tires of this tread design and composition can probably be made available for experimental purposes through 1962 or possibly longer.
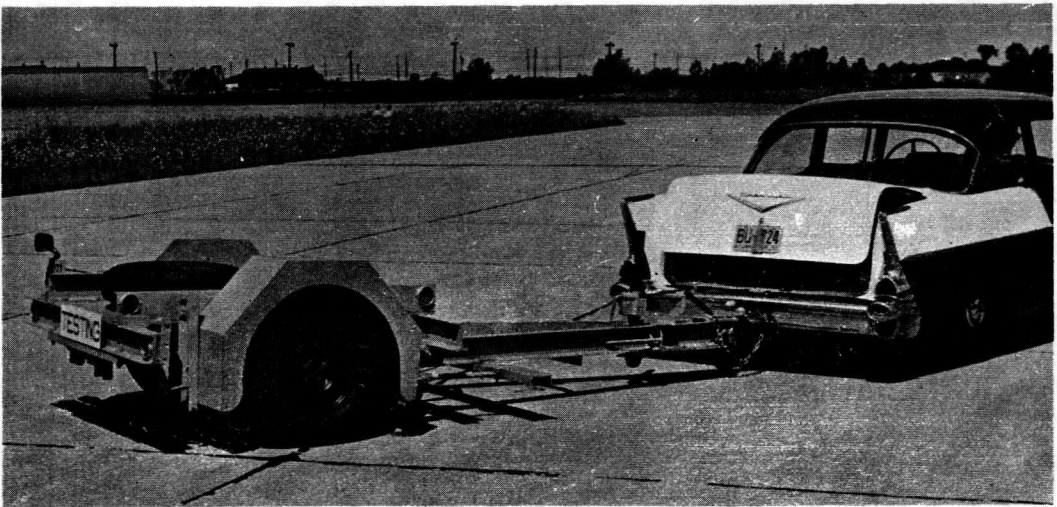

Figure 2. In the Portland Cement Association equipment both wheels are locked and the dragging force is measured by electrical strain gages attached to two drag link beams (see Appendix).
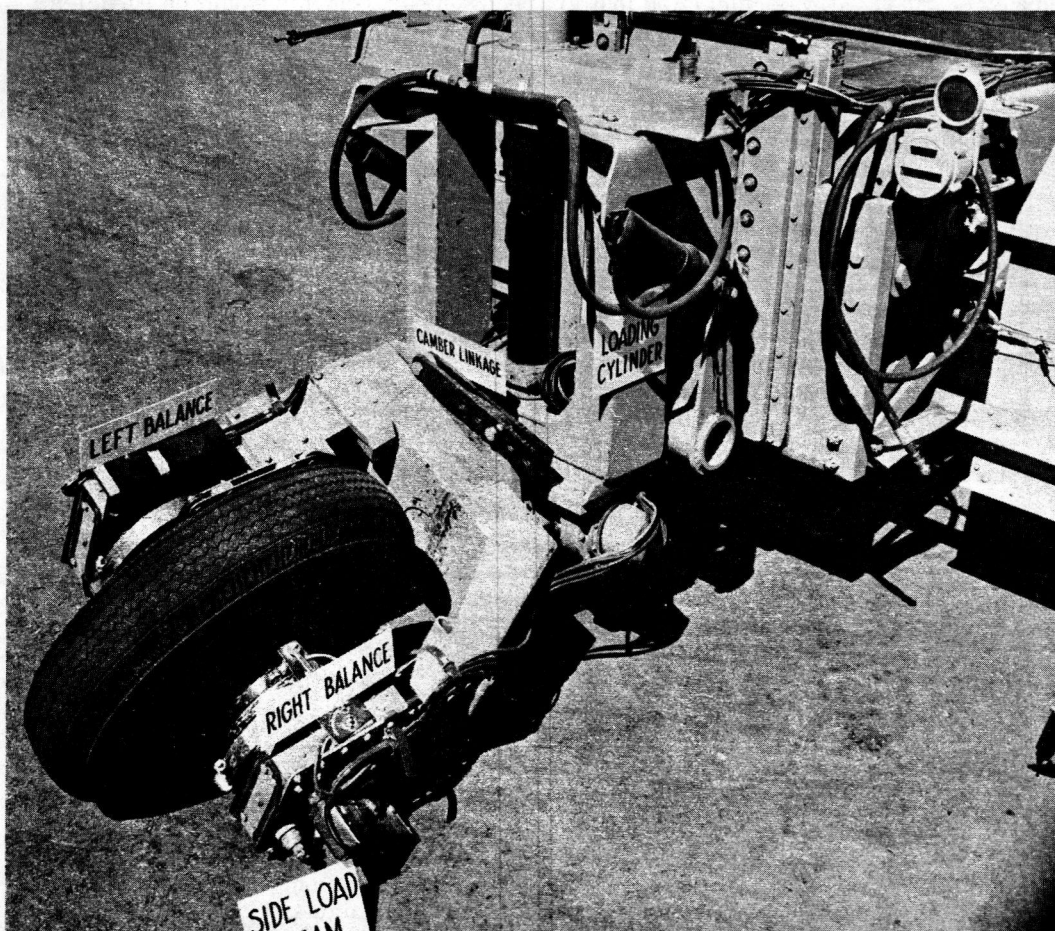
Figure 3.   In the Cornell Aeronautical Laboratory equipment, in contrast to the other trailers, the wheel is loaded pneumatically. Electrical strain gages measure the forces from which the coefficient is computed.   The machine is also capable of measuring the sideway force coefficient by measuring the forces generated as the wheel is rotated 30 deg from the direction of travel ([1]).

DESCRIPTION OF TESTS

Testing Procedure

The measurements on each level were made in a series of "runs." For the Series X (regular tire) and also for the Series Y (standard tire) each machine made one measurement during each run for six runs. In Series X and Y, the tests were made at 40 mph. The sequence was randomized within each run so as to avoid order effects. In Series Z the sequence of measurements was generally arranged for practical reasons and was systematic rather than random. The Series Z measurements were made after the Series X and Series Y tests were completed.

Test Site Descriptions

A typical test site layout is shown in Figure 11. Each 300-ft test site was marked into six 50-ft zones so as to permit control over the longitudinal position of the measurement. For each measurement the operator of the test vehicle was told to begin his measurement at a particular zone and to end it at another zone. In this way each ma-
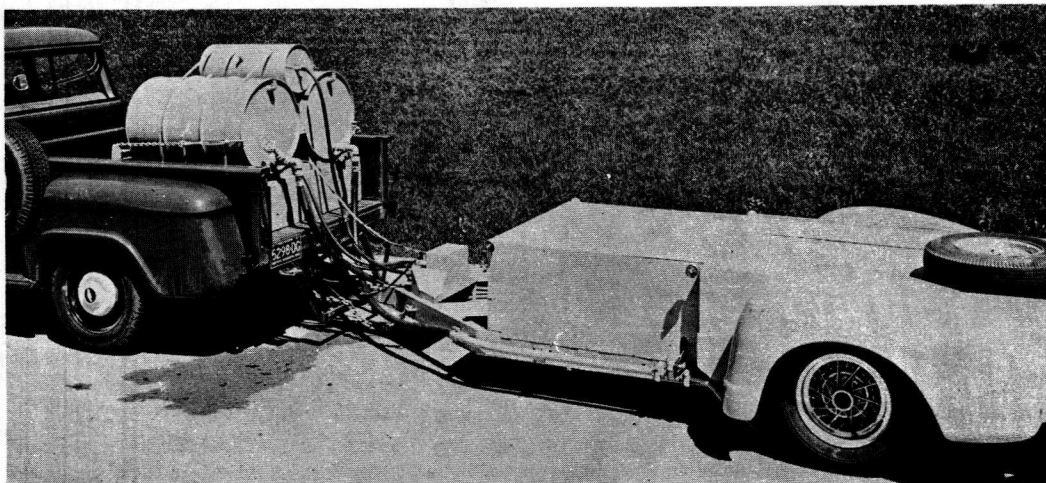
Figure 4.   In the equipment used at the General Motors Proving Grounds both wheels are locked and the force measurements are obtained by measuring the bending in the torque tube by means of strain gages (2).

chine was making measurements throughout each of the zones.

It was decided at the outset that all machines should begin their measurements in the normal wheel paths, but this was not possible because of the differences in the design of the machines. The one-wheel trailers (Bureau of Public Roads, Cornell tire tester, and NASA) have their trailer carts mounted along the centerline of the towing vehicle. On some test sites (good and fair) it was necessary to place the soaker hoses along the boundary of the test lane and these vehicles could not maneuver close enough to the hoses to get the cart in the center of the left wheel path nor could they safely maneuver close enough to the shoulder to get the cart in the center of the right wheel path. The NASA cart was towed by a station wagon, however, so it was possible to come close to the center of the wheel paths. Only for the Bureau of Public Roads machine and the Cornell tire tester on the good and fair sites were the measurements taken in the outer edge of the wheel paths. The other vehicles attempted and generally succeeded in beginning the measurement in the wheel path.
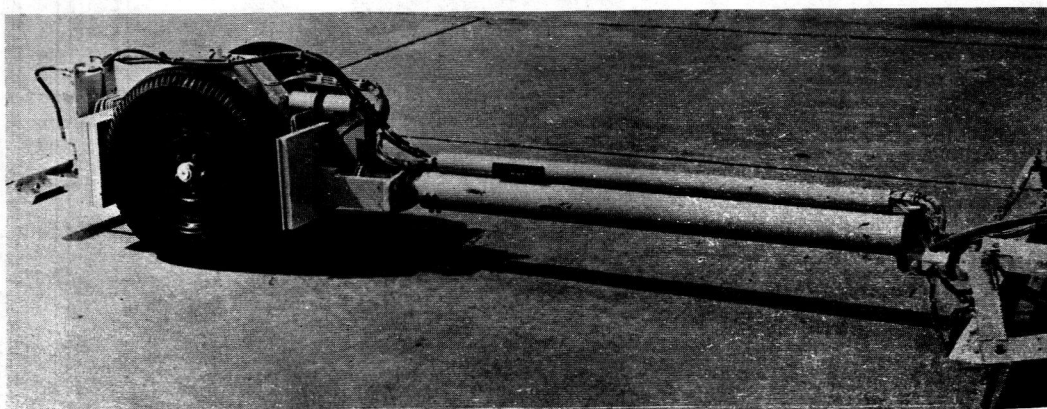

Figure 5.   The cart used by the National Aeronautics and Space Administration, Langley Aeronautical Laboratory, measures the forces created by an "incipient" friction condition.   The two wheels are geared together so that the slower wheel acts as a braking wheel with a small slip ratio (generally set at 0.125) while the faster moving wheel acts as a driving wheel. The torque on the gear box is measured by a commercial strain gage load cell (3).

Figure 6. The car used by the Purdue Joint Highway Research Project eliminates irregular foot braking by utilizing a special vacuum braking system activated by a hand microswitch (4).
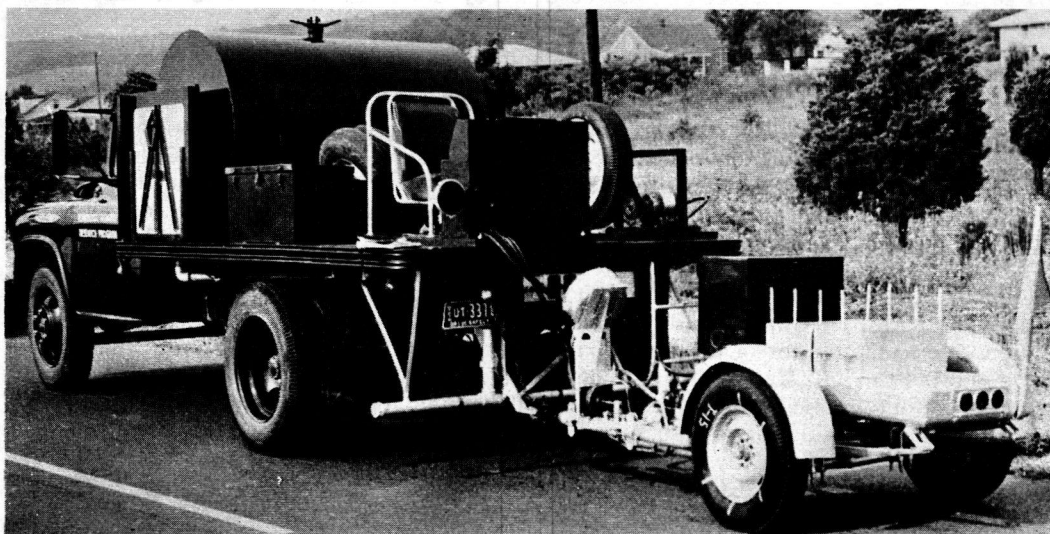

Figure 7. In the equipment of the Tennessee Highway Research Program only the inside wheel is locked and the drawbar force is measured by automatic recording equipment which operates from a fluid pressure device (5).

Figure 8. The skid test car used by the Virginia Council of Highway Investigation and Research utilizes no special braking equipment. Only recording equipment has been added to the commercial vehicle.
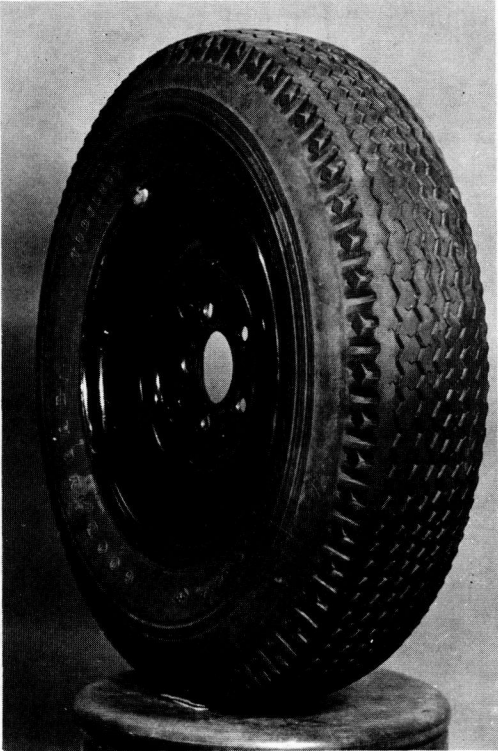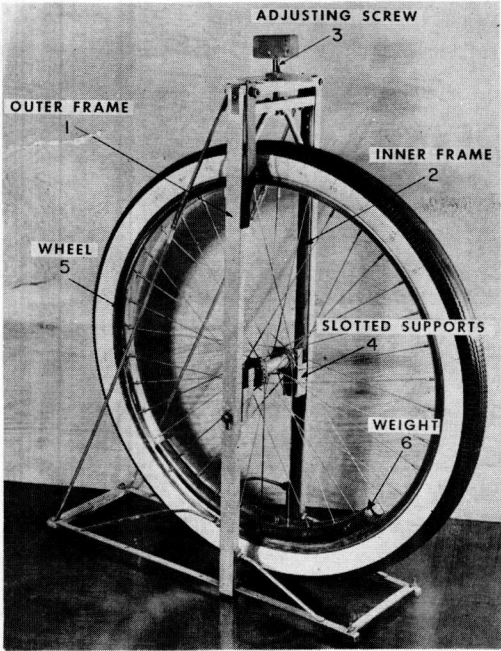
Figure 9. In the National Crushed Stone Association equipment the eccentric weight on the rim drives the wheel. The tread is removed in the portion of the wheel which precedes the zero reading and friction is created as the treaded portion comes in contact with the surface. The central angle through which the wheel passes is an empirical measure of slipperiness.

Figure 10. The Goodyear Tire and Rubber Company was designated by the Tire and Rim Association to supply the standard tires. Specially prepared stock was used and careful control exerted to minimize non-uniformity.

Water Control

Water control was considered a significant factor in the experiment. The watering system layout is shown in Figure 12. Eight 50-ft lengths of canvas garden soaker hose were used, each fed by a separate conduit hose. Tests conducted prior to the experiment showed that a uniform flow of water could not be expected from lengths longer than 50 ft, but a relatively uniform flow of water could be obtained throughout lengths
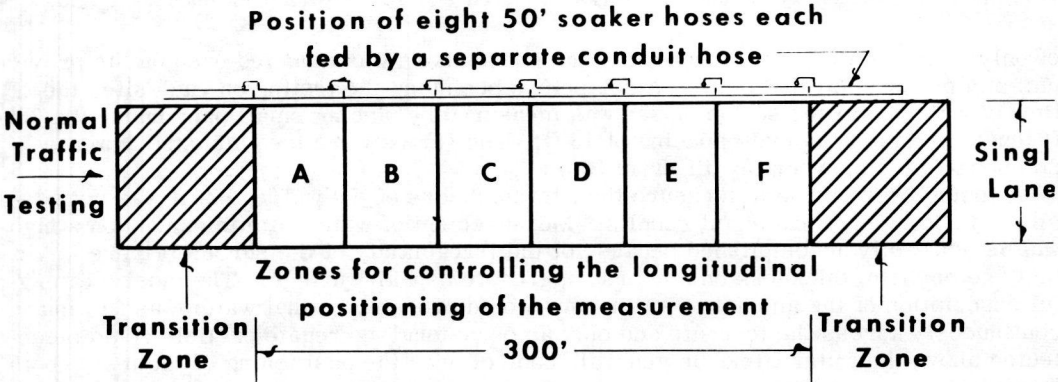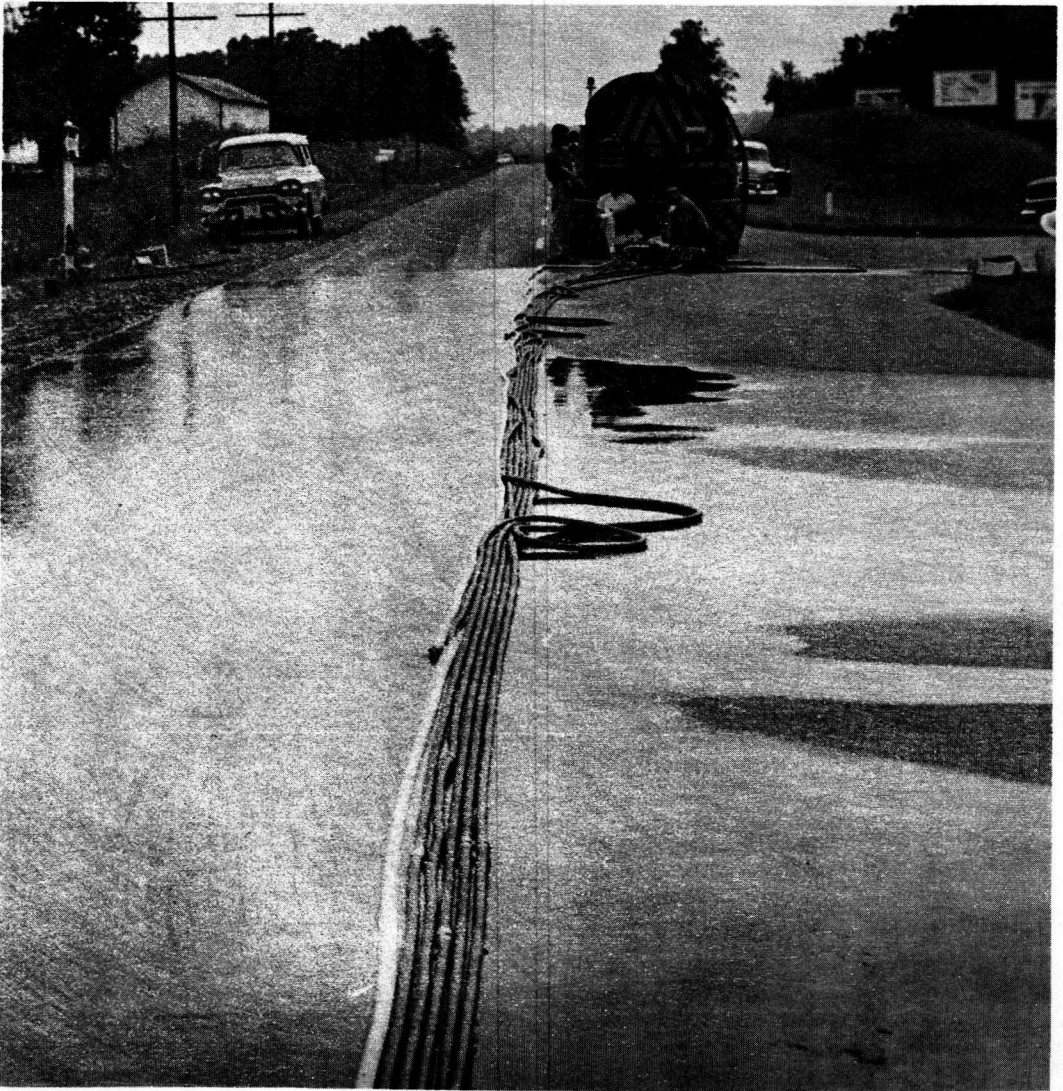

Figure 11. Test site layout.

Figure 12.   Each 50-ft length of soaker hose was fed by a separate conduit hose.   The pressure at the entry of the soaker was checked and standardized on each test site.

of only 50 ft.   A valve at the entry to each soaker hose was adjusted each day to provide uniform pressure at that point.   Also, before beginning the testing on each site, the flow of water from the soaker hoses was measured by placing small pans under the 300-ft length at an approximate spacing of 13 ft.   The valves were then adjusted again to compensate for appreciably different flows.

Attempts were made to measure the film thickness of the water, but it was not possible to obtain any meaningful results.   Measurement of water film thickness on a highway is not easily accomplished because of the irregularity of the surface: there is, in fact, no one film thickness on a coarse aggregate asphalt surface.   The most meaningful description of the amount of water used would probably be that water was flowing continuously across the test site and only an occasional aggregate particle could be detected above the water film.   In general, control over the positioning of the tests, both laterally and longitudinally, and insuring that each vehicle tested over the entire length of the test site, would contribute substantially to minimizing the effect of water film variation.

Figure 13. "Poor" site; dense plant-made asphaltic concrete; limestone aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.
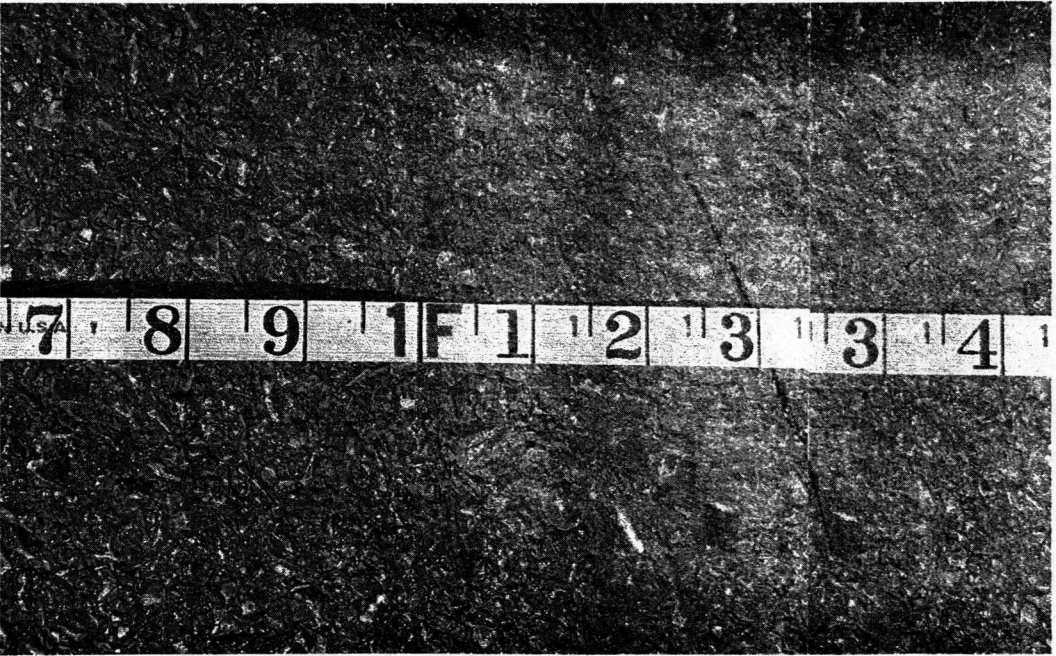

Figure 14. "Fair" site; dense plant-made asphaltic concrete; limestone aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.

Also to minimize the cleansing effects of the water flowing across the pavement as the test was in progress, the entire test section was cleaned of traffic film and dust by watering and brooming before the testing began.

Road Surface Condition

The types of surfaces tested are shown in Figures 13, 14, 15, and 16 which are stereo pairs provided for a three-dimensional view. However, the general texture can
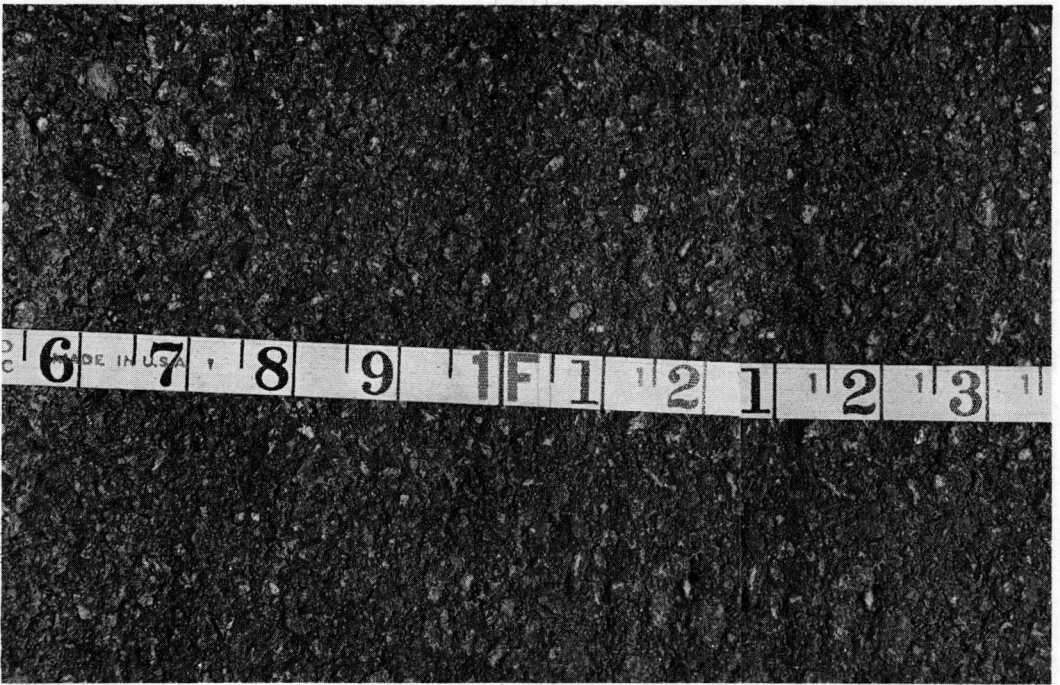
Figure 15. "Good" site; dense plant-made asphaltic concrete; granite aggregate, maximum size $\frac{1}{2}$ in., Virginia grading I-3.
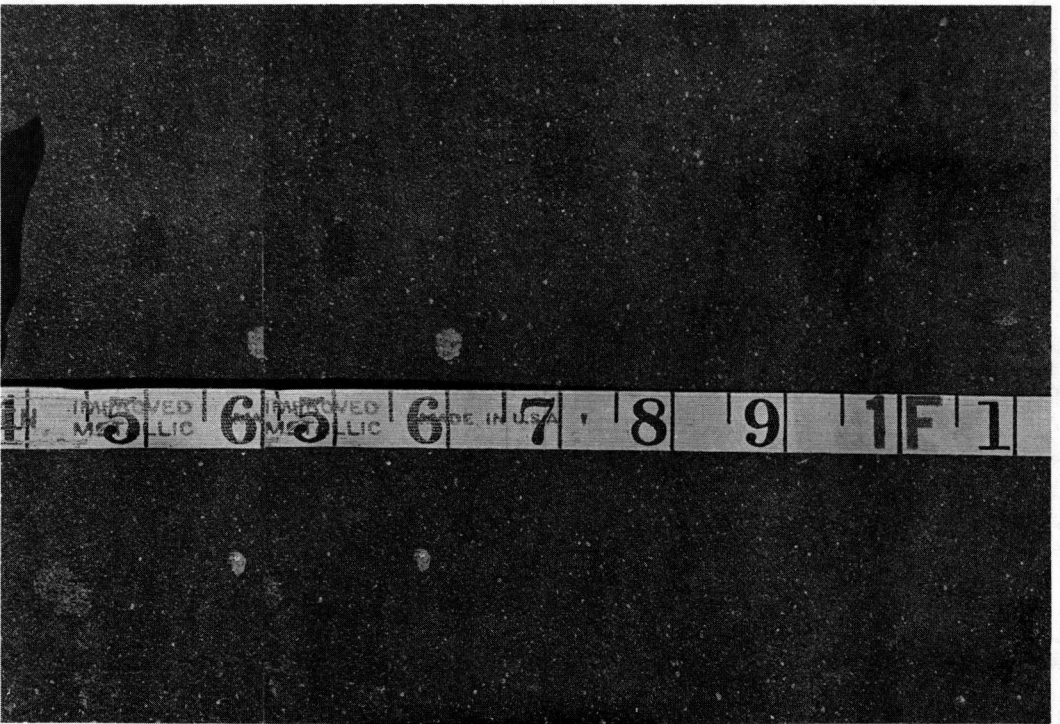

Figure 16. "Excellent" site; plant-made deslicking mix; silica sand aggregate, 100 percent passing No. 10 sieve, Virginia grading F-4.

also be observed with the unaided eye and a more complete description is given in the Appendix. Three of the surfaces were dense-graded $\frac{1}{2}$-in. top size asphaltic concrete and the fourth was a fine plant-made sand deslicking mix. There were some differences in the surfaces with regard to adherence to a true cross-section. No measurements of roughness were made, but the puddling of water or lack of it indicated the surface irregularities. The following evaluation might be applied to the surfaces:

Level	Condition
Poor	Some moderate undulation in the wheel tracks, hence some slight puddling of water (less than $\frac{1}{16}$ in.)
Fair	Some continuous rutting in wheel tracks, hence considerable puddling ($\frac{1}{8}$ to $\frac{1}{4}$ in.)
Good	Smooth, no visible puddling
Excellent	Smooth, no visible puddling

TEST RESULTS, SERIES X AND Y

The Series X measurements were made to provide a comparison between the various machines as they are normally used by the respective agencies. This would give an insight into the relationships of the data previously collected by the various agencies and permit a more meaningful exchange of existing data. But because some important variables (that is, type and tread patterns of tires) were operating, only a limited comparison could be made of the accuracy of the machines themselves. To gain a comparison between the abilities of the machines to measure friction it was necessary to eliminate or minimize the tire variable. This was done by equipping machines with a specially prepared standard tire, as has been previously discussed. The results of these two series are discussed in the following.

The test results for Series X and Series Y are summarized in Table 2. Machine No. 1 did not participate in Series X because it was not feasible to change tires in a short period of time. Because of a breakdown machine No. 2 secured measurements only on the fair and excellent levels.

The trends of the data are shown in Figure 17 for regular tires and in Figure 18 for standard tires. Each plotted point represents the mean of six measurements. It should be pointed out that the abscissa is not a quantitative scale, but (from Table 2) the interval between the grand means of each level is equal to 0.13, 0.13, and 0.11, therefore the plotted points can be considered to approximate a curve.

TABLE 2

SUMMARY OF DATA FOR SERIES X AND Y

Machine No		Mean and Standard Deviation[1]							
		Poor		Fair		Good		Excellent	
		X	Y	X	Y	X	Y	X	Y
1 (BPR)	Mean	-	0 12	-	0.25	-	0.37	-	0 45
	Sta. dev.	-	0 02	-	0 048	-	0.047	-	0 037
2 (PCA)	Mean	-	-	0.38	0.41	-	-	0.63	0.65
	Std. dev.	-	-	0.035	0.032	-	-	0.032	0 014
3 (Cornell)	Mean	0.23	0.22	0.34	0.32	0.56	0.57	0.60	0.62
	Std. dev.	0.01	0 012	0 018	0 009	0.031	0.020	0.031	0.022
4 (GM)	Mean	0.23	0.26	0.38	0.38	0.51	0.51	0.70	0.67
	Std. dev.	0.01	0.010	0.027	0.054	0.018	0.023	0.013	0.029
5 (NASA)	Mean	0.46	0.33	0.57	0.47	0.64	0.66	0.75	0.65
	Std. dev.	0.010	0.013	0.021	0.057	0.013	0.00	0.018	0 017
6 (Purdue)	Mean	0.26	0.29	0.40	0.44	0.48	0.52	0.61	0.63
	Std. dev.	0.045	0.013	0.015	0.008	0.016	0.013	0.015	0.013
7 (Tenn.)	Mean	0.07	0 18	0.18	0.26	0.36	0.40	0.42	0.52
	Std. dev.	0.023	0.012	0.020	0.047	0.033	0.045	0.060	0.031
8 (Va.)	Mean	0.28	0.33	0.41	0.47	0.51	0.57	0.66	0.69
	Std. dev.	0.010	0.016	0.022	0.009	0.014	0.013	0.019	0.014
Mean, all machines		0.25	0.25	0.38	0.37	0.51	0.51	0.62	0.61
Grand mean for each level		0.25		0.38		0.51		0.62	

[1]Six measurements per cell
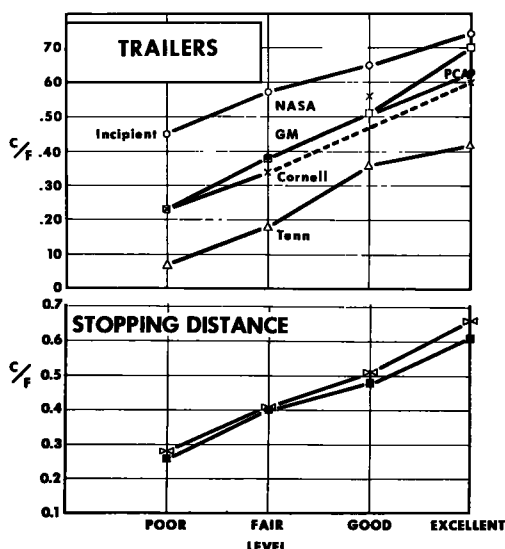
Figure 17. Measurements with regular tires (Series X).

With the regular tires (Fig. 17) the stopping distance methods (Purdue and Virginia) occupy a position similar to GM, PCA, and Cornell. The incipient friction coefficient is well above the others and the Tennessee machine (the only machine using a smooth tread tire) is well below the others.

The greatest divergence occurs on the excellent site, where the locked-wheel coefficients vary from 0.70 (GM) to 0.42 (Tenn.). Because the Tennessee machine used smooth tread tires, it is to be expected that lower values would be obtained.

Inasmuch as the machines utilized different types of tires it is to be expected that some differences would exist. However, even when the vehicles were equipped with the standard tire the divergences were substantial. As can be noted in Figure 18, the maximum difference between the locked-wheel machines is in the order of 0.20 to 0.25, the greatest divergence occurring on the excellent site, where GM obtained 0.67 and BPR 0.45. It is interesting to note that if, say, the fair site were being tested to determine whether it were below a minimum acceptable locked-wheel coefficient of friction of 0.4 (the standard currently used in Virginia), three machines (Purdue, Virginia, and PCA) would have "passed" the site and three would have "failed" it, with one machine (GM) a borderline case.

It should be pointed out that with the Cornell machine the mean of the measurements for the good site has been disregarded in connecting the point on the fair site to the excellent site. There was considerable evidence from visual observation that the test wheel was not locking and it was thought that rolling friction influenced the results. For this reason a straight line has been extended from the fair to the excellent site.

With standard tires the incipient (NASA) coefficient is well above the other trailers except on the excellent site. This is in contrast to the position of the plot on Series X, where the incipient coefficient remained well above the others over all sites. This rather unusual behavior is not readily explainable and will undoubtedly require some additional investigation.

Another point to be noted is that the stopping distance methods, Purdue especially, are not appreciably higher on the good and excellent sites than several of the trailers. It had been anticipated prior to the experiment that the stopping distance methods would yield results higher than the trailers. This is discussed in greater detail in a later section.

Statistical Interpretation

The preceding discussion was based on the means of six measurements, but does not take into account the dispersion of the individual measurements about the means. The question then arose as to whether the
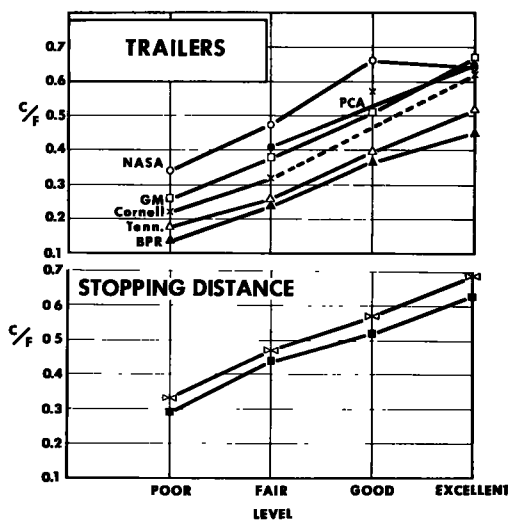

Figure 18. Measurements with standard tires (Series Y).

differences between the means were greater than could be expected from the error of measurement. That is, it is possible that the sample means might differ appreciably but that the dispersion of the individual measurements might be so great as to make imprudent the drawing of conclusions concerning the differences in the means. To take the error of measurement into account a statistical analysis was made. Only the findings of the analysis are presented in the text; the analysis itself is explained in the Appendix.

Results with Standard Tires. From the analysis it was concluded that the results from the trailers, considered as a group, are statistically different, as also are the stopping distance results. An analysis was then carried out to see if any two machines agreed with each other across all levels of friction. It was found that no machine agreed with any other machine (within the statistical error of measurement) at more than one level of friction.

Another pertinent question was whether or not some machines were merely consistently high or low, and agreement could be reached by a simple additive correction factor. The analysis showed that no simple additive factor could make the results for the different machines comparable. That differences in the shape of the "curves" made such equations impossible was verified by the analysis. The results from the two cars can be brought into fair agreement by a simple addition factor, but the trailers cannot be brought into agreement by constant additive factors. There are substantial differences in the design of the machines which may account for the differences in the shapes of the curves. Further research along this line could be very rewarding.

Effects of Tires

Comparisons of the results from Series X and Series Y provide an insight into the effects of tires on the measurement of friction. The interest here is not in the rating of tires with regard to their ability to develop high friction, but on the qualitative influence of tires on the friction measurement.

The analysis showed that for every machine except No. 3 (Cornell) and No. 4 (General Motors) the results were significantly different with the two sets of tires. A question of greater interest, however, is whether results with one set can be equated to those with the other by a simple correction factor. If so, control of the tire variable in future measurements would be much more feasible. Except for the NASA machine, which measured rolling friction, it was found that results for the different sets of tires could be equated by a simple additive correction factor. Although such a conclusion must be restricted to the conditions and tires (GRS) embodied in this experiment, this was true even for the Tennessee machine, which used smooth tread tires.

Variability of Measurements

Another question, in addition to the average coefficient of friction obtained, is how closely successive individual measurements of the same pavement agree with one another. The standard deviation is the measure of the scatter of successive measurements of the same pavement by the same machine. The smaller the standard deviation, the more reliable the measurement.

The data (Table 3) showed that there were substantial differences in variability between machines. The cars had consistently smaller standard deviations, with an overall average of 0.014. Trailers obtained average values from 0.021 to 0.039. Two machines (Nos. 4 and 5) had significantly higher variabilities in the Y Series, which used standard tires. The cause of this difference in variabilities is not clear, but examination of the data suggests that these machines were affected more by the water film variations on the fair site than the other machines. For this reason the average standard deviation for these machines (Table 3) shows two average variabilities, one including the variability from all sites and the other excluding the fair site variabilities.

From the standard deviations, it is possible to estimate the number of measurements required for a given degree of precision. To be 95 percent confident that the average of N measurements will be within a tolerance T, the number of measurements required

TABLE 3
AVERAGE[1] STANDARD DEVIATIONS

Machine No.	Series X[2]	Series Y[3]	Both Series	No. Measurements for Tolerance + 0.02
1 (BPR)	–	0 0397	0.0397	16
2 (PCA)	0.0297	0.0207	0.0256	7
3 (Cornell)	0 0243	0 0164	0.0208	5
4 (GM)	0.0185	0.0225[4] - 0.0332	0.0203[4] - 0.0269	5 or 8
5 (NASA)	0.0161	0.0121[4] - 0.0303	0.0145[4] - 0.0243	3 or 6
6 (Purdue)	0.0138	0.0121	0.0130	2
7 (Tenn.)	0 0378	0.0365	0.0371	14
8 (Va.)	0.0172	0.0134	0.0154	3

[1] Root mean square method.
[2] Regular tires.
[3] Standard tires
[4] Excluding measurements on fair site.

can be estimated from $N = \left(\dfrac{2SD}{T}\right)^2$ in which SD is the standard deviation. The number of measurements needed by the various machines to be within the tolerance of ± 0.02 is also shown in Table 3. It should be noted that for the least variable machine (Purdue) the number of measurements required for a tolerance of ± 0.02 is $\left(\dfrac{2 \times 0.013}{0.02}\right)^2 = 1.6 = 2$ measurements. For the most variable machine (BPR), $\left(\dfrac{2 \times 0.0397}{0.02}\right)^2 = 16$ measurements would be needed. In ordinary field work, somewhat higher standard deviations might be expected.

The machine of the Bureau of Public Roads was only in the development stage at the time of the test and this undoubtedly accounts for some of the variability. However it is important to note from Table 3 that the most variable machines were of the drawbar force type, and further that the least variable were those employing the stopping distance methods. The differences in the precision of the various methods appear to be related to their basic design or method of measurement. A more thorough study of the variability as related to method of obtaining the coefficient is warranted by these data.

The variability was also analyzed to see if the variability of measurements was different at different levels of friction. When the deviant sets of GM and NASA previously mentioned were excluded, it was found that no machine with either set of tires had consistently different precision of measurement for a high-friction pavement than for a low-friction one. Results also suggest that the common procedure of reporting precision of coefficients of friction in percent (that is, ± 5 percent) is in error. Precision should be reported in units of the coefficient (that is, 1.3 ± 0.05).

Comments on Series X and Y

The analysis has shown that the differences among various machines were statistically significant. Examination of Figures 17 and 18 shows that the differences are significant from a practical viewpoint as well, which can be easily seen when the problem of establishing a minimum coefficient is faced. The best interest of the traveling public demands that pavements that are slippery when wet be eliminated from the highway system and this means establishing a minimum acceptable coefficient of friction. As long as the differences in results obtained by the various methods are substantial this minimum can not have much meaning. To attempt to correlate all of the various machines with each other would be exhausting. Search for the causes of the differences in the results seems much more promising, and it is hoped that the data provided in this paper will serve as an impetus to this end.

TEST RESULTS, SERIES Z

As has been pointed out earlier, Series Z was a grouping of miscellaneous sub-experiments. Although no less care was taken in securing the Z measurements, it is true that they were taken after Series X and Y were completed and the pavement had therefore been subjected to considerable wear. In some instances (for example, in Zb, where readings at 55-40-15 mph are compared) the 40-mph reading was taken during

the Y Series several hours before the 55-mph and 15-mph readings and the analysis must take this into account. All measurements were taken on wet pavements at 40 mph (with exceptions noted) with the standard tires.

Za: Comparison of Coefficients of Friction Computed from Stopping Distance and Decelerometer

A decelerometer was rigidly mounted in the center of the space normally occupied by the back seat in the Virginia skid test car. A film recording was made of the decelerometer readings, a speedometer, and a stop meter for each of 48 measurements. Curves of six measurements for each site in the Y Series (Fig. 19) show the deceleration of the skid test car as the stopping distance test was being made. The plots exhibit typical deceleration-speed relationships of a fully braked vehicle. The deceleration of the vehicle increases rapidly as the driver jams on the brakes; the maximum impending coefficient is reached, then the brakes lock and the rate of deceleration is
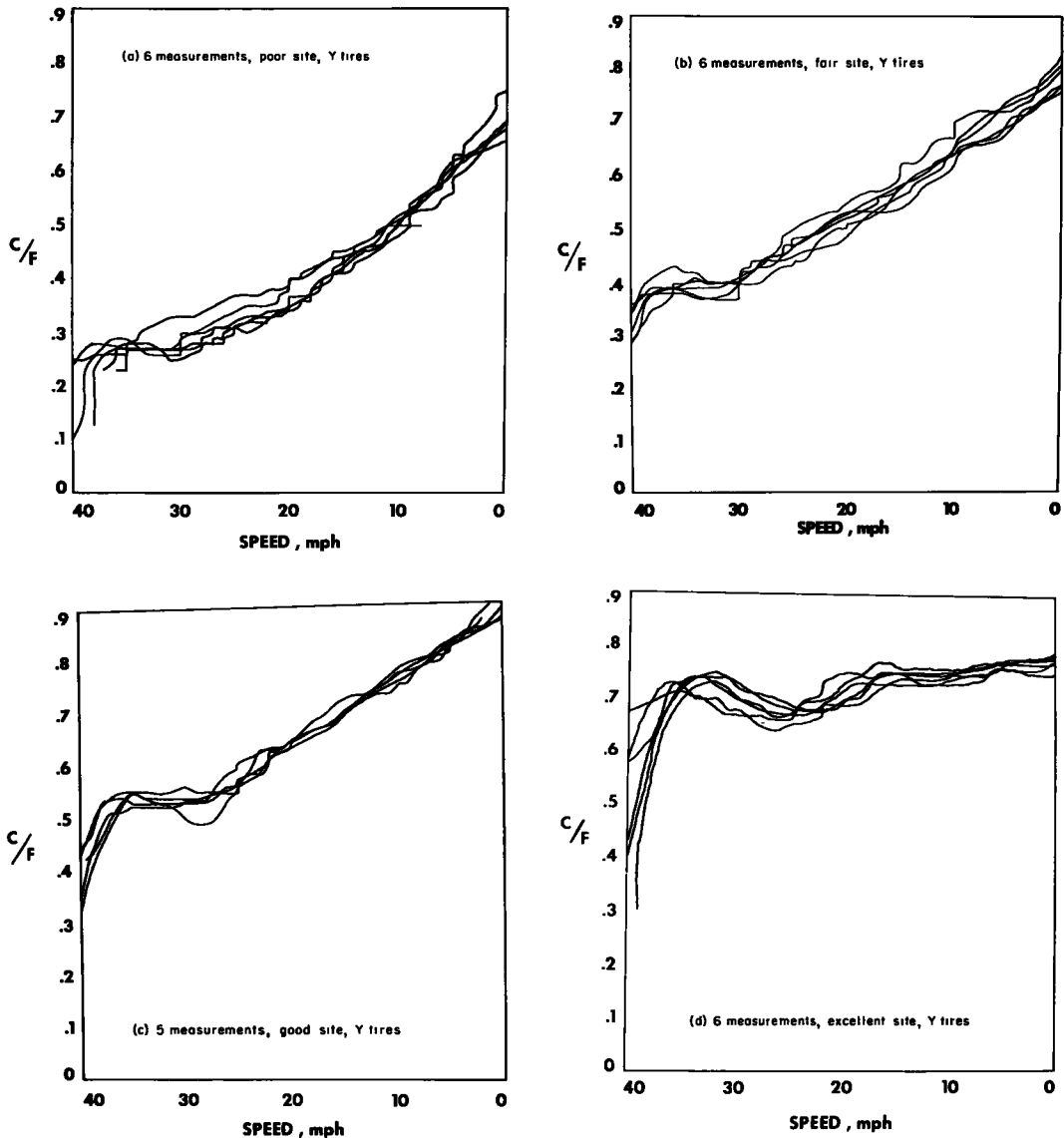
Figure 19. Coefficient of friction vs speed-decelerometer.
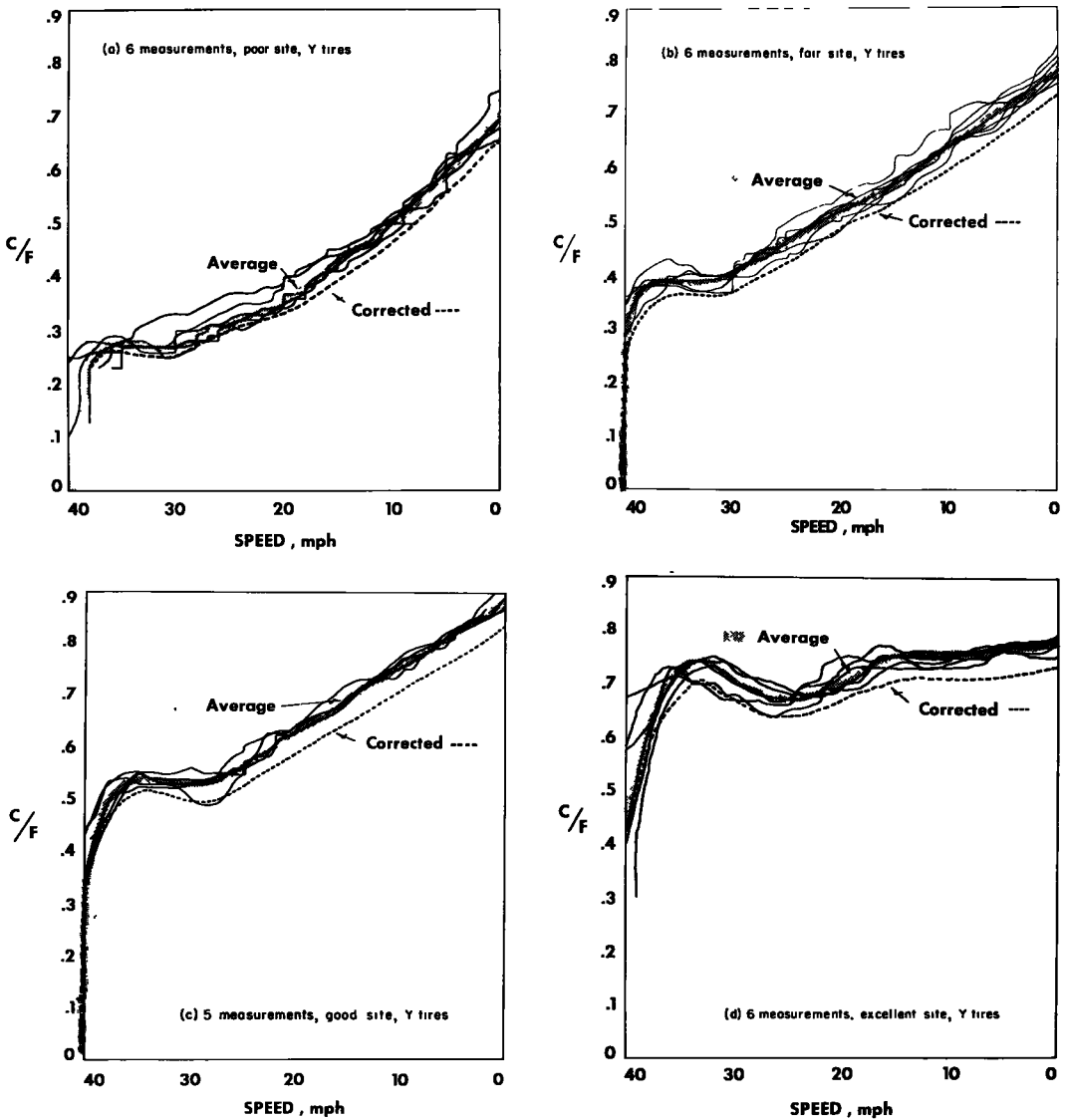
Figure 20. Coefficient of friction vs speed-decelerometer.

somewhat less. Once the brakes are locked the rate of deceleration increases as the speed of the skidding vehicle decreases. A plot of deceleration vs speed for a single wheel would exhibit a more pronounced incipient peak, but the four wheels did not lock at the same instant and the incipient peak and the minimum locked-wheel value are thereby obscured somewhat.

It is interesting to note the difference between the general shape of the plot on the excellent site (Fig. 19d) and those of the other three sites. On the excellent site a maximum deceleration is attained at about 20 mph and the deceleration levels off beyond this in contrast to a continued increase in deceleration on the other three sites. The significance here is that on the excellent site a different relationship is suggested, one in which the coefficient of friction is not influenced by speed as significantly as it is on some other surfaces. (This same conclusion is suggested by Figure 21.)

The average coefficient of friction for each site was computed by integrating the corrected average curve for each site (Fig. 20) by use of a planimeter. The correction
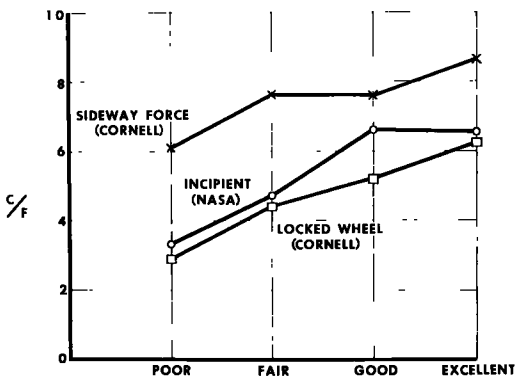
Figure 21. Comparison of the sideway force, incipient, and locked-wheel coefficients of friction.

is for the tilt of the skid test car. Displacement of the decelerometer pendulum is caused by a combination of the non-horizontal position of the car during skidding and the deceleration of the vehicle. The tilt correction was made as explained in the Appendix.

The results obtained from the decelerometer are compared with the stopping distance results in Table 4. For practical purposes the comparison is quite favorable with a maximum deviation of 0.04.

It was hoped that the deceleration curves would provide an insight into the coefficient of friction that would have been obtained if the Virginia skid test car had been towed at a constant speed of 40 mph. This w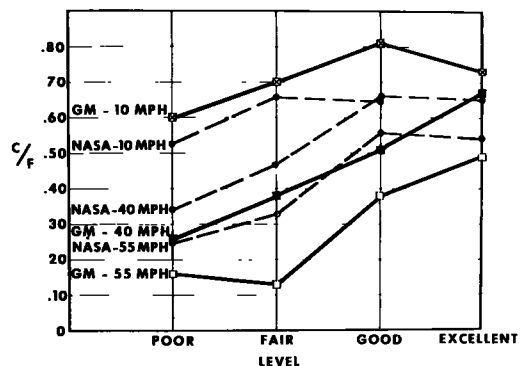as to be accomplished by extrapolating the locked-wheel portion of the deceleration-speed curve to 40 mph. Some problems have been encountered in doing this and in the interest of completing a version of the paper this phase of the analysis has not been completed. It is hoped that this topic may be the subject of a subsequent paper.

Zb: Comparison of Incipient, Locked-Wheel, and Sideway Force Coefficients

The sideway force coefficient has been used little in this country, but has been used extensively in Europe. Its adherents see many advantages in the method, the most significant here probably being that it is indicative of the action of a tire on an undriven wheel which has skidded because of too high a speed when rounding a curve.

The incipient coefficient is generally considered to be the maximum coefficient (see comments in Zc) that can be obtained when tire and wheel are traveling perpendicular to the axle of the wheel and generally occurs at slip ratios of about 0.10 to 0.15. In automobiles the incipient condition is attainable, but few drivers can adequately control the brake pressure to provide the proper slip without locking the wheels. For those in the highway transportation field the incipient coefficient is of interest primarily because it generally represents the maximum that can be developed in the road-tire-brake system at high speeds.

The most widely used coefficient in this country is the locked-wheel value, which realistically represents the conditions met by a vehicle locking its wheels in an emergency straight ahead skid.

Figure 21 provides a comparison between the three coefficients. The data show that the sideway force coefficient is considerably greater in magnitude than the other two, also that the numerical difference between the values on the poor and the excellent sites are less than the incipient or locked-wheel coefficients. The average slope of the curves is greatest for the locked-wheel coefficient, which could be interpreted as meaning that the locked-wheel coefficient is more sensitive to the differ-

TABLE 4

COMPARISON OF COEFFICIENT FROM STOPPING DISTANCE AND DECELERATION CURVES

Method	Poor		Fair		Good		Excellent	
	X	Y	X	Y	X	Y	X	Y
Stopping distance	0.28	0.33	0 41	0.47	0.51	0.57	0.66	0.69
Decelerometer	0.29	0.37	0.41	0.50	0 55	0.61	0.63	0.67

Figure 22. Influence of speed on locked wheel and incipient coefficient.

Machines Participating	Level											
	Poor			Fair			Good			Excellent[1]		
	10	40	55	10	40	55	10	40	55	10	40	55
GM (4)	0.60	0.26	0.16	0.70	0.38	0.13	0.81	0.51	0.38	0.73	0.67	0.49
NASA (5)	0.53	0.33	0.25	0.66	0.47	0.33	0.65	0.66	0 56	-	0.65	0 54

[1]Some noticeable erosion of surface as tests proceeded. Thus, results at 10 and 55 mph are considered as taken on a surface "different" from that on which the 40-mph measurements were taken.

ences that occur in the road surfaces. The standard patterned tires were used on the three vehicles.

The data illustrate, as has been done many times before, that the utilization of the incipient condition during an emergency stop from high speeds would appreciably contribute to safety. For instance, if in an emergency condition on a poor road surface an average coefficient of 0.34 could be attained instead of 0.22 (locked-wheel), the stopping distance would be reduced from 243 ft to 157 ft, a difference of 86 ft. At 50 mph the difference would be even greater, of the order of 170 ft.

Zc: Comparison of Effect of Speed on Incipient and Locked-Wheel Coefficients

The purpose in Series Zc was to compare the influences of speed on the two coefficients across the four levels of friction. The data are plotted in Figure 22.

It should be noted that at 10 mph the locked-wheel coefficients are greater than the incipient values across all levels. At 40 mph the incipient coefficient of friction is greater than the locked-wheel value. According to these data, there is a speed (which probably differs for each site) between 10 and 40 mph where the locked-wheel and the incipient values are equal.

Zd: Correlation of Bicycle Wheel with a Stopping Distance Method (Virginia)

The bicycle wheel machine of the National Crushed Stone Association secured measurements when the field testing equipment was not operating over the test site. A minimum of 100 readings were made over the 300-ft length of each test site.

The slipperiness readings are not expressible in terms of the coefficient of friction, but are an empirical indication of road surface slipperiness. The coefficient of friction and the stopping distances are plotted against slipperiness readings in Figure 23.

The bicycle wheel apparatus is an inexpensive device, costing less than $100 to build, and would be suitable for laboratory as well as field measurements. The National Crushed Stone Association uses the device to indicate slipperiness on a laboratory test track and has found it valuable. The method shows considerable promise for use in this way, as shown by Figure 23.

The one outstanding question about devices of this nature is whether the textural influence of the surfaces might not differ inordinately on surfaces of various types, as the contact patch of the bicycle wheel is approximately a 1-in. square. It is possible that great variations might result if the device were used on very coarse mixes made from two aggregates with widely different slipperiness characteristics. The contact area might alternately be testing the individual aggregates in contrast to an automobile tire (with a contact patch approximately 4 in. by 6 in.), which would be influenced by both aggregates at the same time.

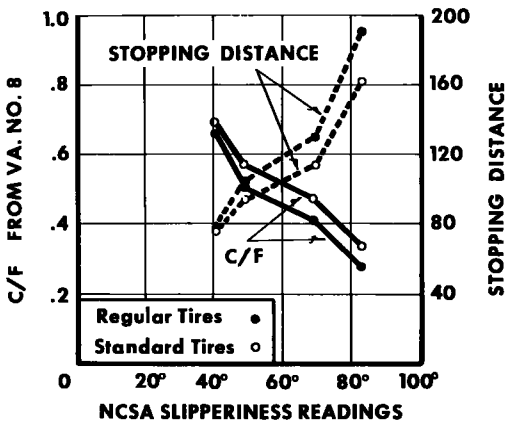The mixes tested in the correlation study were mixes made from a single type of ag-

Figure 23. Coefficient of friction and stopping distance vs slipperiness.

gregate and were dense gradings with relatively fine textures. Because the bicycle wheel is an empirical measure of slipperiness, establishment of the relationship between it and a stopping distance method should include as broad a range of surfaces as found in practice. This condition was not met in this experiment.

Correlation study results obtained from the wheel are encouraging. If further comparisons on a variety of surfaces are as good, the wheel will provide a valuable link between laboratory and field measurements.

CONCLUSIONS

From the results of this study, the following general conclusions seem warranted:

1. The coefficients of pavement friction obtained by the different machines included in the study differed substantially, both statistically and from a practical standpoint. Qualitative differences in results made it impossible to make measurements of the different machines comparable to one another by the use of an additive factor.

2. Relationships between measurements made by trailers and measurements made by the stopping distance method were not clarified. Some trailer results were higher than expected, some lower, with respect to the stopping distance results. Further research is needed on this problem.

3. The locked-wheel coefficients obtained with different types of tires indicate that results from different tires can be correlated by an additive factor. Although this factor will differ from tire to tire, it appears to hold across the various levels of friction.

4. There were important differences between machines in terms of the variability of successive measurements of the same pavement. The data suggest that variability is related to design characteristics of the machines.

5. The variability of measurements was not influenced by level of friction. This indicates that the precision of measurement of coefficient of friction is about the same for high-friction pavements as for low-friction pavements.

There is no doubt whatsoever that the machines that participated in the study, and others as well, have been valuable tools for initially assessing the variables operative in the road-tire-vehicle system. Substantial improvements in road surfaces, brakes, and tires, have been brought about by the measurements from these machines. Further experiments with these machines will add even more enlightenment to this area. However, until the differences, which are both qualitative and quantitative, are accounted for there will be significant doubt about whether a particular variable would have been shown to be operating in the same way when measured by two different machines. As research activities in slipperiness prevention increase and probing goes deeper, confidence in the method of test is essential. Determination of the causes of differences in the coefficient of friction and the variability of the various machines would undoubtedly be a great step forward.

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Appendix

BUREAU OF PUBLIC ROADS APPARATUS

Equipment developed by the Bureau of Public Roads for measuring the skid resistance characteristics of pavement surfaces is a single-wheel trailer designed to measure either straight-skid or side-skid forces. The trailer is towed by a 2-ton truck. A portable plywood shelter on the truck body houses the operator and the recording equipment. An intercom system, installed in the truck cab and the shelter, provides a means for two-way communication between the instrument operator and the truck driver.

The trailer has a single wheel formed by two rings, which clamp to a $4\frac{1}{2}$- by 15-in. rim on which a 6.70- by 15-in. tire is mounted. A large 15- by 3-in. electric brake, bolted to the wheel, is used for the straight-skid locked-wheel tests. The hub of the wheel is mounted by tapered bearings to a 2-in. axle, which supports the trailer frame on a pair of standard automobile leaf springs. The trailer frame is rectangular and is made of heavy structural steel channel. A bridge over the wheel supports a mudguard, lights, and a sign.

Two structural steel channels bolted to the front corners of the rectangular frame converge and form a wye. A plate at the front end is supported by a tee with two side links to form a hitch at the center rear of the towing truck. This hitch is designed to carry all of the vertical load, to prevent overturning of the trailer, and to allow the trailer to follow around turns.

A dynamometer used to measure forces for the straight-skid locked-wheel condition forms a second hitch and connects the trailer axle to a standard trailer ball hitch on the truck. This dynamometer linkage begins as a yoke connected to bronze bearings on the axle. A round steel bar with threaded ends and a reduced central cross-section is screwed into tapped blocks bolted to the yoke at the rear. Two electrical resistance strain gages cemented to the reduced section and covered with waterproofing material are used to indicate strain in the steel bar. Four round bars held by square end blocks surround the ball hitch on the truck. The front end of the dynamometer is screwed into the rear end block.

Signals from the strain gages on the dynamometer are amplified and recorded by an oscillograph in the truck shelter. Wheel revolutions of the trailer are obtained from a microswitch mounted against a cam on the trailer wheel hub and recorded on the oscillograph. Wheel revolutions are also registered on an electromagnetic counter. Alternating current (110-v, 60-cycle) for the oscillograph is obtained from a 1,200-watt motor generator mounted on a platform under the right rear corner of the truck. A voltmeter on the instrument table indicates the voltage supplied by the motor generator. A standard manual control arm for operating the electric brake is mounted at the end of the instrument table.

PORTLAND CEMENT ASSOCIATION APPARATUS

The Portland Cement Association test apparatus consists of a two-wheel trailer and road watering system. The trailer is drawn by a Chevrolet 210 coach, which also contains the major components of the watering system.

The trailer was designed to provide a low center of gravity and a nominal 925-lb load on each tire. The axle and springs are from a 1949 Ford. The suspension is such that the vertical loads are taken by the vertical shackles at each end of the springs. These shackles are of sufficient length and adjusted to a geometric relation such that

the residual horizontal component of the load due to their angularity is negligible. The horizontal drag load of each end of the axle is transmitted by links to the drag link beam secured to the cross beam under the tongue ahead of the axle. The reduced portions of these aluminum drag link beams carry the strain gages that indicate a drag load occurring at the tire-ground contact. The vertical shackles are supported by similar horizontal beams, which could be instrumented to indicate the load on the axle directly, if this becomes desirable. Aluminum strain gage beams have been used to take advantage of their lower modulus of elasticity and proportionately higher output from a strain gage system. The lateral loads on the axle are transmitted by horizontal arms of a Watts linkage to the center rocker, whose center bearing is on the trailer centerline just aft of the axle. This removes the lateral force inputs due to vertical motion of the axle with respect to the trailer, which occur with the simple sway bar arrangement, and is in part responsible for the lack of side sway experienced during operation.

The brakes are conventional Ford hydraulic brakes which came with the axle, but larger front brake actuating cylinders have been substituted. A Chevrolet master cylinder is installed at the hitch of the tongue to operate the brakes. The master cylinder, which is operated by a hydraulic brake booster, is actuated through a push-pull cable system in the car. Both wheels are locked during the test run.

GRADATIONS OF THE ASPHALTIC SURFACES TESTED

Specifications—Virginia Designation I-3[1]

U.S. Sieve	Percent Passing
½ in.	100
⅜ in.	80-100
No. 4	50-70
No. 10	35-50
No. 40	10-25
No. 80	3-15
No. 200	2-10

Asphalt content: 6.25 percent

Specifications—Deslicking Mix[1]
(Excellent Site)

U.S. Sieve	Percent Passing
No. 4	100
No. 10	100-95
No. 40	40-95
No. 80	12-30
No. 200	0-8

Asphalt centent: 7.5-9.5 percent

[1]Sand for these mixes must be 95 percent silicon dioxide.

STATISTICAL ANALYSIS

Statistical analysis of the data consisted of three main parts: analysis of variance of Series Y (standard tires); analysis of variance of Series X and Series Y combined; and analysis of the variability between individual measurements. Although the three parts are interrelated, and the actual chronological order of the analysis was quite different, the foregoing order was chosen for simplicity of presentation. Standard statistical procedures were used.

Series Y

Table 6 shows the analysis of variance for the seven machines for which there were complete data with standard tires. This was basically a 7 x 14 factorial with six measurements per cell. The variation between machines was subdivided into two parts—variation between types of machines (trailers vs cars), and within types (between trailers, and between cars). Because there were large differences in the error variance for the two types, separate error terms were used.

All main effects are significant far be-

TABLE 6

ANALYSIS OF VARIANCE, Y SERIES ONLY

Source of Variation	df	SS	MS	F
Trailers vs cars	1	0 240482	0.2404822	302.1[1]
Between trailers	4	0 738900	0.1847250	177.6[1]
Between cars	1	0.024300	0 0243000	148.2[1]
Levels of friction	3	3 133590	1 0445309	1314.8[1]
Levels x trailers vs cars	3	0.034375	0 0114585	14 4[1]
Levels x trailers	12	0.100240	0 0083533	8.0[1]
Levels x cars	3	0.001933	0 0006444	3.9[2]
Error, trailers	100	0.104033	0.0010433	
Error, cars	39	0.006397	0.0001640	
Error, total	139	0.110430	0.0007945	
Total	166	4.384250		

[1]Significant beyond 0.01 level. [2]Significant beyond 0.05 level

yond the 0.01 level. The significance of the Methods x Levels interaction indicates that the shape of the average curve for trailers was substantially different from that for the cars. The Trailers x Levels interaction indicates differences in the shape of curves for the different trailers. As was mentioned in the text, trailer No. 5, which measured rolling friction, seemed to obtain qualitatively different results. Even with this machine removed, however, this interaction was still highly significant. Examination of Figures 17 and 18 showed the differences in shape to be substantial. Therefore, no simple additive correction factor can make results comparable at all levels. The Cars x Levels interaction was significant only at the 0.05 level, and differences in curve shape are small enough that a simple additive correction factor can bring results for the two cars into fair agreement.

Individual cell means for different machines were compared to see if any one machine got substantial agreement with any other one machine. Each machine was compared to every other machine, at each level of friction. Because of heterogeneity of variance, the variance estimate for each comparison was based on the variabilities of the two cells involved. Only a few of the cell means were not significantly different. Only machines No. 5 (trailer measuring rolling friction) and No. 6 (a car) had means not significantly different at more than one level of friction. But since the results of these machines should differ on a theoretical basis, and differences between these machines at the other two levels were marked, these agreements can only be deemed fortuitous. The statistical analysis, then, bears out the conclusion suggested by examination of the data: No machine obtained friction measurements which were in agreement with those of any other machine.

Combined Series X and Y

The measurements made with the tires regularly used by each machine make possible comparisons with previous measurements with those tires. However, the only general information Series X can add concerns the effects of tires on the measurement of friction.

Table 7 shows the analysis of variance including both standard tires and regular tires. (This is not a factorial design, as the "regular" tires were different for each machine.) The individual comparisons listed under "tires within machines" show that for all machines except No. 3 and No. 4, the regular tires obtained measurements sig-

TABLE 7

ANALYSIS OF VARIANCE, COMBINED X AND Y SERIES

Source of Variation	df	SS	MS	F
Machines	5	1.744346	0.348869	589.53
Tires within machines:				
No. 3	1	0.000075	0.000075	0.17
No. 4	1	0.000002	0.000002	0.00
No. 5	1	0.079218	0.079218	134.75[1]
No. 6	1	0.012675	0.012675	75.74[1]
No. 7	1	0.080033	0.080033	58.03[1]
No. 8	1	0.031008	0.031008	130.11[1]
Levels	3	5.545736	1.848578	3125.24[1]
Levels x machines	15	0.185251	0.012350	20.88[1]
Levels x tires within machines:				
No. 3	3	0.003075	0.001025	2.38
No. 4	3	0.003899	0.001296	1.79
No. 5	3	0.033073	0.011024	18.75[1]
No. 6	3	0.000742	0.000247	1.48
No. 7	3	0.008050	0.002683	1.95
No. 8	3	0.001625	0.005417	2.27
Error:				
No. 3	40	0.017233	0.000431	
No. 4	40	0.028983	0.000725	
No. 5	40	0.023517	0.000588	
No. 6	38	0.006360	0.000167	
No. 7	40	0.055167	0.001379	
No. 8	40	0.009533	0.000238	
Total	238	0.140793	0.000592	
Total	285	7.869601		

[1]Significant beyond 0.01 level.

nificantly higher or lower than the standard tires. The "levels x tires within machines" is of particular importance. With the exception of machine No. 5, a simple additive correction can make results with regular tires in essential agreement with results with the standard tires.

Error Variance

The foregoing analysis was based on comparison of the average coefficients of

TABLE 8

VALUES OF CHI-SQUARE FOR BARTLETT'S TEST FOR HOMOGENEITY OF VARIANCE BETWEEN LEVELS OF FRICTION

Machine	X Series	Y Series
No. 1	-	3.36
No. 3	6.17	4.76
No. 4	4.77	10.61[1]
No. 5	2.85	17.96[2]
No. 6	7.51	1.77
No. 7	7.13	7.42
No. 8	2.87	2.38

[1] Significant beyond 0.05 level
[2] Significant beyond 0.01 level.

friction. Of equal importance is the variability of measurement (that is, the differences between successive measurements of the same pavement by the same machine). The variance of each cell was computed, and comparisons were made using Bartlett's test.

The first question was whether or not variability of measurement was different at different levels of friction. If variability were related to coefficient of friction, a suitable transformation should be sought. For each machine and each series, the variabilities at each level of friction were compared using Bartlett's test. The values of chi-square are shown in Table 8. Since day-to-day changes in variability were expected, and since these changes were confounded with levels of friction, significant results would not necessarily indicate that variability was related to level of friction. Only for machines No. 4 and No. 5 with standard tires was the value of chi-square significant. These results seem to be due to the unusually large variances obtained by these machines at the fair site already referred to in the text.

A plot of cell means and cell standard deviations showed no evidence of any relationship between variability and level of friction. Therefore, it was concluded that the coefficient of friction was the appropriate variable to use for statistical analysis. A plot of coefficient of variation did show evidence of a relationship. The usual procedure of reporting variability of measurement of coefficients of friction (that is, ± 5 percent) assumes the coefficient of variation is constant. It is therefore suggested that this procedure should be changed in accordance with the foregoing results, and variability should be reported in terms of the coefficient (that is, ± 0.02).

CORRECTION FOR TILTING OF CAR DURING LOCKED-WHEEL TEST

The correction for tilt was made on the basis of data supplied by General Motors Proving Grounds, whose tests have shown that the maximum angle that the horizontal axis of a 1958 Chevrolet will develop with the road is about 2 deg 40 min at deceleration rate of 25 ft per sec per sec. This deceleration rate equals 0.78 g's, which corresponds to a coefficient of 0.78, neglecting wind resistance of the car. It was assumed that a linear relationship existed between tilt and rate of deceleration (g's), hence between tilt and the instantaneous coefficient of friction ($a_X = K_2 R_t$). Now, since the influence of tilt on the decelerometer reading, which is in g's, can be determined ($R_C = K_1 a_X$), the correction can be made as follows:

$R_t = R_a - R_C$ in which R_t = true deceleration;

R_a = apparent deceleration; and

R_C = reading due to tilt and not deceleration.

But $R_C = K_1 a_X$ in which a_X is the angle of tilt, and $a_X = K_2 R_t$.

K_1 and K_2 can be evaluated from the previous assumptions, and

$R_t = R_a - K_1 K_2 R_t$

$R_t = R_a - K_3 R_t$

$R_t = \dfrac{R_a}{1 + K_3}$

After evaluating the constant it was found that $R_t = 0.941 R_a$

Discussion

W. A. MC CONNELL, Manager, Vehicles Testing Laboratories, Ford Motor Company—
Preliminary results of this study show apparatus used by the Tennessee Highway Department and the Bureau of Public Roads to yield significantly lower values of friction coefficient than General Motors and Cornell equipment. Specifically, comparable average values for the various road samples checked are: Tennessee, 0.34; BPR, 0.38; Cornell, 0.43; and GM, 0.45. It is understood that these are revised values in which differences in weight transfer from the test tire to the pintle hook during braking, which arise from differences in trailer hitch height and length, have been allowed for.

Examination of the force measuring systems on the four machines show that the Tennessee machine measures the drawbar pull exerted by the braked trailer, a pull comprised of the tire-road reaction force less any decelerative forces on the trailer itself. Similarly, the measuring system of the BPR rig is sensitive to both friction force and inertial force for the entire trailer, although in this case much of the trailer weight is carried by the towing truck, and not on the test wheel. The weighing system of the Cornell trailer unit is connected to the axle, and will register friction force of the tire-toad contact less inertial force of the wheel and axle assembly only. The General Motors device weighs the torque reaction of the braked wheels. While the wheels decelerate the reading will be influenced both by friction force and polar moment of the wheels in an additive way. After the wheels lock, the reading should be a function of friction force only.

Although exact masses of the various units are not known, an estimate of these masses and the magnitude of the resulting inertial effects suggest that all four machines are observing identical tire-to-road friction forces. When appropriate corrections are made, all machines should show about the 0.45 value given by the General Motors trailer.

For example, the Tennessee trailer is estimated to weigh 1,700 lb with 835 lb on the test wheel. It is towed by what is estimated to be a 7,000-lb truck. When the trailer brake is applied and the weighing system indicates a 0.34 coefficient, approximately 0.34 x 835, or 285 lb, retarding force is applied to the towing truck. This force will produce a 0.04-g deceleration in the 7,000-lb truck, and, since they are connected, in the trailer. When a 1,700-lb trailer decelerates at a rate of 0.04 g, a 70-lb force is required. This 70 lb comes from the tire-road reaction, but will not be measured by the load cell between the trailer and the towing truck. Thus, the true road reaction is 285 + 70 lb, or 355 lb in this situation, and the true friction coefficient is 355/835, or 0.43.

It is understood that tests were conducted at an initial speed of 40 mph, over 150-ft distances, or a time interval of about 2.5 sec. The 0.04-g deceleration in this time interval would produce about a 2-mph change in speed, which would probably be imperceptible to the machine operator.

Similar estimates of the inertial effects on the BPR unit yield a corrected value of 0.43. The inertia of the wheel axle assembly on the Cornell tire tester is sufficiently light and the truck sufficiently heavy that their 0.43 value would not be materially increased.

The percent error introduced in the results will be equal to the mass behind the load cell divided by the mass ahead of the cell, and will be constant regardless of the magnitude of the deceleration produced by application of the trailer brakes. Thus, the Tennessee apparatus has a built-in error of 1,700/7,000 = 25 percent; the BPR equipment is in error by 1,360/11,000 ≒ 12.3 percent; the Cornell system by 100/17,000 = 0.6 percent. These errors will be somewhat variable as the water supply and weight of the towing truck varies.

It appears, therefore, that all units used in the correlation study are experiencing nearly identical tire-road friction coefficients; but careful evaluation must be made of the inertial effects as well as the geometry of each apparatus if the numbers presented by the various weighing arrangements are to be interpreted correctly. Even imperceptible decelerations and gradients of even a fraction of a percent cannot be ignored with the drawbar type weighing method.

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geometry of each apparatus, but also of the technique employed in each case for measuring some parameter which may then be interpreted in terms of coefficient of friction. It is suggested, however, that until much more is known about the several factors influencing the resistance between a sliding tire and the pavement surface on which it slides, and about the measurement of these factors, efforts to numerically equate the results of one apparatus with those of another be exercised with great caution.

Finally, the hope is expressed that extensive discussion of why one apparatus does not give results numerically identical to another will not cloud the highly significant and highly gratifying fact that so many pieces of equipment differing to a great degree in concept and design could test four pavements of previously unknown quality and rate them in an essentially identical manner.

RICHARD H. SAWYER, Langley Aeronautical Laboratory, National Aeronautics and Space Administration—After a careful analysis of the problem of the low friction coefficient values obtained in the correlation study by the vehicles using measurements of tow-bar force, the writer agrees with Mr. McConnell's analysis of the problem. For the assumed case of no change in driving power and a steady value of the skidding force, it is interesting to note that the following expression can be used to obtain the skidding force from the tow-bar force without the necessity of calculating the deceleration of the vehicles:

$$F_S = F_{TB} \, (1 + W_2/W_1)$$

in which

$$F_S = \text{skidding force;}$$
$$F_{TB} = \text{tow-bar force;}$$
$$W_2 = \text{weight of trailer; and}$$
$$W_1 = \text{weight of towing vehicle.}$$

Because the tow-bar method of measurement is also subject to error caused by accelerations produced by power changes as well as by the skidding force, the correlation study data should not be corrected by the foregoing, but calculations might be made as Mr. McConnell indicated to show that better agreement would result by such considerations. Inasmuch as the error due to neglecting effects of acceleration is so large, it appears that the tow-bar method of measurement is at considerable disadvantage with other methods, particularly since, even if attempts are made to correct the results by measurement of the acceleration, accurate measurements of such small values of acceleration in the presence of other transient accelerations caused by road unevenesses, etc., would appear to be extremely difficult.

C.G. GILES, Head, Road Surface Characteristics Branch, British Road Research Laboratory

NOTE:—Several weeks after completion of testing for the study, 4-in. cores were cut from the four test sites and offered to any group interested for laboratory testing. Two cores from each of the test sites were sent to Mr. Giles. After testing the cores in the laboratory's portable testing apparatus, as described briefly elsewhere (6), he sent the following data and comments by letter.

These samples are not really large enough to employ the British Road Research Laboratory's standard test conditions (3-in. wide slider and 5-in. sliding length), so a narrower slider and shorter sliding distance were required. However, the results so obtained are thought to be not too far from what would result if the normal conditions of test could be used.

Comparison of the results with the measurements obtained with the Virginia and Purdue skidding distance cars, which is probably the fairest comparison that can be made, seems to indicate quite reasonable correlation. The BRRL tester generally shows slightly higher values than the full-scale machines, but this is the usual finding when making comparisons of the two methods in Britain.

SUMMARY OF TEST RESULTS ON CORES FROM
CORRELATION TEST SITES IN VIRGINIA

Sample	Classification	Coef. of Friction Brit. Rd. Res Lab.[1]			Full-Scale Machines[2]	
		A[3]	B[3]	Mean	Purdue	Virginia
P6	P	0.45	0 38	0.39	0.29	0. 33
P8		0:36	0.35			
F10	F	0.50	0.43	0 51	0.44	0 47
F14		0.57	0.53			
G4	G	0.62	0.55	0 58	0.52	0.57
G11		0.60	0.56			
G14	E	0.63	0.66	0.65	0.63	0.69
G12		0 65	0.66			

[1] As measured by British Road Research Laboratory portable
tester on samples cut from the test roads.
[2] Tests with 3-in. wide slider and 3-in. sliding length; may be
some "edge" effects due to slider striking edge of block.
[3] Tests with 1¼-in. wide slider and 3¾-in. sliding length, no
"edge" effects.

Quite apart from this, too, it has been found on previous occasions that however carefully a sample is cut from the road there is always a possibility that its surface condition may change before it is tested in the laboratory. In some cases the coefficient of friction on the cut sample has been found to be as much as 0.1 higher in the laboratory than the value measured in situ, before the sample was removed. Therefore, the results must be treated with some caution.