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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **151**

LOCKED-WHEEL PAVEMENT SKID TESTER CORRELATION AND CALIBRATION TECHNIQUES

TRANSPORTATION RESEARCH BOARD
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LOCKED-WHEEL PAVEMENT SKID TESTER CORRELATION AND CALIBRATION TECHNIQUES

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AREAS OF INTEREST:

- PAVEMENT PERFORMANCE
- MAINTENANCE, GENERAL
- HIGHWAY SAFETY

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1974

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation
Research Board

Implementation of the recommendations contained in this report will result in substantial improvement in the reliability of pavement skid resistance measurements with locked-wheel skid testers conforming to ASTM Method E-274. The recommendations result from a skid tester correlation program held at The Pennsylvania State University with 12 skid testers participating. During the two-week program, use of the recommended techniques resulted in about a 70 percent improvement in correlation among the skid testers involved. Due to the urgent need to implement any information that could reduce highway accidents, personnel responsible for the measurement of pavement skid resistance and for safety programs should study this report carefully and schedule immediate implementation of appropriate recommendations.

The skid resistance of wet pavements is one of the critical factors influencing highway traffic safety. The majority of highway agencies in the U. S. measure pavement skid resistance with locked-wheel skid testers. However, it has been demonstrated that the repeatability of measurements by a tester and correlation between testers of this type is generally not adequate, particularly from the standpoint of attainment of national safety goals. A degree of uncertainty must be accepted with any measurement due to imperfections in the measurement process and the variability of the item being measured. Skid testers are complex measuring devices containing many components, each contributing to uncertainty in the measured quantity. Pavements have inherent variability caused by the influence of such factors as materials, construction, maintenance, traffic, and the environment.

The objective of this project was development and verification of methods for improving the ability to measure reliably the skid resistance of wet pavement surfaces with skid testers in conformance with ASTM Method E-274. The approach used by The Pennsylvania State University researchers to meet this objective involved (a) contacts with skid tester owners to collect information on test equipment and operating procedures, (b) conduct of laboratory and field experiments to determine the effect of specific variables on skid resistance measurements, (c) computer simulation studies on the influence of equipment dynamics on skid tester performance, (d) development of tentative recommendations for reducing variability in skid resistance measurement, and (e) conduct of a two-week skid tester correlation program to verify and modify the tentative recommendations.

The reliability of skid resistance measurement depends on both tester precision and accuracy. Precision is a measure of the repeatability of the results of a single tester and accuracy is a measure of correlation among skid testers. An analysis of variance performed on data collected during the correlation program indicates that the precision of skid testers, although not completely satisfactory, is generally better than their accuracy. Implementation of recommendations contained in the report will aid highway agencies in obtaining more accurate pavement skid resistance measurements with existing skid testers and, when combined with operation of the FHWA-sponsored Field Test and Evaluation Centers for skid testers, will provide a sound basis for calibration of skid testers that will bring about substantial improvement in their correlation nationwide.

CONTENTS

ACKNOWLEDGMENTS

The work reported herein was conducted by the Pennsylvania Transportation and Traffic Safety Center of The Pennsylvania State University under NCHRP Project 1-12(2). Wolfgang E. Meyer, Professor of Mechanical Engineering, and Rudolph R. Hegmon, Research Associate, acted as co-principal investigators. They were assisted by Thomas D. Gillespie, Research Associate (now with the Ford Motor Company).

Appreciation is expressed to members of the organizations involved in skid testing who so generously gave of their time and experience for this research. These include many state highway and transportation departments, industrial and university institutions, the Federal Highway Administration, and the National Bureau of Standards. The last, under a research project sponsored by the Federal Highway Administration, performed all force calibrations during the Skid Tester Correlation Program. The ready cooperation offered by all involved contributed significantly to accomplishment of the work.

In addition to the authors of this report, substantial contributions were made by Walter Benson in conduct of the research; Dr. J. C. Wambold and Messrs. E. T. Napp and L. Eastman in the computer simulation studies; Professor J. DeCarolis in preparation of instrumentation; Ronald Slavecki in the statistical analysis and data evaluation; and by graduate assistants J. P. Besse, J. Tung, D. Kunkle, R. Gustafson, W. Zimmerman, and T. Matsumoto.

LOCKED-WHEEL PAVEMENT SKID TESTER CORRELATION AND CALIBRATION TECHNIQUES

SUMMARY

The objectives of the project were to determine the reasons for poor correlation among locked-wheel pavement skid testers, and to propose measures for improving correlation, as well as to verify the effectiveness of the measures. To meet these objectives four approaches were used: investigative. experimental, analytical, and verification.

Most highway departments in the United States were contacted for information on skid-testing equipment and procedures. Several were visited to observe the operation of different skid testers, to discuss experience in skid testing, and to obtain details on tester design and performance.

Two skid testers, one a two-wheel and the other a single-wheel design, were used in an extensive field test program to determine effects of specific variables on skid-resistance measurement. Primary attention was given to the effects of pavement wetting and trailer dynamics. Temperature effects were studied both in the field and on an indoor circular track apparatus. Repeatability was studied to separate the effects of random errors from those of systematic errors in testing. The magnitude of each error source was determined.

A skid tester dynamics model was developed and programed on a hybrid computer. Design and operational parameters were varied over a wide range to study their effects on skid test results. Programing pavement profiles from perfectly smooth to actual, rough-road profiles while maintaining a constant coefficient of friction allowed the study of dynamic effects on tester performance independent of friction effects.

In the first phase of the project sources of error in skid testing were identified, their magnitudes determined, and measures to reduce their effects were recommended. In the second phase of the project, a two-week correlation program involving 12 skid testers was held to evaluate the benefits obtained in practice from application of the recommended corrective measures. The participating locked-wheel skid testers were considered representative of the designs currently in use in the United States. The test benefits were measured by examining correlations before and after application of the corrective measures. Speed and tracking errors, which can be significant in inventory testing, were closely controlled during the correlation program and, therefore, introduced no appreciable errors.

The results of the correlation program indicated that:

1. In the condition in which the skid testers arrived, the distribution of the mean skid numbers (SN) from all testers yielded a standard deviation of 4.08 SN (on one test site, the range of mean skid number values from all testers extended as high as 24 SN).

2. After application of corrective measures (including calibrations), the reduced variability resulted in a 1.04 SN standard deviation (the range of mean skid numbers on an individual test site was reduced to 5 SN).

3. The factors (in order of decreasing effect) most responsible for the initially

poor correlation were force calibration and wheel load errors, chart interpretation and evaluation, watering systems, and temperature differences.

Test data were analyzed by statistical methods. The major factors controlling the accuracy of skid-resistance measurement were identified. Methods for applying statistical concepts to skid-test programs were developed, from which the required number of tests per pavement section can be determined for a prescribed degree of accuracy.

Recommendations are made for improving skid-testing equipment and the calibration, operation, and data evaluation procedures. Though no major equipment changes appear necessary, the need for high-quality instrumentation is stressed, and a standardized pavement watering method is recommended. Calibration procedures should be standardized, and frequent force and test wheel load calibrations are needed. Tighter operating procedures combined with better operator training will reduce errors in testing. Lengthening skid tests to permit evaluation of longer portions of the skid trace, more precise methods of evaluation, and recognition of the statistical uncertainty associated with the data are also recommended as means to improve the quality of skid test results.

It is generally recommended that ASTM E 274 be reviewed and changed to incorporate the corrective measures formulated in this project for improving skid tester performance. A standardized design of a skid tester for inventory testing is recommended as a means to simplify the correlation problem and allow uniform calibration and operating procedures to be employed. Ultimately, the development of standard calibration surfaces available to each tester is considered the best method for dynamic calibration of skid testers.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT AND OBJECTIVES

The skid resistance of wet pavements is one of the critical factors in automotive traffic safety. Although several methods of measuring pavement skid resistance are in use, the majority of highway departments in the United States use locked-wheel skid testers whose method of use has been standardized in ASTM E 274 (*1*). In the ASTM method, the friction force on a locked test wheel equipped with a standard test tire, in accordance with ASTM E 249 (*2*), is measured as the locked wheel is dragged over a wetted pavement surface at constant speed and under constant load. The results are expressed as skid numbers (SN) that indicate the relative safety of pavements under wet conditions.

Many years of experience in measuring skid resistance have brought improvements in skid tester design and instrumentation, although repeatability in skid testing and correlation among skid testers have not improved correspondingly. Poor correlation between skid testers is detrimental to the efforts of obtaining a uniform evaluation of the skid-resistance levels on the nation's highway network and also hinders the effective study of methods for improving pavement skid resistance characteristics. Uniform, dependable, and accurate means of measurement must be available in order to prescribe minimum skid-resistance requirements for pavements. (Pavement skid resistance, however, should not be considered as being representative of traffic performance. It is rather a function of the method of measurement and only characterizes the capability of pavements to contribute to tire-pavement friction under wet conditions.)

The present project had as its objectives the determination of error sources in pavement skid-resistance measurement and the development of corrective measures. These

achievements are expected to lead to better correlation between skid testers and better repeatability for any one skid tester.

Any measurement must be awarded a degree of uncertainty because of imperfections of the measuring devices and procedures and of variability in the measured quantity. Pavements have inherently large variability because ". . . materials used in construction vary over wide limits, . . . equipment and methods have limitations and the methods of measuring . . . are in themselves inaccurate and a source of variation" (*3*). This statement applies also to skid resistance and its measurement. A skid tester is a complex measuring device containing many components, each of which contributes to the uncertainty in the measured quantity. The acceptable degree of inaccuracy, or error, is usually a compromise between the desired accuracy and the effort required to improve the measuring system. In the past, the total error in skid testing has clearly been too large. The problem, therefore, is to identify the individual errors, to determine their causes, and to find means of reducing them.

Based on past experience, more complex and expensive equipment has come into use but without corresponding gains in repeatability and correlation. Some discrepancies in skid testing are unavoidable and the question arises as to what magnitude of error must be accepted under various testing conditions, on different pavements, and in different modes of testing. The three modes of testing considered are:

1. A single skid tester making repeat tests on the same stretch of pavement.
2. A single skid tester making successive tests on a presumably homogenous section of pavement.
3. Several skid testers making repeat tests on the same stretch of pavement.

Mode 1 is the type of testing done in research work, and mode 2 corresponds to inventory testing of a highway system. Mode 3 represents a correlation program between various testers. In all three cases skid resistance is determined from several repeat tests. The number of repeat tests required may be defined as whatever number is needed for a tester to reproduce its own mean within an acceptable error band. Repeatability is clearly a function of the over-all variability in skid testing.

In a correlation program, discrepancies can occur between the mean skid numbers for several testers even though the testers perform on a common test site. Such discrepancies may be within the accepted error band or may result from real differences between the testers. Highway departments, and users of skid testers in general, should know what accuracy to expect from their own skid testers under various conditions and where to look for trouble should a given tester not deliver results within its acceptable error limits.

RESEARCH APPROACH

The approach taken in this project was to determine the expected error limits in skid testing by investigating each factor involved, determining the probable range of variation for each in light of the ability to control that factor, and forming a judgment on its effect on the measured skid number. To estimate the over-all effect of all error sources, the relative weight of each error must be considered as well as the frequency of its occurrence.

The first year (Phase A) of the project was concerned with investigation of the error sources associated with 12 major factors that influence pavement skid-resistance measurement. A highly detailed analysis of these factors and their associated aspects as sources of error is given in Appendix A. Information was gathered from skid tester users to identify the differences in tester design and operation, which could be sources of error. Field and laboratory tests were conducted to determine the influence of each factor and the ability to control that factor in testing. A computer simulation of a skid tester was developed for the purpose of studying the influence of dynamics on tester performance. As a result of this work, a number of corrective measures for reducing skid testing errors were recommended. The recommendations generally stressed better speed maintenance; correction for temperature effects; adoption of a standard watering method; precise calibrations of load, torque and/or force; increasing the data evaluation interval; and tighter procedures.

In Phase B of the project, a skid tester correlation program was conducted. The program was designed to test correlations among representative skid testers, apply corrective measures, and evaluate effectiveness of the measures. Factor analysis was applied to the test data to separate and identify individual error sources.

The most significant findings of the study and those that provide the basis for the project conclusions and recommendations result from the correlation program, which is discussed in Chapter Two. The highly detailed analysis of the influence of 12 major factors on pavement skid-resistance measurement is given in Appendix A. Additional details concerning the correlation program such as participants, procedures, compositions of test surfaces, and the like, are given in subsequent appendices.

CHAPTER TWO

FINDINGS—SKID TESTER CORRELATION

During October 1972, a two-week skid tester correlation program was conducted at the Pennsylvania Transportation and Traffic Safety Center's Pavement Durability Facility. Twelve participating organizations sponsored skid testers (with their operating crews), which group provided a representative sample of all testers known to be in use in the United States. Detailed information concerning the correlation program, such as participating organizations, the types of skid testers, and the like, is given in Appendix B.

The first week of the program was devoted to a tightly controlled calibration and correlation procedures in which all 12 testers participated. Five skid testers participated in the second week's program, which was reserved for further skid testing as well as diagnosis and correction of error sources. At the conclusion of the correlation program an open test period was held with two additional highway departments participating. All tests were conducted on specially prepared test surfaces:

1. Coefficient stripes.
2. ID-2A wearing course.
3. Jennite.
4. Sand-epoxy.
5. Burlap drag concrete.
6. ID-2A wearing course.
7. Fluted concrete.
8. SR-1A (popcorn) mix.
9. Tread Matting.
10. ID-2A bituminous concrete binder course.

During the first week, four of the surfaces (No. 3 through 6) were used in two sets of correlation tests. More detailed information is given in Appendix C.

SKID TESTER CORRELATION PROGRAM

Design of Test Program—First Week

The test program was based on three variables—skid tester, test site, and test speed. All other factors, such as tires, inflation pressure, and pavement wetting, were to be held constant. Temperature during testing was measured.

To reduce effects of extraneous factors, such as temperature, pavement preconditioning, and pavement changes, random testing was required. Because complete randomization would have required more time for the same number of tests and could have been achieved only by a drastic reduction in the total number of tests, a compromise test sequence in which testers were randomly assigned was established. Testing was organized into four groups each composed of four testers. The testing pattern, shown in Figure 1, was organized into four groups each of which was composed of four testers. One tester in each group repeated in a second group and served as a control. After the calibration of the skid testers, a second correlation was made among testers in Groups 5 to 8, which were arranged as Groups 1 to 4 but with different testers assigned to the groups. This arrangement allowed most of the testers to run three complete test sequences. Details are given in Appendix B.

Data Processing

Skid and speed data were processed independently by both the tester crews and the program staff. In addition, several sets of test data were recorded on magnetic tape and processed electronically (Appendix A, Section 10). Speed was measured by the program staff by means of electronic timers and tape switches spaced at a measured distance on the test sites. The same tape switches served also to record the lateral position of the skid testers on the test sites (Appendix A, Section 1.3).

Data evaluation by the tester crews was performed according to their own established procedures. Staff evaluation of the skid traces was done independently and fed into a computer for further processing. For testers calibrated in force (F) or in torque (T), the staff computed the skid numbers according to ASTM E 274 equations:

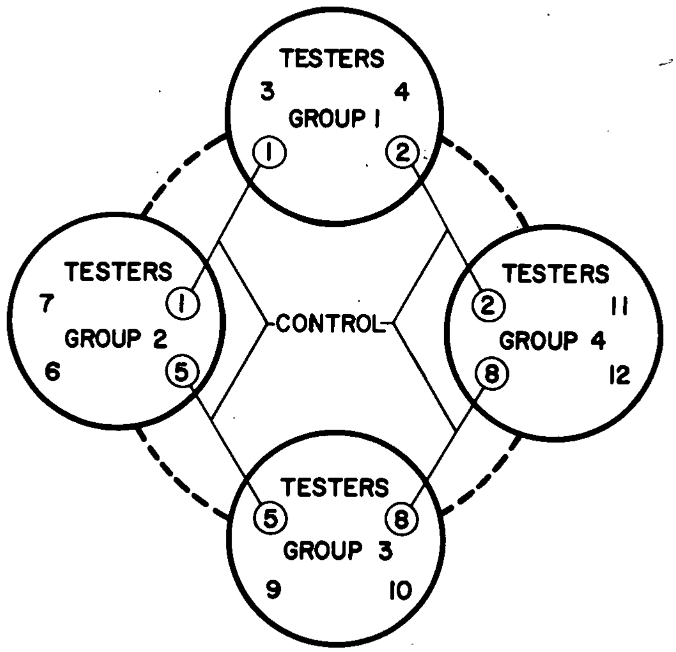

Figure 1. Schematic plan of testing pattern.

$$SN = \frac{100F}{W_o - HF/L} \text{ or } SN = \frac{100T/F}{W_o - HT/LR}$$

to correct for unloading effects. The values for static wheel load (W_0), hitch height (H), trailer length (L), and wheel radius (R), although initially supplied by the tester crews, were checked during tester calibration and corrected as needed.

All data reported are based on two sets of correlation tests. The first set was taken by the testers in the condition as they arrived. The second set was taken after adopting a standard watering method (Appendix A, Sections 3.2 and 3.3) and mounting a new test tire. The new tires purchased from a single production batch had been run in and tested prior to the Program (Appendix A, Section 5.3). Each test set included a full test sequence * for each of 15 testers. A full sequence consisted of a total of 80 skids, each skid being made at four speeds (40, 30, and 50 mph and a repeat test at 40 mph) on four test sites, each of which was repeated five times. Thus, a full set of tests was comprised of 15 testers each making a sequence of 80 skids for a total of 1,200 skids.

Both sets of 1200 skid data each were processed in an analysis of variance with various corrections applied to the test data. To identify the different results all analyses are given in Table 1 and will be referred to by these numbers throughout this report. Appendix D gives details of the statistical analysis. In addition, second-order polynomials were fitted to the data, separate for each test site, with speed being the independent variable and skid number the dependent variable.

* Sixteen sequences were planned, but one tester dropped out after its first test sequence because of instrumentation failure. Its data are omitted.

Test Results

All test results are discussed in terms of mean skid numbers of five repeat tests and are based on the computer evaluation. Data tabulations are given in Appendix E. All data are compared to the over-all, corrected grand means, based on 300 data points per test site. These will be considered the true skid numbers of the test sites to which all data are compared, each data set to its true mean skid numbers. Figure 2 is a plot of mean skid number versus speed for the two test sets on the four sites. The difference between the two sets is probably due to a decrease in pavement skid resistance during testing. Test site 5, a PCC pavement, showed almost no change.

The difference in skid number for each tester over all speeds relative to the true mean is shown in Figure 3. Here the first uncorrected set of data, ANOV-1, is shown together with the second set to which all corrections have been applied, ANOV-9, to illustrate the over-all improvement achieved during the correlation program. The standard deviations were reduced as much as 70 percent as a result of all corrections. (The 90-percent confidence interval, shown in the figure, spans an error band of approximately 10 percent on the corrected data. It is believed that further reduction of the interval width would be extremely difficult.

Table 1 gives all the analyses and corresponding stan-

TABLE 1

ANALYSIS OF VARIANCE

ANOV NO.	DATA FROM ANOV NO.	CORRECTIONS	STANDARD DEVIATION: VALUE	REDUCTION: RELATIVE TO ANOV NO.	REDUCTION: %
Data set 1, before calibration:					
1	—	None	4.08	—	—
1a	1	Temperature, 0.4%/deg F	5.21	—	—
2	1	Chart evaluation	3.25	1	20
2a	2	Temperature, 0.4%/deg F	4.27	—	—
3	2	Calibration [a]	1.49	2	54
3a	3	Temperature, 0.4%/deg F	2.63	—	—
Data set 2, after calibration: [b]					
4	—	Chart evaluation	2.83	2	13
5	4	Calibration [a]	1.53	4	46
6	5	Temperature, 0.4%/deg F	1.08	5	30
7	5	Lateral position	1.52	5	<1
7a	7	Temperature, 0.4%/deg F	1.07	7	30
8	7	Zero shift	1.24	7	19
				3	17
				4	56
9	8	Temperature, 0.4%/deg F	1.04	8	16
10	9	Pavement deterioration	1.49	—	—
11	7	Temperature, 0.13%/deg F	1.31	7	14
12	7a	Speed	1.13	—	—

[a] Includes correction for force calibration and tester constants.
[b] Includes mounting of standard nozzle and tire.

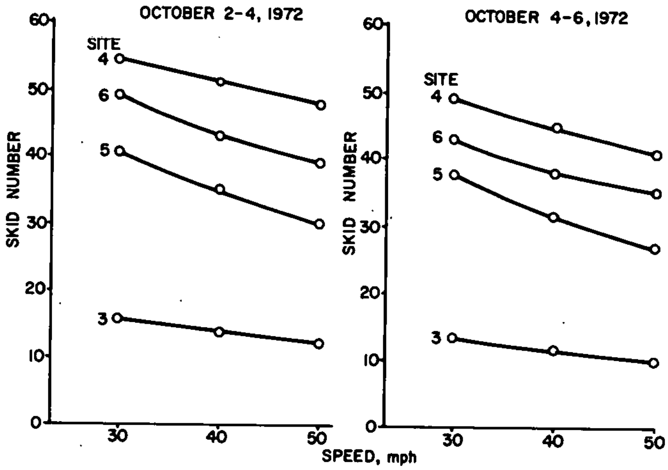

Figure 2. A plot of mean skid numbers versus speed for two test sets on all four sites.

dard deviations. It can be seen that some of the corrections caused a decrease and some an increase of the standard deviation. Table 2 gives the standard deviation among testers separately for each test site. Only those corrections that improved the results significantly are given and they are discussed in the next section.

Two measures of tester standard deviations were examined. One (s_T) is the variation due to testers and isolated from all other effects; the other (s_A) is based on total variation, including tester and tester interactions with pavement and speed. Both values can be obtained from the analysis of variance by the equations

$$s_T^2 = \frac{MS_T - MS_E}{b\,c\,n}$$

and

$$s_A^2 = \frac{SS_T + SS_{TP} + SS_{TV} + SS_{TPV}}{(a-1)\,b\,c\,n}$$

where MS is the mean square and is equal to the sum of squares SS divided by the degree of freedom (Appendix D). The indices E, P, T, and V stand for error, test site, tester, and speed, respectively; a is the number of testers, b the number of test sites, c the number of speeds, and n the number of repeat tests.

Comparison of these equations shows clearly that $s_T^2 < s_A^2$. It can also be shown that s_A is equivalent to the means of all standard deviations computed separately for each test site and test speed (Appendix D). s_A may be considered

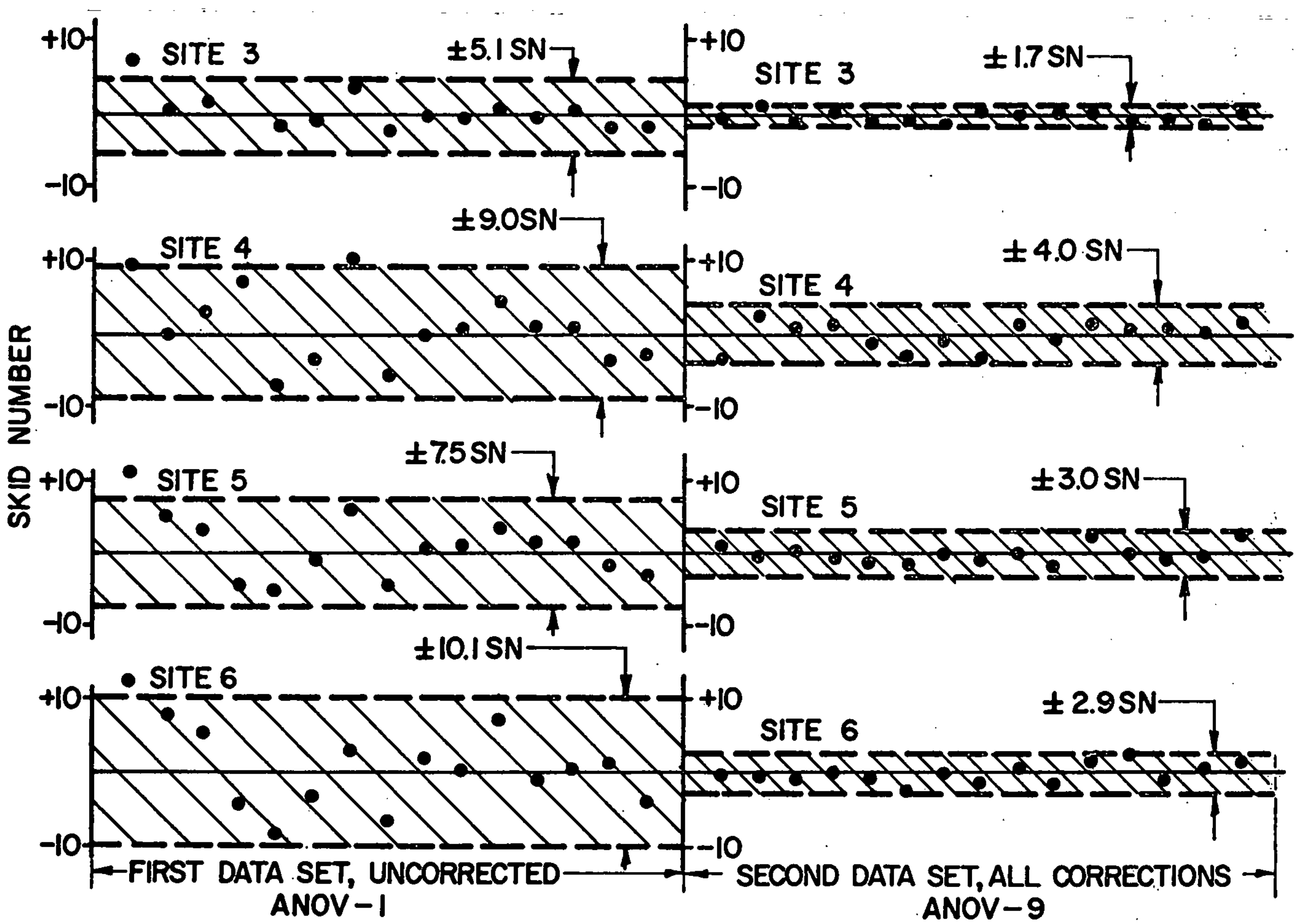

Figure 3. 90-percent confidence limits about mean skid numbers.

TABLE 2

STANDARD DEVIATION OF MEAN SKID NUMBER FOR VARIOUS TEST SITES

ANOV NO.	STANDARD DEVIATION					REDUCTION		CORRECTIONS APPLIED
	SITE 3	SITE 4	SITE 5	SITE 6	MEAN	RELATIVE TO ANOV NO.	%	
1	3.10	5.50	4.55	6.18	4.96	—	—	—
2	1.59	4.69	3.61	5.12	3.99	1	20	Evaluation
3	0.97	2.52	2.38	3.54	2.52	2	37	Calibration
4	1.34	4.23	2.65	4.76	3.51	2	12	Nozzle, tire
5	1.03	2.44	2.43	3.22	2.41	3, 4	44, 31	Calibration
7	1.06	2.42	2.06	1.78	1.83	5	24	Lateral position
8	0.95	2.24	1.96	1.70	1.71	7	6.6	Zero shift
9	0.88	2.10	1.58	1.59	1.60	8	6.4	Temperature

the *standard deviation in skid testing,* because it includes the interactions of tester and other variables. It is the standard deviation normally determined when measurements of several skid testers are compared. To isolate the standard deviation of the tester (s_T), an analysis of variance must be performed. It should be pointed out that throughout this report tester variance includes effects of operators and procedures. These items could have been separated by intentionally treating them as variables, but such was beyond the scope of this project.

Correction Applied to Test Results

Table 2 shows that the greatest reduction in standard deviations—37 percent from ANOV-2 to ANOV-3, and 31 percent from ANOV-4 to ANOV-5—was obtained through accurate calibration. During calibration the correct values of force versus chart reading, wheel load, tester length, hitch height, and wheel radius were established (Appendix F), but no adjustments were made to the testers or the instrumentation. Therefore, the same corrections apply to both data sets. The reduced standard deviation reflects all five factors, but the greatest errors were found in the force calibration and in the test wheel static load.

Errors in chart evaluation are also large and are caused by zero drift and by averaging. Their corrections account for the second largest reduction in standard deviation—20 percent from ANOV-1 to ANOV-2, and 24 percent from ANOV-5 to ANOV-8. The latter includes correction for lateral position, which is, however, small as can be seen from Table 1, ANOV-5 to ANOV-7. Only a small number of data points had to be corrected for lateral position and the effect on over-all variance was small. The correction did, however, reduce the standard deviation of individual testers. Frequency response was checked by skid testing the coefficient stripes, test site 1, and was found to be adequate on all skid testers (Appendix A, Section 10).

The reduction in standard deviation of approximately 15 percent from ANOV-2 to ANOV-4 and ANOV-3 to ANOV-8 can be credited to the use of standard water nozzles and tires from the same batch. ANOV's 2 and 4 are without, ANOV's 3 and 8 are with corrections for calibration, and all four have data evaluation errors corrected. Thus, the comparisons are valid and the major differences between these pairs are the nozzles and tires. Separation of their respective effects is further discussed.

Pavement temperatures during the tests ranged from 40 to 90 deg F. Based on laboratory results a correction of 0.4 percent per degree Fahrenheit was applied to all data (Appendix A, Section 2.3). This correction reduced the standard deviation in some cases by as much as 30 percent (Table 1), but made correlation worse in others. To explain these unexpected results, regressions of skid number versus temperature were run separately for each pavement. From experience a negative temperature dependence was expected and was indeed found on all four test sites in the second data set. The regression equations and percentage corrections are shown in Figure 4. However, the slopes were smaller than expected indicating that the 0.4 percent correction was clearly too large. With the first data set, skid resistance of two surfaces was found to increase with temperature. Therefore, a smaller correction of 0.13 percent, estimated from the slopes of the regression lines, was applied to all data. It further reduced the standard deviation of one test site in the second data set, but the over-all standard deviation was greater than with the 0.4 percent correction. With the first data set the standard deviation was greater with correction than without. The positive slopes of two of the skid resistance-temperature curves were clearly responsible for the increased standard deviations. It had to be assumed that these positive skid resistance-temperature slopes were caused by other error sources that masked the temperature effects.

From these results the researchers concluded that temperature effects are very small and are often overshadowed by the data spread due to other causes. Correction factors will vary with pavement type. To determine temperature correction factors, a single skid tester should be used in a large number of repeat tests over a large temperature range and within a short time period. Unless the data spread from other sources can be kept to a minimum, temperature corrections need not be considered.

In addition to temperature correction, which made correlation poorer in some cases, corrections for pavement

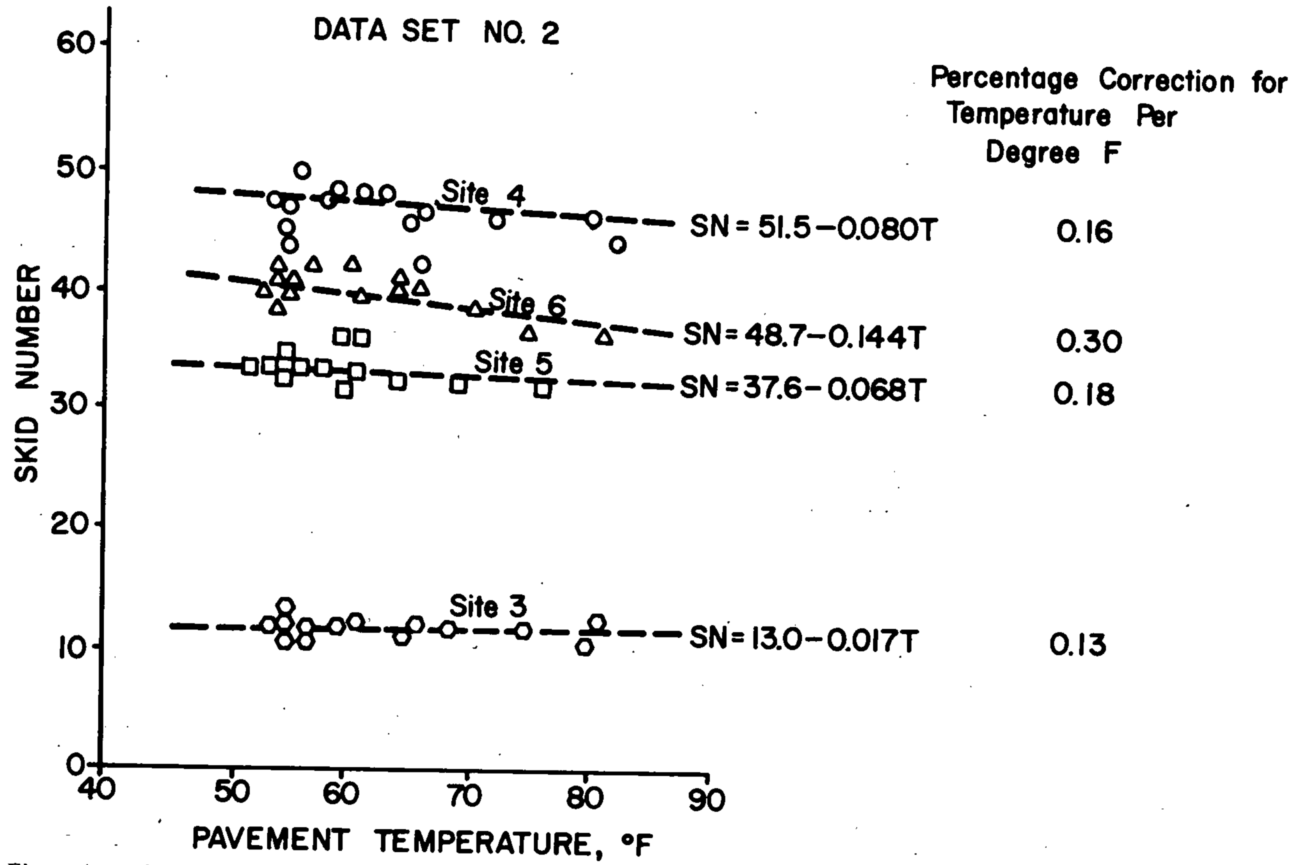

Figure 4. A plot of skid numbers versus temperatures.

deterioration (ANOV-10) and speed (ANOV-12) also resulted in poorer correlation. As for pavement deterioration, the effect was overestimated and too large a correction was applied. With regard to speed, the variances were so small that speed effects became negligible as compared to random variations.

Standard Deviations of Single Skid Testers

Individual tester variance was based on five repeat tests on each test site and at each test speed. These variances determined the experimental error in the analysis of variance, which was relatively small (Appendix D). Some of the variances within five repeat tests were too large as a result of testing too close to the edges of the test sites where skid resistance was much higher (Fig. 5). Because lateral position was measured (Appendix A, Section 1.3), these data points were identified and corrections were applied to points at the extreme edges of the test sites.

Tester variances given in Table 3 are the means of 16 variances. Some of the variances in ANOV-1 are smaller than in ANOV-5, probably because the lateral variation in skid resistance was smaller during the first correlation tests. With corrections for lateral position (ANOV-9), the variances for all skid testers are appreciably smaller than in ANOV-1. The percent reductions listed in the table are probably the result of several factors:

1. No corrections for lateral positions were applied to ANOV-1, although there may have been some lateral variations in skid number.
2. Familiarity of the crews with the test site was better in the second correlation tests.
3. Each tester used the same nozzle correctly mounted to provide more uniform distribution of water.
4. Tester flow rate before calibration was unknown and may have been too small in some cases.

Tester No. 12 used the same nozzle in both correlation programs. Therefore, its reduction in variance excludes the watering system as a factor. Using this as a reference, the reductions above 27 percent may be attributed, at least in part, to the water system. Four testers having reductions in variance greater than 50 percent had small, loosely mounted nozzles. All others, Tester No. 5 excepted, had well-designed nozzles or at least nozzles with sturdy mountings, which reduced variations between successive tests.

The standard deviations, computed from ANOV-9, are given in Table 3. They vary between 1 and 1.5 SN approximately and, for the present, must be considered the lower limit obtainable in repeat tests under controlled conditions. These standard deviations are based on the variabilities of the skid testers and include effects of operators and procedures.

Table 3 also gives the speed variances for each speed separately as well as the over-all standard deviation for each tester. All but one tester stayed within less than ±1 mph at a 95-percent confidence level. This allowance

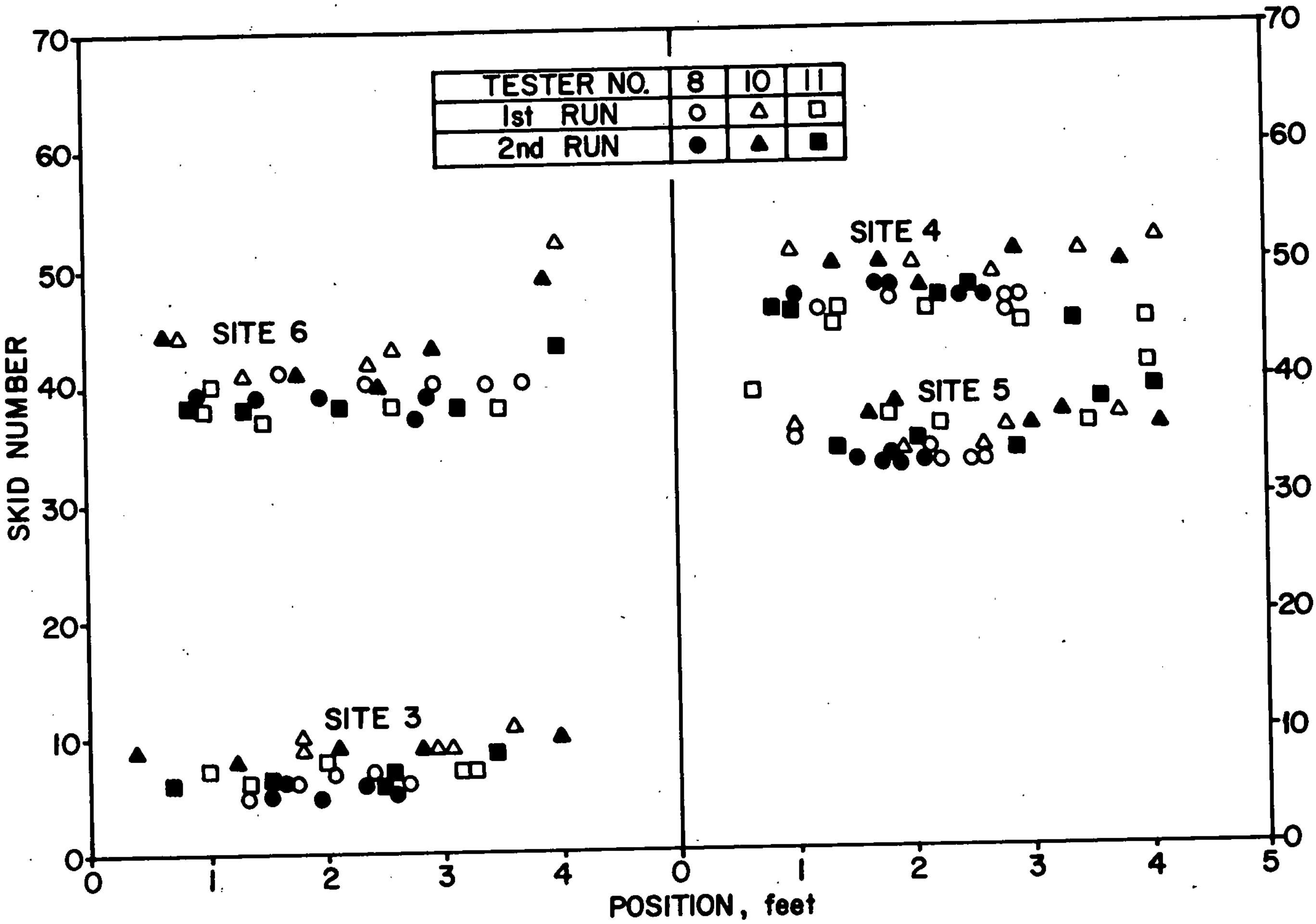

Figure 5. Lateral variation of skid resistance at end of second correlation.

TABLE 3

SKID TESTER VARIANCES—GRAND MEANS

TESTER	SKID NUMBER VARIANCE ANOV–1	ANOV–5	ANOV–9	REDUCTION, ANOV–1—ANOV–9 (%)	SN STD. DEV. ANOV–9	SPEED VARIANCE (MPH) 40 MPH	30 MPH	50 MPH	40 MPH	MEAN	STD. DEV.	95% CONF. LIMIT (MPH)
* 1	2.11	2.48	1.62	23	1.27	0.178	0.199	0.239	0.283	0.225	0.48	0.94
2	2.95	1.13	1.08	63	1.04	0.021	0.018	0.087	0.015	0.035	0.06	0.12
3	2.69	1.40	1.14	58	1.07	0.173	0.130	0.243	0.148	0.173	0.42	0.82
5	1.26	0.99	0.99	21	0.99	0.087	0.134	0.141	0.212	0.143	0.38	0.74
6	1.61	1.55	1.43	11	1.19	0.063	0.038	0.060	0.030	0.048	0.07	0.14
7	2.58	1.43	1.18	54	1.09	0.203	0.166	0.301	0.126	0.199	0.45	0.88
8	1.28	0.75	0.73	43	0.86	0.134	0.158	0.278	0.211	0.195	0.44	0.86
9	1.89	2.10	1.37	27	1.18	0.107	0.067	0.211	0.167	0.138	0.37	0.72
10	3.38	3.47	1.62	52	1.27	0.759	0.126	0.480	0.190	0.389	0.62	1.21
11	2.14	2.21	1.62	24	1.27	0.156	0.131	0.169	0.165	0.155	0.39	0.76
12	2.80	4.57	2.05	27	1.43	0.345	0.176	0.259	0.083	0.216	0.46	0.90

Mean, all skid testers:

	VARIANCE	STD. DEV.
ANOV–1	2.06	1.48
ANOV–11	1.24	1.12

* see p. 74 for identification of testers

is within the recommended speed tolerance and was relatively easy to maintain under the conditions of the test track because there was no interference by other traffic, etc.

Mean skid numbers over all speeds for each of the eight groups (according to Fig. 1), are given separately for each test site in Table 4. The control test data are also shown. Using the variances of the individual testers as given in Table 3, the 90-percent confidence intervals * for a tester to repeat its means can be found. For a sample size of five repeat tests, it is between 2.1 and 3.1 SN, but the actual differences between some of the control tests were larger. Therefore, an attempt to correct group mean skid numbers by control tester data did not reduce the differences between these means, and these corrections were not applied in any of the analyses. Figure 6 shows mean skid resistance by groups, with and without corrections. Except for group 2 on site 6, the uncorrected data are at least as consistent as the corrected data.

Polynomial Approximation to Skid Resistance-Speed Data

Pavement skid resistance is frequently plotted versus speed and generally decreases with speed. Because of the relatively large data spread, a consistent functional relationship between skid resistance and speed is difficult to find. A second order polynomial was considered because its terms can be related to physical phenomena (Fig. 7). The term with linear speed dependence may be considered to represent the penetration of the water layer beneath the tire. It has a negative coefficient because speed reduces the length of the semi-dry contact. That portion of water expelled from the contact area experiences acceleration. The inertia force resisting acceleration is proportional to velocity squared and is represented by the second-order term in the polynomial.

Separate polynomials for each test site were fitted to the test data of each skid tester (20 data points), but the coefficients were found to behave erratically. When the data points from all testers were pooled for each test site (300 points) the resulting polynomials had consistent coefficients, that is, negative for the first-order term and positive for the second-order term. The polynomials are plotted in Figure 8 with the data points of Figure 2 shown.

Skid resistance-speed gradients were obtained by differentiation. Correlation with measured outflow times (*4*) could only be achieved by taking percent gradients and then only at one speed, 60 mph (Fig. 9).

Chart Evaluation

Evaluation of the analog record of friction force, wheel load (where applicable), and speed may lead to errors for several reasons. One of the error sources is the human evaluator whose task it is to visually average a trace of approximately ½ to 2 in. long, depending on the chart speed. Most evaluators use a template which reduces the error but does not eliminate it.

In the correlation program, the tester crews were asked to evaluate their charts before turning them in for staff evaluation. The crews were instructed to mark on the charts only the portion of the trace evaluated, but not the level of the trace.

* Confidence limits = $\bar{SN} \pm t_{1-\alpha/2}\, s/\sqrt{n}$

TABLE 4

MEAN SKID NUMBERS AND CONTROL TEST BY GROUPS ANOV-3 AND ANOV-9

GROUP		SKID NUMBER SITE 3	SITE 4	SITE 5	SITE 6	
	CT[a]	13.2	52.5	38.5	49.6	
1	Mean	13.6	51.0	34.7	45.3	
	CT	14.5	52.6	31.8	42.6	CT
	CT	13.4	48.8	29.1	37.5	CT
2	Mean	13.4	50.3	33.1	39.8	
	CT	12.8	48.8	32.6	38.6	CT
	CT	13.2	50.2	33.6	40.2	CT
3	Mean	12.8	50.4	34.7	43.8	
	CT	13.0	50.7	35.1	45.3	CT
	CT	14.6	51.9	36.0	43.8	CT
4	Mean	12.5	49.8	34.2	42.5	
	CT	12.8	50.6	35.2	41.3	CT
Mean 1–4:		13.0	50.4	34.2	42.8	
5	Mean	12.0	45.5	32.1	38.2	
	CT	11.2	45.8	32.2	37.5	CT
	CT	11.4	41.8	30.5	35.8	CT
6	Mean	11.2	42.8	31.2	37.3	
	CT	10.9	44.1	31.9	38.7	CT
	CT	12.0	46.2	31.9	39.3	CT
7	Mean	11.8	45.6	32.2	39.5	
	CT	12.0	46.3	34.8	40.3	CT
	CT	12.4	46.7	35.0	40.3	CT
8	Mean	11.5	46.0	32.7	39.0	
Mean 5–8:		11.7	45.0	32.0	38.5	

[a] CT indicates control tests.

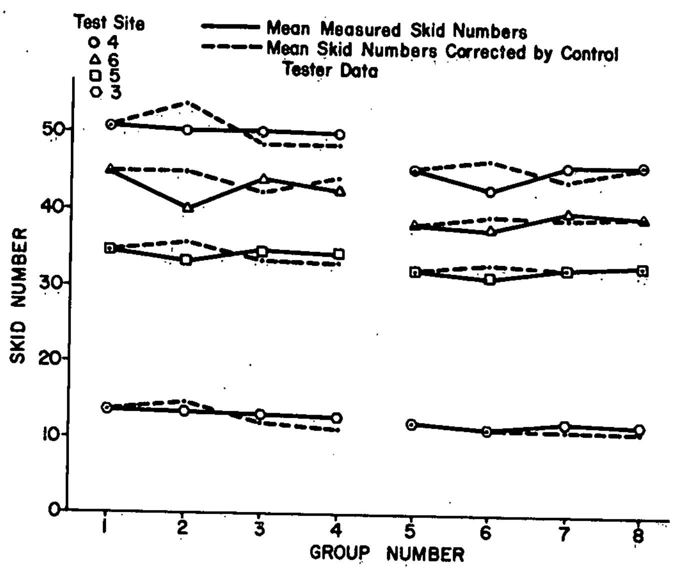

Figure 6. Mean skid numbers, uncorrected and corrected, by test groups.

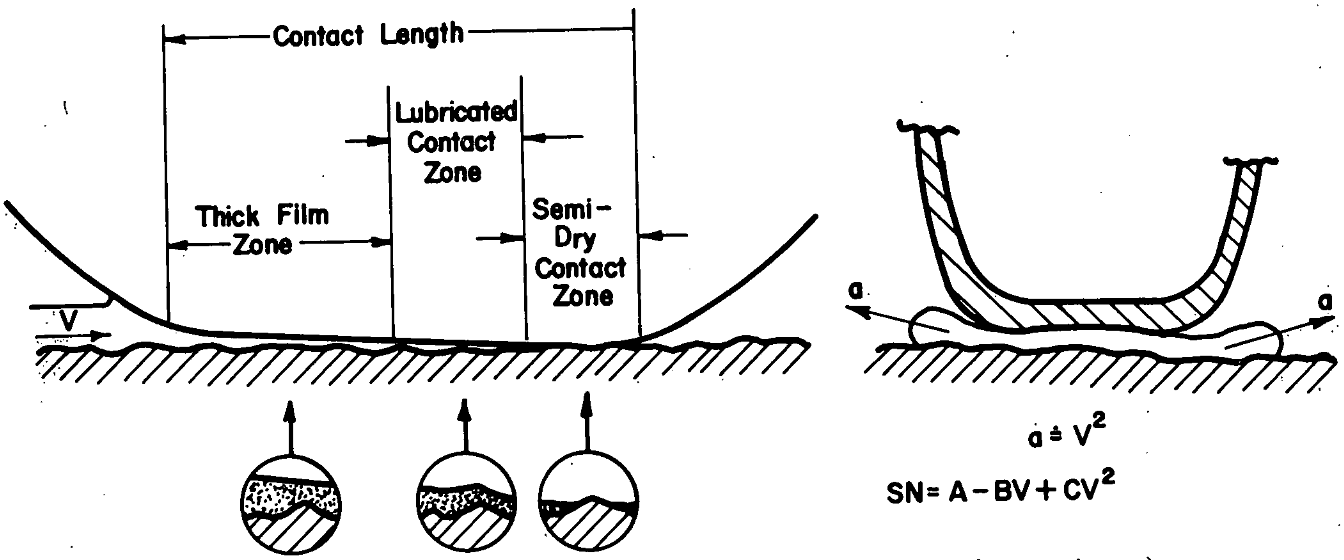

Figure 7. Three-zone concept of tire-pavement friction (V *equals sliding speed;* A *equals acceleration of water*).

A comparison of two sets of data for each tester gave the results listed in Table 5.

The largest difference in reading of a single trace was 4.2 chart units. The largest difference in means was 2.75 chart units. These differences were due partly to human error and partly to different interpretation of zero setting. The human error seems to be systematic because the staff evaluator read consistently higher for nine testers and lower for three testers.

Speed was measured uniformly for all testers by tape switches on the test sites. The speed was computed from the elapsed time between triggering of the two switches. Some of the skid testers independently recorded speeds, which were compared with the computed speeds (Table 6).

The differences were consistent except for tester No. 9. The error is due partly to chart evaluation and partly to inaccurate measuring systems. The inconsistency of tester No. 9 may have been the result of chart evaluation only.

Second-Week Test Program

Five skid testers, including the Penn State tester, participated during the second week of the program. Activities during this period were conducted on a less formal schedule. A list of potential test activities had been prepared beforehand and some of these were selected in consultation with participants and in order of priority. The tests that were conducted are described here briefly and in more detail throughout this report, where appropriate.

Separation of Effect of Water Nozzle and Tires

The first set of test data was taken with each tester using its original nozzle and tire. These were replaced with uniform nozzles and tires before the second correlation. The time schedule did not allow replacement of one item at a time because another set of tests would have been re-

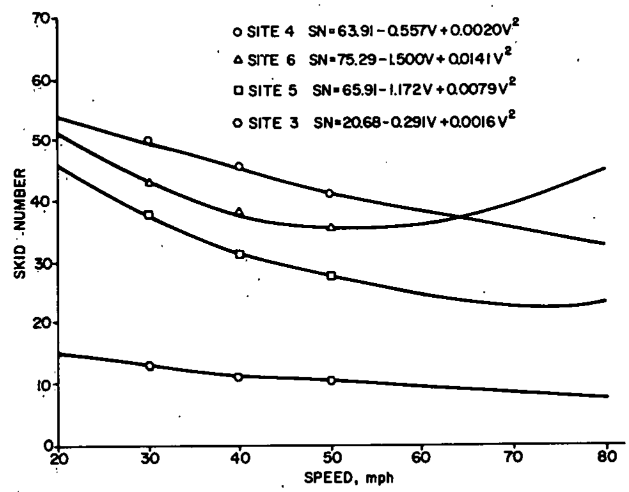

Figure 8. Computed skid resistance versus speed; solid lines are best-fit polynomials to 300 data points per test site. Points are means of data points at nominal speeds (see Fig. 2).

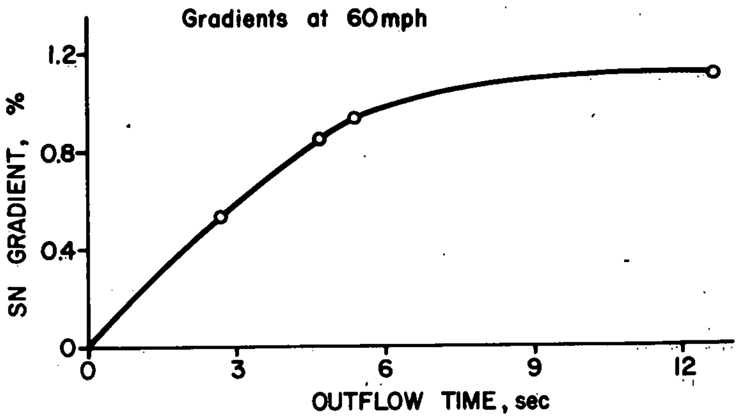

Figure 9. Skid resistance gradients versus outflow time; gradients from polynomials; outflow time measured with high-pressure outflow meter.

TABLE 5

COMPARISON OF CREW AND STAFF EVALUATION OF SKID RESISTANCE RECORDS

TESTER NO.	DIFF. IN SKID NO. Δ [a]	$\overline{\Delta}$ [b]
1	0.75	0.30
2	1.50	0.45
3	2.00	1.20
4	1.25	1.00
5	2.35	1.25
6	1.75	1.20
7	−1.75	−1.00
8	0.30	0.20
9	−3.00	−1.50
10	2.00	0.00
11	−4.20	−2.75
12	2.40	1.10

[a] Staff evaluation minus crew evaluation, largest single difference.
[b] Staff evaluation minus crew evaluation, difference between means.

TABLE 6

LARGEST DIFFERENCE IN SINGLE SPEED MEASUREMENT; TESTER SYSTEM MINUS SPEED COMPUTED FROM TAPE SWITCH DATA

TESTER NO.	LARGEST DIFF., Δ (MPH)	COMMENT
1	−1.6	All low.
2	+0.6	All high.
5	−3.3	All low.
6	+0.3	All high.
9	0.9	Some low, some high.
11	−1.3	All low.

quired. Thus, the 15-percent reduction in standard deviation can be credited partly to the nozzle and partly to the tire.

To estimate the contribution to improved correlation by substituting tires from the same production batch, comparison tests between these and the old tires were conducted. Three testers conducted a total of 25 repeat tests, each at 40 mph on each of the same four sites as were used in the correlation program. Testers No. 3 and No. 9 used their original tire, changed to the program tire and back again to their original tire. Tester No. 12 used a new tire from the same batch as the program tires to replace its program tire.

The test results on each test site are shown in Figure 10. The only consistent difference between the left and right halves of the figure is that the new tire measured higher skid resistance on all four surfaces. The same data are averaged over all four test sites and plotted again in Figure 11, together with data of the same three testers from the second correlation (ANOV-8). It can be seen that differences between testers remain about the same throughout. For any one tester, the difference between the program tire and its original tire is insignificant, although the new tire gave somewhat higher results. Thus, the effect of changing tires is small and most of the improvement in correlation must be credited to improved watering.

Skid Tests on Surfaces Not Used in the Correlation Programs

All five skid testers tested three additional surfaces—fluted concrete, SR-1A (popcorn) mix, and Tread Matting. The test sequence was the same as that in the correlation program, except that only 30-mph tests were made on Tread Matting. Details of the test results are given in Appendix C and are quite similar to the results obtained during the first week.

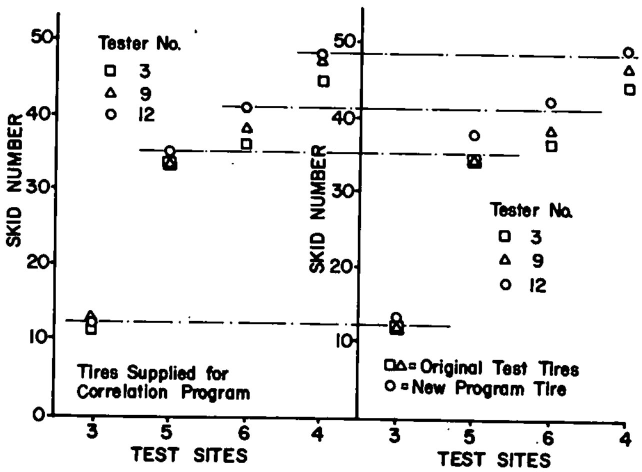

Figure 10. Effect of tires on skid resistance.

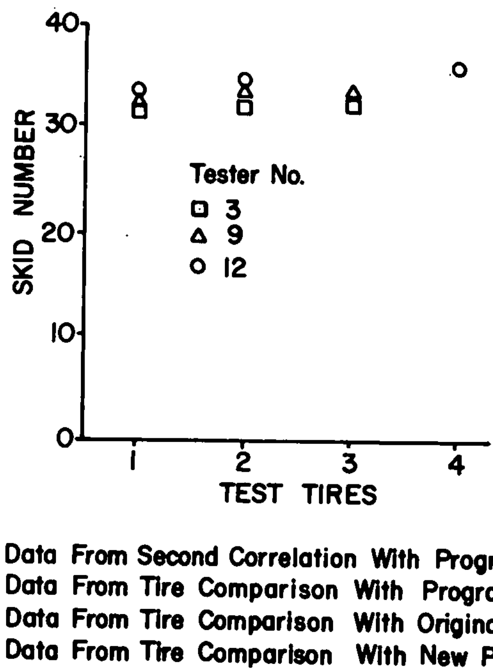

Figure 11. Skid resistance with different tires.

Lateral Variation of Skid Resistance

Four skid testers participated in a test series on test site 6, an ID-2A-surface course. Each tester repeated five tests in the same lateral position and the sequence was then shifted to a different position. The exact positions were measured by means of the tape switches (Appendix A, Section 1.3). All testers measured a similar lateral variation with much higher skid resistance at the left edge (Appendix C).

Aerodynamic Effects on Wheel Load

One skid tester with wheel load transducer was driven around the test track at different speeds, part in free rolling and part in skidding. Wheel load was recorded on a magnetic tape recorder. The tests were repeated with and without a spoiler at the rear of the trailer. With the spoiler, load on the test wheel increased up to 40 lb. (Appendix A, Section 6.3).

Effect of Road Roughness

Road roughness was simulated by fixing artificial bumps on test site 8 at 50-ft intervals. The test results are discussed in Appendix A, Section 11.1. Dynamic effects generally were found to have little influence on mean skid resistance.

Torque Calibration

Torque arm calibrations were made on skid testers No. 5 and No. 9 to verify proper functioning of their transducers and instrumentation. The results were compared with platform calibration and the differences were computed (Appendix A, Section 9).

Calibration of Watering System

The watering systems of two skid testers were recalibrated. One tester's flow rate was not proportional to speed and correct valve settings were determined to obtain the required flow rates at various speeds. The other tester had its original nozzle re-installed to determine whether or not it affected the calibration. The original nozzle was similar to that used in the second correlation, except that it had internal vanes. No significant difference was found.

Open Test Period

The test facilities were opened the second week after the correlation program to allow other testers to duplicate the tests on four surfaces. Afterward, the testers were given

Two testers (A and B), accompanied by the Penn State unit as control tester, repeated the program sequence of

TABLE 7

SKID NUMBER ABOVE ADJUSTED MEAN

	SKID NUMBER	
SITE	TESTER A	TESTER B
3	3.3	4.9
4	4.5	1.9
5	3.0	5.9
6	4.0	5.7

tests on four surfaces. Afterward, the testers were given a water-flow rate, force, and load calibrations.

These testers' results were examined and error sources similar to those revealed during the main program were diagnosed. They included:

a. Nonproportional water flow because of insufficient pumping capacity above 40 mph.
b. Speed measurement error of 8 percent.
c. Transducer hysteresis of 20 lb or more.
d. Procedural error of 25 percent in interpretation of skid data.
e. Load error of 2.4 percent.

Corrections for some of these errors were applied to the test data before correlation. Mean skid resistance obtained during the second correlation program was adjusted by the difference in the data of the control tester. Test results of testers A and B were compared with the adjusted means and were found to be high for both testers (Table 7).

The differences were much larger than those obtained in the main program. Some of the possible reasons are that a common watering method was not used, the calibrations were not so accurate, and skid number evaluations were made by the tester crews.

The data before corrections are not given in Table 7. The 25-percent procedural error would have added 5.5 SN on site 3 and as much as 16.5 SN on site 4. Speed errors were corrected by plotting versus measured, not nominal, speeds; and the corrected static wheel loads, as found in the calibration, were used. These two corrections happened to have opposing effects so that the results improved only slightly.

In the course of the correlation program and the following open test period, improper functioning of different skid tester components was encountered. Some of these malfunctions were corrected. A complete list is given in Appendix G.

CHAPTER THREE

INTERPRETATION AND APPLICATION OF RESEARCH FINDINGS

The preceding chapter discusses potential error sources in skid testing, which are common to all testers. Design or operating features peculiar to individual testers have not been treated, although they may be additional sources of error. To keep errors to a minimum, tester crews must maintain vigilance, strict observance of procedures, and close familiarity with the equipment and its operation.

Individual errors do not all add up; some are cancelled out. The total error in skid testing determines the precision and accuracy of the test results. The data obtained in the correlation program were analyzed, and the major contributing factors to the measurement error were identified. Occurrence of these factors was reduced by means of controlling conditions, counseling tester crews, and correcting data so that over-all accuracy was of the order of ±10 percent. The questions remain: Could a further reduction have been achieved? If so, why was it not?

Some further reduction in data spread probably could have been achieved if the initial spread had been smaller or if more time had been available. The fact that most of the skid testers were not in full compliance with the specifications in ASTM E 274 accounts for, at least in part, the large initial data spread.

ASTM E 274 is essentially a set of performance specifications. Some of these have been found to need revision and a review is recommended. However, once the specifications have been revised, compliance by all skid tester users becomes important. This is a prerequisite to better correlation in the future and for better accuracy in survey testing. No basic design changes are required on existing testers, the changes are mostly in auxiliary equipment and procedures. For new skid testers, especially those for use in survey testing, standardized design parameters should be considered. Standardization would reduce tester variability and would make correlation at the FHWA Field Test and Evaluation Centers (*5*) easier and would free their personnel for other tasks, such as improvement of procedures and training of operators.

Once skid testers have been correlated and close agreement has been achieved, the problem of retaining this performance in survey testing remains. High reliability of the equipment is crucial in order to have confidence in the measurements. To cover a state highway network, survey testing may start in early spring and continue through late fall. Neither the weather nor the pavement are stable over such a long period of time. Statistical tests will have to be applied for significance of test results relative to prescribed standards. Some methods of resolution have been proposed (*6*), but the final choice can be made only after such standards are formulated.

This chapter considers how precision and accuracy in skid testing can be estimated and improved. Based on the estimated tester precision, methods of determining the required number of tests and judging the test results are developed.

PRECISION AND ACCURACY IN SKID TESTING

In analyzing the precision of each individual tester in the correlation program, the basic measure of repeatability was the standard deviation in five repeat tests. Poor repeatability, or lack of precision, is caused by random errors. Systematic errors do not affect precision.

The accuracy of a skid tester depends on both its precision and the magnitude of the systematic error (*7*). The systematic error is defined as the difference between the true skid number and the mean skid number computed from several repeat tests by the particular tester. The true skid number is unknown and probably can never be ascertained. Instead, a best estimate is used, sometimes called the "limiting means" (*8*). In the present case, the mean of all test results by all testers was used as an estimate of the true mean.

Correlation is, therefore, a measure of the accuracy of individual skid testers. An implicit assumption is made when standard deviation is used as a measure of lack of correlation. This assumption is (with a sufficient number of skid testers participating) that the number of testers giving readings above the true value is approximately equal to the number of those reading below the true value. This is the justification for using the mean skid number measured by all the testers as estimate of the true mean.

The results of the analysis of variance showed, in all cases, that the differences between the skid resistance measured by several testers under presumably identical conditions were significant. Another way of stating this is to say that the systematic errors were much larger than the random errors. (Similar results were found in an informal correlation, Appendix A, Section 12.1.1.) Some error sources are constant, until corrected, although others may occur with varying frequencies. Incorrect calibration is an example of the former; straying off the wheel track, of the latter.

The imprecisions and inaccuracies found in the correlation program are the result of the combined effects of all the error sources. Repeated analyses of the data made it possible to break down the total error, identify several groups of error sources, and determine the contribution of each group to the total error. Further breakdown according to individual error sources was either impossible or would have required excessive effort.

REDUCING ERRORS IN SKID TESTING

Based on the results of this study, Table 8 gives a summary of the sources and magnitudes of errors in skid resistance measurement. Column 1 lists the error sources and classifies them as random or systematic. Column 2 lists the largest probable error in skid-resistance measurement associated with the particular source. This column is not meant to imply that errors of this magnitude are normally encountered. Columns 3 and 5 list error bands of the source and of their effects on the skid-resistance measurements. Where possible, numerical values have been attached to these bands based on the experience gained in the correlation program. The reductions in error bandwidth from column 3 to column 5 are believed to be attainable by improved procedures. Some of these estimates have been verified by the correlation program. Column 4 lists the recommendations for corrective action. Comments keyed to the numbers of column 1 are:

1. Being off-speed causes a random error depending on the skid-resistance speed gradient. Speed holding can be improved by the use of a speed-deviation indicator (Appendix A, Section 1). Incorrect speed measurement causes a systematic error. Correct by use of better equipment and calibration.

2. Temperatures change slowly and, therefore, do not affect precision (except possibly when local tire heating occurs as a consequence of repeated wheel lock-ups). To correct for temperature effects, correction factors must be determined and may differ with pavement type (Chapter Two, "Correction Applied to Test Results"). Temperature correction, however, is justified only if skid resistance and temperature measurements are highly reliable.

3. Water discharge characteristics and incorrect calibration of flow rate may cause systematic error. Dynamic effects on nozzle discharge or loosely mounted nozzles may cause random errors. Use uniform watering system and calibrate to specifications (Appendix A, Sections 3.2 and 3.3).

4. Skid-resistance variations across or along the pavement cause random errors. These may be reduced by better tracking. Decrease in skid resistance during repeat testing of the same pavement section causes systematic error; this error can be avoided by randomizing or corrected by control data (Appendix A, Section 4).

5. Tire variability, from changing tires, may cause a systematic error. This can be determined by comparison tests with old and new tires. Based on limited evidence, the variability in skid testing may be somewhat reduced by the use of radial tires. Use tires within specified range of wear and check them for uniform wear. Check inflation pressure with a reliable gage, which should be checked periodically (Appendix A, Section 5).

6. According to ASTM E 274, wheel load should be between 885 and 1,085 lb. This 200-lb range is too large and should be reduced. With the present ASTM E 249 test tire, a range of 1,000 to 1,100 lb could be specified. Should a new test tire requiring higher loads be adopted, the allowed range should not exceed 100 lb. In every case the actual wheel load should be determined with 0.5-percent accuracy and maintained constant (Appendix A, Section 6). Dynamic wheel load causes random errors that can be kept small by good tester design. Use smooth, low-profile tester body to reduce aerodynamic loading (Appendix A, Section 6.3). Select a suspension system having near-critical damping and with a natural frequency of about 1 Hz (Appendix H), which will reduce the duration of load shifts. Recording of wheel load introduces additional evaluation errors, but may be useful if used with electronic integration. For correlation purposes, corrected static wheel load should be used, unless all testers measure wheel load.

7. Instrumentation may cause random and systematic errors, depending on the type of instrumentation fault. Select reliable instrumentation, check it periodically, and observe recommended procedures. Resolution should be 10 lb per chart division (Appendix A, Sections 7 and 9).

8. Increase braking cycle to 3 sec minimum to allow for longer delay between lock-up and evaluation and for a minimum of 1.5-sec evaluation time. Specify tolerances on test speed and tracking as guide for acceptance or voiding of tests. (Appendix A, Section 8).

9. For recommended calibration accuracy, see Appendix A, Section 9. Perform torque calibration at least once a year and more often if malfunction is suspected. Platform calibration should be done weekly as well as whenever a tire is changed.

10. Both visual and electronic evaluation may cause random and systematic errors. Increase delay time to 1.5 sec after brake application to reduce effect of transients and evaluation time to 1.5 sec for increased accuracy (Appendix A, Section 10).

11. Direct effect of tester dynamics is negligible, although it affects skid number computation through load shifting. Maintain tester in good condition to avoid troublesome changes over long periods of time.

12. Maintain records of tester performance and update estimates of standard deviations.

Prior to the correlation program, an estimate was made of the combined effect of all error sources. It is clearly smaller than the sum of all errors and can be estimated by applying a theorem from statistical quality control (*9*). "Whenever it is reasonable to assume that the tolerance ranges . . . are proportional to the (standard deviations), such tolerance ranges may be combined by taking the square root of the sum of the squares." The standard deviation here is a measure of the precision of each factor. For small samples, "the sample range is a reasonably efficient substitute for . . . the estimate of standard deviation . . . (*10*, p. 2-6). The estimate of the combined error was updated in light of the experience gained in the correlation program and is given in Appendix A, Section 6.3. A comparison between the estimated and computed standard deviations is given in Table 9.

The estimates for the uncorrected conditions were too high for the single tester and too low for a group of testers. Evidently random errors were overestimated and systematic errors underestimated.

Two measures of computed standard deviations are shown, both derived from an analysis of variance (see Chapter Two). s_T was defined as the standard deviation

TABLE 8

SUMMARY OF FACTORS IN SKID RESISTANCE MEASUREMENT

ERROR SOURCE: RANDOM	SYSTEMATIC		MAXIMUM EFFECT	AVERAGE ERROR BAND: FACTOR	AVERAGE ERROR BAND: SKID RESISTANCE	CORRECTIVE ACTION	REDUCED ERROR BAND: FACTOR	REDUCED ERROR BAND: SKID RESISTANCE
X		Speed holding (1) *	At 40 mph ±1.2 SN per mph	±2 mph	±1.5 SN	Speed deviation indicator	±1 mph	±0.8 SN
	X	Speed measurement (1)	Same	±5%	±1.5 SN	Fifth wheel and a) tachometer-generator b) pulse-generator	a) ±2% b) ±0.5%	a) ±0.8 SN b) ±0.2 SN
	X	Water temperature (1)	Negligible					
	X	Air temperature (2)	Indirect effect through pavement and tire temperature.					
X		Pavement or tire temperature (2)	±4%/10° F	Depends on season and geographical region	±2%/10° F	Correction requires accurate skid resistance and temperature measurement		±1%/10°F
X	X	Water film (3)	±1 SN for ±10% variation	±25%	Negligible on most pavements, on some ±2.5 SN	Specify calibration method, reduce tolerance to ±5%	±5%	Negligible on most pavements, on some ±1 SN
	X	Water flow (3)	Strong	Large		Uniform watering system, calibrated flow rate proportional to speed		Negligible
X		Pavement variability, (4) lateral	10 SN	15 in.	±4 SN	Operator awareness	5 in.	±2 SN
X		Pavement variability, (4) longitudinal	7 SN in mile		±2 SN	Number of samples (wheel-locks) per test based on standard deviation of tester		±2 SN
X		Conditioning and deterioration (4)	4 SN per day		−2 SN	Run control tests, randomize test sequence, correct data		−1 SN
	X	Tire variability (5)	2.5 SN		±1 SN	Check before use		±0.5 SN
	X	Tire construction (5)	2 SN		±1 SN	Belted tire		±0.5 SN
	X	Tire condition (5)	Within wear range 1 SN		±1 SN	Check for uniform wear		±1 SN
	X	Inflation pressure (5)	1 SN in operating range	24 to 28 psi	1 SN	Use reliable gage		1 SN
	X	Wheel-load error (6)	% SN error equal to % weight error	±2%	±2%	Use scale of minimum resolution of 5 lb	±0.5%	±0.5%
	X	Wheel-load range (6)	1 SN/100 lb	880 to 1080 lb	2 SN	Reduce range		1 SN

TABLE 8 (Continued)

ERROR SOURCE RANDOM	SYSTEMATIC		MAXIMUM EFFECT	AVERAGE ERROR BAND FACTOR	AVERAGE ERROR BAND SKID RESISTANCE	CORRECTIVE ACTION	REDUCED ERROR BAND FACTOR	REDUCED ERROR BAND SKID RESISTANCE
X		Dynamic wheel-load change (6)	2 SN		±1 SN	Avoid aerodynamic loads, wheel-load recording with electronic evaluation		±0.5 SN
X	X	Instrumentation (7)	Drift		10% or more	Reliable instrumentation, observing operating procedure		±1%
X	X	Operating procedure (8)		Controls other error sources		Follow correct procedure		
	X	Torque calibration (9)	Negligible			See procedure		±0.5% (±2 lb)
	X	Platform calibration (9)	±10%		±4.5%	See procedure		±2% (±5 lb)
X	X	Data eval.: (10) Operator	±5 SN		±3 SN	Adequate resolution, correct operating procedure		±1 SN
	X	Braking cycle	±2%	Minimum cycle 2 sec	±2%	Optimal filtering increase interval	Minimum cycle 3 sec	±1%
X		Dynamics (11)	Negligible direct effect					
		Statistical control (12)		Repeat tests		Estimate standard deviation of tester, determine number of repeat tests	Repeat tests	

* Numbers indicate corresponding sections in Appendix A.

among skid testers, and s_A as the standard deviation in skid testing. The latter includes interactions of skid testers and pavements and can also be computed from the definition of variance:

$$s_A^2 = \frac{1}{n-1}\left[\Sigma\, \mathrm{SN}^2 - n(\overline{\mathrm{SN}})^2\right]$$

The reductions in standard deviations, discussed in Chapter 2, are summarized in Table 10 for both s_T and s_A.

CONFIDENCE CRITERIA FOR A SKID TEST PROGRAM

Previously precision and accuracy were discussed, and it was concluded that lack of precision results from random errors and lack of accuracy from systematic errors. Individual error sources have also been discussed and classified.

Systematic errors are present when results of skid tests that are conducted under identical conditions by two or more skid testers, or by a single tester in successive tests, differ significantly. A difference is considered significant when it exceeds the statistical limits ascribable to random errors, which will be discussed later. To correct for systematic errors, the error source should preferably be eliminated or a correction factor can be applied to the data.

TABLE 9

ESTIMATED AND COMPUTED STANDARD DEVIATIONS

TEST CONDITION	STANDARD DEVIATION COMP. s_T [a]	COMP. s_A [b]	EST. s [c]
Single tester, five repeated tests:			
Uncorrected	—	1.43	4.1
Corrected	—	1.12	1.7
Correlation program:			
Uncorrected	4.08	4.96	2.9
Corrected	1.04	1.60	1.3

[a] s_T^2 is tester variance.
[b] s_A^2 is skid testing variance.
[c] See Appendix I.

Statistical treatment of data *cannot* correct for systematic errors.

Random errors are evidenced by a large data spread and can be recognized by analyzing the data of a single tester. Such errors can be reduced in part by eliminating error

sources but cannot be avoided altogether. Statistical methods should be used to establish the precision of the test results. It must be emphasized that precision alone does not assure accuracy (i.e., reliable information). To obtain reliable skid data, a skid tester must be checked at regular intervals against a standard tester. If, between such correlations, changes in precision occur, a change in accuracy may also be suspected and the tester should be rechecked against a standard or other reliable tester.

This section presents a statistical method that can be used in planning a skid test program. Obviously other inputs, not discussed here, are needed for a complete test program. The method outlined here gives an objective measure of confidence that can be attached to the test data and also checks the validity of the estimate of the standard deviation. It can be used in different ways, as will be shown, and is equally applicable to inventory testing, to a correlation program, and to a research project. It is especially important in inventory testing for which, unlike correlation and research testing, no other data for comparison are available.

Precision in skid testing can be improved by increasing the number of tests per test section. ASTM E 274 specifies "at least five determinations of the skid resistance . . . in each test section." To show how the confidence in the test results depends on the number of tests, two statistical measures (*10*, pp. 1-11 to 1-14) will first be defined.

A *confidence interval* is an interval within which a given population parameter is contained. In this case, it is a measure of the largest probable difference between the mean skid number of a small number of tests and the mean skid number that theoretically would be obtained in an infinite number of tests.

The *statistical tolerance limits* for a given population are the limits within which a stated proportion of the population is contained. In this case, these limits contain the largest spread of individual data points explainable by random errors.

Generally the confidence interval is a function of the standard deviation divided by the square root of the sample size. When an estimate is used for the standard deviation, a probability is associated with the confidence interval (*11*). To find the sample size for a prescribed confidence interval, a confidence coefficient and probability must be selected.

Statistical tolerance limits also depend on the choice of the confidence coefficient and probability. The limits are given by $\pm K_s$ where s is again the estimated standard deviation; the factor K, found in Table A-6 of Reference (*10*, pp. 1-11 to 1-14) is a function of the sample size n and approaches a finite value as n goes to infinity. In this presentation a confidence coefficient and probability value of 0.9 was selected.

The confidence interval can be used to determine the number of tests required for a desired accuracy or, conversely, to find the accuracy of test results obtained with an arbitrarily selected number of tests. In both cases, some estimate of tester standard deviation must be available. Chapter 2 shows the standard deviation of all testers in the correlation program to be between 1.0 and 1.5 SN, after all corrections had been applied. Thus, a standard deviation of 2 SN may be a good starting point if no other estimate is available. This should be considered the largest acceptable value and actual estimates should be made as sufficient data become available. To this end it is advisable to maintain a record of variances for every set of test data and compute means at specified intervals. Means may be taken over all variances or separately for each pavement type, etc., but should be based on no less than 20 data sets. From these mean variances, the standard deviation can be computed and updated. As procedures improve and operators gain experience, it should decrease. A standard deviation of 1.0 SN on a pavement of medium skid resistance should be the goal. Increasing standard deviation is an indication of lack of control and calls for corrective action.

Figure 12 shows sample size plotted for confidence interval and tolerance limits. One curve in Figure 12 shows the required sample size to ensure with 90-percent probability that the confidence interval for the mean (skid number) having a confidence coefficient 0.9 will be shorter than a specified interval. This interval goes to zero as sample size goes to infinity because, by definition, it measures the difference between means of finite and infinite sample size. The other curve shows the sample size required to contain 90 percent of the (skid) measurements with 90 percent confidence within the tolerance limits. These limits approach a constant value as the sample size increases. The scale of confidence interval and tolerance limits is in units of standard deviation.

The above statements can best be clarified by a theoretical example. Assume that the standard deviation of a skid tester is 2 SN and the skid resistance of a pavement section is to be measured. Skid resistance is computed as the mean of a number of skids, and the larger this number the more confidence can be attached to the mean (assum-

TABLE 10

REDUCTION IN STANDARD DEVIATIONS WITH CORRECTIVE MEASURES[a]

CORRECTIVE MEASURE	STANDARD DEVIATION	
	s_T [b]	s_A [c]
Testers in as-arrived conditions	4.08	4.96
Data evaluation procedures corrected	3.25	3.99
Uniform watering nozzles and tires mounted	2.83	3.51
Force and load calibration	1.53	2.41
Correction for zero drift	1.24	1.71
Correction for temperature differences	1.04	1.60

[a] Based on 15 test sequences by 11 skid testers on 4 test sites at 4 speeds for a total of 1200 skids.
[b] s_T is the standard deviation of skid testers, including operators and procedures.
[c] s_A is the s_T plus interaction factors between skid testers, pavement, and speeds.

ing the pavement does not change during testing). For reasons discussed in Appendix A, Section 12, only a small number of skids can be made. How many skids need be prescribed when it is desired that the mean of the measurements be within ±1.5 SN of the mean of a large number of skids? The answer can be found from the confidence curve in Figure 12.

Enter the graph at 0.75 (1.5 SN divided by the standard deviation of 2 SN) on the horizontal scale and travel up the vertical line to the point of intersection of the vertical line with the confidence interval curve. This leads to $n = 10$ on the vertical scale. We now have 90-percent probability that the mean of 10 measurements will be at most 1.5 SN off the pavement mean, which would have been found by a large number of skids by the same tester. Following now the horizontal line at $n = 10$, its intersection with the curve of tolerance limits gives a horizontal scale value of 2.5. Thus, for a standard deviation of 2 SN there exists 90-percent probability that 9 out of 10 tests will be within ±5 SN (2.5 times the standard deviation of 2 SN) of the mean.

A second example assumes a sample size of 5, the standard number of tests per test section. Figure 12 is used to find the confidence interval and tolerance limtis by entering the graph at $n = 5$ on the vertical scale. The horizontal line intersects the two curves at 1.25 and 3.5, which, for a standard deviation of 2 SN, gives a confidence interval of ±2.5 SN and tolerance limits of ±7 SN. These figures may be too large where pavements with marginal skid resistance are concerned. Instead of running the same number of tests on all test sections, run an increased number of tests on marginal pavements and a decreased number on pavements of high skid resistance, which does not affect the total number of tests made. Use of the proposed method may actually reduce the total effort in inventory testing (*6*). With a standard deviation of 2 SN, more than five tests per test section will be needed only if the measured mean skid number is less than 2.5 SN above the required minimum skid resistance. Three measurements are sufficient for any pavement whose skid resistance is 5 or more SN above the required minimum. With a standard deviation of 1 SN, these values are halved to 1.25 and 2.5 SN, respectively.

The required accuracy may be selected while planning the tests, based on previous test results on these test sites, or it may be left to the operator and based on the first test in each test section. The mean skid resistance can then be reported with a known confidence (at the given probability), provided that the selected percentage of data points are within the tolerance limits (in the example, 9 out of 10 points should be within ±5 SN of the mean). If the percentage of data points outside these limits is larger than specified, it may mean that the estimate of the standard deviation was too low or the selected test section is not sufficiently uniform. In the latter case, the test section may have to be broken up into smaller sections of better uniformity. The choice of a test section requires judgment and will depend on local conditions, but it should be as uniform as possible.

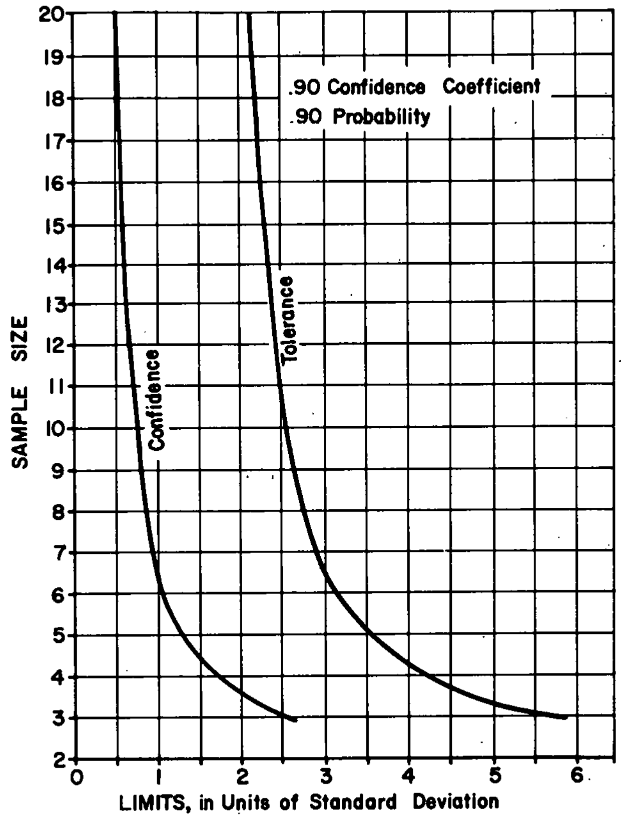

Figure 12. Confidence limits for mean of given sample size and tolerance limits for percentage of sample.

To summarize the use of Figure 12, the confidence curve is a measure of the precision of the mean skid number; the tolerance curve is a measure of how far the individual data points may spread within the sample. Both intervals are proportional to the standard deviation, and the only way of reducing them is to reduce the standard deviation. No inference about accuracy can be made from these measures, that is, they give no information whatsoever of how far our mean is from the true mean, if that were known, or from the mean any other tester might measure. Inaccuracy depends on the combined effect of all systematic errors and can be determined only through correlation or through comparison with a standard tester.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

All major factors that can affect pavement skid resistance and skid-resistance measurement have been scrutinized and their roles in skid testing determined. Many sources of information and prior experience were supplemented with experimental work and computer simulation. A representative sample of skid testers was inspected and observed in operation. In a correlation program 12 skid testers performed a large number of tests under controlled conditions. Significant improvements in correlation were achieved through corrective measures, applied while the tests were in progress. Tester performance was analyzed in detail. The following conclusions are based on careful consideration of all available evidence.

All test conditions, except temperature, are amenable to control within limits and, by tightening control, skid tester correlation can be improved. Inadequate or poorly implemented procedures for calibration, operation, and data evaluation are the primary causes for poor repeatability of skid-resistance measurements and for discrepancies between the results of different testers. Correct procedures must be established and adhered to. Generally operators are not involved in devising procedures and are frequently unaware of their importance and the reasons behind them. Attention to the problem of operator training and qualifications will probably give the best return on the investment for improving skid tester performance.

Another observation worth noting is that most of the skid testers seen during the course of this project were not in full compliance with the specifications of ASTM E 274. Noncompliance with specifications introduces unknowns that can affect correlation. An item by item review of these specifications, in light of the findings of this project, shows that they are on the whole well-founded and realistic. Some changes are recommended and are summarized in Table 11. Strict adherence to specifications will contribute to better correlations in the future.

Tester dynamics have not been found to have a direct effect on skid-resistance measurement and, therefore, no constructional changes on existing equipment are required. Support equipment such as the watering system, speed-measuring system, and instrumentation do affect performance and should be improved on nearly all existing skid testers.

Skid tester performance can be measured in terms of precision and accuracy. Precision is a measure of the repeatability of a single skid tester and depends on the magnitude of random errors. Accuracy is a measure of correlation among skid testers and depends on the magnitude of systematic errors. An analysis of variance performed on skid data taken during the correlation program leads to the conclusion that the precision of the testers, although not satisfactory, is generally better than their accuracy.

MEASURES FOR REDUCING ERRORS IN SKID TESTING

This is a summary of recommended measures whose implementation will improve accuracy in skid testing. Numerical specifications can be found in Tables 8 and 11, and a detailed discussion is given in Appendix A. These, together with ASTM E 274, should be used when preparing specifications for design or procurement of new testers. This is not a complete set of specifications, rather it is a supplement to ASTM E 274 and treats only those items that have been shown by recent experience to need amplification or revision. It is hoped that these recommendations will be considered when the method is reviewed.

Equipment

All instrumentation should be of high-quality and be stable for at least 24 hr. Resolution of readout and recording equipment should be 0.5 percent or better. Electronic integrators, either installed on the tester or using taped information, are highly recommended. Specifications and procedures for electronic integrators are urgently needed.

For improved accuracy in tester speed measurement and speed holding, fifth-wheel driven systems having speed monitor devices that indicate to a driver a departure from the selected speed are recommended. Speed should always be recorded and evaluated in the same way as other skid test data.

A standardized pavement wetting system should be adopted. The method described in Appendix A, Section 3, has proven reliable and can serve as the basis for a standard pavement wetting system. The total system flow rate should be determined with ±2-percent accuracy. The range of 24 to 30 gpm is based on the ASTM E 249 test tire and may have to be changed for another tire.

It is recommended that the test wheel load should be changed to 1,100 + 0 − 100 lb for the current ASTM E 249 tire. Testers should have low and smooth profiles to minimize aerodynamic loading, which should not be disturbed by the addition of flags, signs, etc. Trailer suspension should have close-to-critical damping, such that 90 percent of excursion amplitude will decay within 1 sec.

Calibration

All calibration procedures should be standardized. Those discussed herein can serve as the basis for developing calibration standards and, in the interim, can be used as guidelines.

In torque arm calibration (Appendix A, Section 9.2), the over-all accuracy shall be ±0.5 percent or ±2 lb (equivalent friction force), whichever is smaller. In plat-

TABLE 11

SUGGESTED CHANGES TO ASTM E 274 SPECIFICATION

PARAGRAPH	RECOMMENDATION [a]
3.2.1 Braking System	Change the second sentence to read: "The brake system shall be capable of locking the wheel *within 0.5 s on any wetted pavement* at the conditions specified in 3.1 . . .
3.2.2 Wheel Load	Change the equal static load figures from 1085 +0−200 lb to *1100+0−100 lb* (and metric equivalents) Add new sentence *"Recalibrate when changes are made."*
3.3.1 General Requirements for Measuring System	Change over-all system accuracy limit from ±3 percent of full scale to ±2 *percent or ±5 lb (equivalent friction force), whichever is smaller.*
3.3.5 Vehicle Speed-Measuring Transducers	Change the second sentence to read: "Output *from the tachometer should be a speed deviation indicator (±0.5 mph or better resolution at set speed)* directly viewable by the operator and be simultaneously recorded."
3.4.1	Change third sentence to read: "All signal conditioning and recording equipment is to be capable of providing linear output, and shall allow *0.5* percent data reading resolution."
3.4.2	Change last sentence to read: "The calibration signal shall be recorded *and be at least 50 percent of full scale.*"
3.5.1 and 3.5.2	Revise these paragraphs on the basis of the findings given in Appendix A of this report, with particular respect to Section 3, Pavement Wetting.
5.1 Speed	Revise this paragraph on the basis of the findings given in Appendix A of this report, with particular respect to Section 1, Par. 1.3.2, Speed and Lateral Placement.
5.2 Skid Resistance Force	Revise this paragraph to outline separate standard methods for torque arm calibration and platform calibration on the basis of the findings given in Appendix A of this report, with particular respect to Section 9, Calibration of Skid Testers.
(5.3) [b]	Add new paragraph to read: "5.3 Check test wheel load with ±0.5 percent accuracy whenever tractive force is calibrated.
6.3 Skid Resistance of a Test Section	Revise paragraph on the basis of the findings given in Chapter Three of this report in the section "Confidence Criteria for a Skid Test Program."
6.5 Test Speeds	Delete last sentence and substitute: *"Maintain all test speeds within ±1 mph."*
7.1	Revise last two sentences to read: *"Not sooner than ±0.5 s* after beginning of the water delivery, apply the test wheel brake to lock the wheel completely. Allow the brake to remain applied for at least *3 s after brake application.*
7.3.2	Revise first sentence to read: "Evaluate the trace from a point of *1 s after wheel lock-up or 1.5 s after brake application* to a point *3 s* after brake application.
(7.3.3) [b]	Prepare specifications and procedures for use of electronic integration of skid-resistance data on the basis of the findings given in Appendix A of this report, with particular respect to Section 10, Data Evaluation Procedure. Add new paragraph to read: "7.3.3 Use procedure in 7.3.2 for wheel load record evaluation."
9.1	Revise this paragraph on the basis of the findings given in Chapter Three of this report in the section "Confidence Criteria for a Skid Test Program."
10.2.11	Revise first sentence to read: "Average skid number for test section and speed at which reported average was obtained; *also mean skid number, confidence limits, and number of tests.* (Highest and lowest values entered into the average may also be reported; . . . .)

[a] Italics indicate new or revised wording.
[b] Additional section recommended.

form calibration (Appendix A, Section 9.3), the over-all accuracy shall be ±2 percent or ±5 lb (equivalent friction force), whichever is smaller. The latter calibration shall be done weekly as well as whenever a tire is changed.

Test wheel load should be determined with an accuracy of ±0.5 percent and kept constant. It should be rechecked during platform calibration.

To calibrate the watering system, the nozzle position

should be adjusted for a ±5-percent accuracy of flow rate per wetted width (Appendix A, Section 3.2).

Speed should be calibrated on a level tangent of about 200 ft with a ±1.0-percent accuracy.

Operating Procedures

The time from brake application to release should be increased to a minimum of 3 sec to accommodate the recommended increased intervals for data evaluation (see following section, "Data Evaluation"). The total test cycle should be increased accordingly and the watering cycle should begin not less than 0.5 sec before brake application.

Depending on the desired accuracy in determining the mean skid number of a pavement section, the number of tests per section should be selected by the procedure described in Chapter Three, "Confidence Criteria for a Skid Test Program."

Field checks of instrument zero and gain calibration, and adjustments when needed, should be done by the operator following strict procedures (Appendix A, Section 8). Before recording data, several dummy skids should be made for preconditioning and zero and calibration rechecked.

During a test the driver should be able to concentrate on speed holding and tracking. The procedures should specify the permissible speed and tracking errors, and tests outside these tolerances should be voided.

Between correlations with standard or other testers, no changes should be made on the tester that may affect static or dynamic wheel load.

Data Evaluation

It is recommended for both visual and electronic averaging of friction (and wheel load where applicable) signals to allow 1.5 sec after brake application and to average from this point for at least 1.5 sec. The mean force or torque should be scaled relative to the static zero or calibration signal (Appendix A, Section 8). Compute skid numbers and compare the spread of data from a pavement section with the predicted spread (Chapter Three). If 90 percent of the data is within tolerance limits, report the computed skid numbers, the mean skid number, and confidence limits. If more than 10 percent of data points is outside the tolerance limits, additional tests are needed for prescribed confidence limits, or confidence limits must be broadened. Evaluate test speed and report for each skid number.

If temperature corrections are considered necessary in a particular test program, a correction factor must be determined using Appendix A, Section 2.3, as a guide. To correct for speed errors, the gradient at the speed on the particular pavement must be known. Both temperature and speed corrections should be attempted only if the data are of acceptable accuracy.

Operator Training

The recommendations discussed require well-trained, motivated operators. Error sources in skid should be discussed in training and an operator should be taught how he can minimize many of them.

General Recommendations

As a means of implementing and extending the findings and recommendations of this project, the following actions are suggested:

a. Review ASTM E-274 with the view toward incorporating the specific changes and additions shown by this project to be desirable and beneficial.

b. Design a standard skid tester in strict conformance with the requirements of the thus revised ASTM E 274. This design should be acceptable to FHWA and other agencies for all routine survey and policing work. If the standard tester eventually supplanted, except for research, the multitude of types now in use, the correlation problem would be much simplified. Even more importantly, detailed calibration and operating procedures could be universally employed and enforced because peculiarities of individual designs would no longer require special procedures. In this event, the FHWA Field Test and Evaluation Centers would not have to devote their capabilities and facilities for diagnostic work, but could apply them fully to calibrating testers and to training operators. With a standard tester design and the prescription of rigid operating procedures, operator ability and skill would remain the last uncontrolled major error sources.

c. Ideally testers are calibrated dynamically, which requires standard surfaces. Their design and cost should be such that they can be feasibly installed at least at the home base of each tester. There may be a need for primary and secondary surfaces because all surfaces are subject to wear and other causes of variations.

d. In improvement programs, incremental steps generally show progressively lower cost effectiveness; this is true for the accuracy and precision of skid-resistance measurements. On the other hand, there are limits to the cost-benefit ratios of the requirements for routine and compliance tests. Further investigation is recommended to determine the point (or points) beyond which further refinement of the measurement process is not warranted. These would provide the basis for optimum utilization of resources in the attainment of quantitatively defined objectives.

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APPENDIX A

FACTORS IN SKID TESTING

Skid resistance of a pavement is not an absolute value but depends on the conditions during the test and the method of testing, the latter being that specified in ASTM E 274. Some of the test conditions can be controlled to within specified limits, others cannot. For example, speed during a test is measured and a driver tries to maintain a prescribed speed. A desired water flow rate is obtained by periodic calibration, though no adjustment can be made during a test. Temperature cannot be controlled in the field; it can at best be measured and recorded. Other conditions, such as location of wheel track and contamination of the pavement, can only be rated subjectively by the operator because no means of measurement are available.

To compensate for varying conditions, test data can, in principle, be corrected for deviation from standard. This, however, implies capability for reliable measurements and availability of correction factors. Reliability of measurement is a prerequisite for controlling conditions or for correcting test data when control is impossible or inadequate. In order to achieve better agreement in skid-resistance measurements and take account of the test conditions, uniform methods of measurement and calibration are needed. These factors, and others, and their effects on measured pavement skid resistance are further discussed in detail.

1. SPEED

1.1 General

Two aspects of speed discussed in this section are (a) speed control, i.e., maintaining the desired speed, and (b) speed measurement, i.e., accuracy of speed measurements. Skid resistance of wet pavements generally decreases with increasing speed. The rate of decrease varies and, for a given tire, is mainly a function of pavement type. Figure A-1 shows test data from four different sources; each point represents the mean skid resistance of several tests and pavements. The West Virginia data have been plotted in two groups: one of skid resistance-speed gradients above the mean gradient; the other, below. Table A-1 gives the corresponding average and maximum gradients for speeds of 20 to 70 mph. These gradients are believed to be representative of a large majority of pavements. Deviation from the desired test speed will cause a measurement error proportional to the gradient.

In skid testing the actual test speed varies, for reasons to be discussed, from the nominal speed; and this discrepancy is one of the error sources in skid-resistance measurement. Figures A-2 and A-3, which were adapted from the speed record of sets of typical skid tests, show distributions of test speeds about nominal speeds. In these tests the test speed was off by 1 mph or more in every second test, and by 2 mph or more in every fourth test.

Because the speed error is approximately the same at all speeds although the gradient is larger at the lower speeds, the error in skid-resistance measurement resulting from speed errors is also larger at the lower speeds. For this reason skid testing below the standard speed of 40 mph should be done only where conditions so dictate. Testing above the standard speed would be preferable, provided the watering system and other factors are adequate for higher speeds.

1.2 Control

Speed control errors result from inability to maintain a desired speed; this deviation is measured and recorded by the speed-measuring system. If the towing vehicle is underpowered, the remedy is obvious. Assuming sufficient power, a skilled driver can normally maintain a prescribed speed within ±1 mph, provided he is alerted to any speed error before it becomes too large. Regular speedometers and electric speed indicators do not have sufficient resolution and are not easily and accurately read fast enough to aid the driver in taking instantaneous corrective action.

The speed control function can be regulated by the use of a commercially available, vehicular automatic speed control device. However, experience with these in skid testing has generally been unsatisfactory because (a) the devices by design operate with steady-speed errors (slow going upgrade and fast going down), (b) they lack the

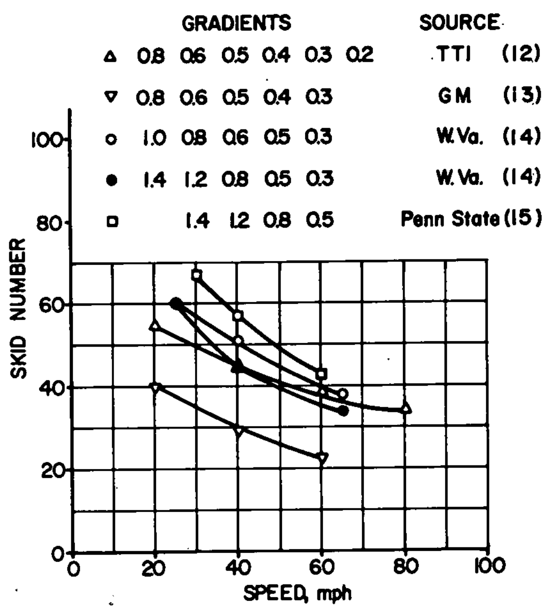


Figure A-1. Mean skid-resistance values from several independent groups of experiments, each group involving several pavements.

TABLE A-1
SKID RESISTANCE-SPEED GRADIENTS

TEST SPEED (MPH)	GRADIENT (SN/MPH) AVG.	MAX.
20	1.0	1.4
30	0.92	1.4
40	0.72	1.2
50	0.52	0.8
60	0.34	0.5
70	0.20	0.2

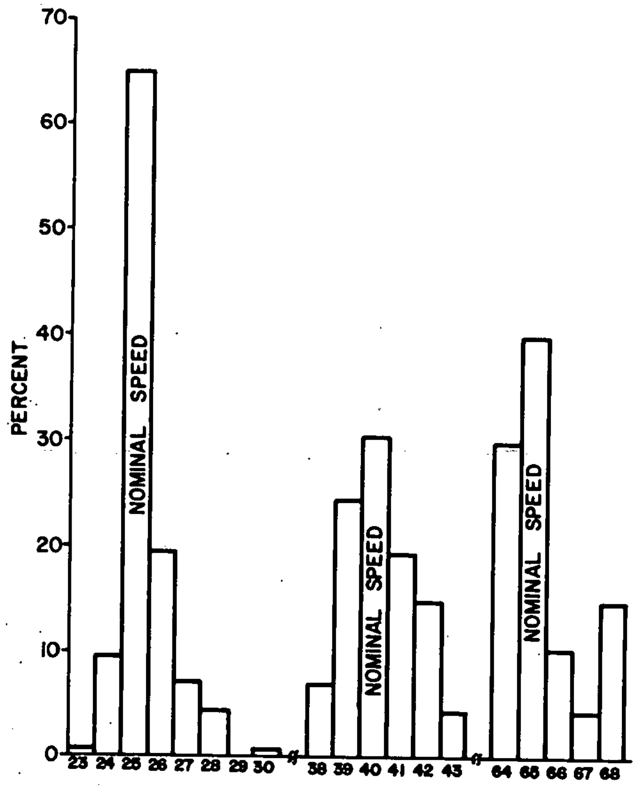


Figure A-2. Test speed variations of one tester.

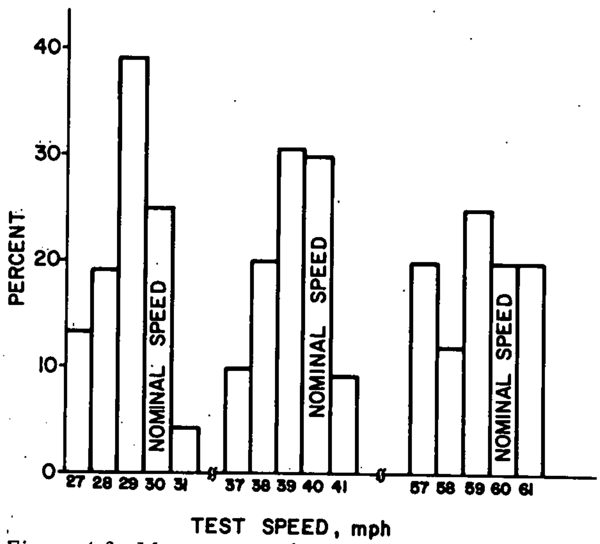


Figure A-3. Mean test speed variations of six testers.

human operator's ability to anticipate disturbances due to changes in grade and lock-up of the test wheel, and (c) none can control speed with the desired accuracy of ±1 mph.

1.2.1 Monitor Design Criteria

The design of a speed monitor for use by the driver of a skid test vehicle should take into account both the human factor and the control requirements imposed by testing. The suggested design criteria require that:

a. Speed information should be provided by other than visual means. Skid tester operation involves far more visual observation than just that required for driving. Testing in heavy traffic while maintaining constant speed frequently leads to run-up on vehicles ahead in a manner that would be avoided in normal driving. For safety and proper control of all factors, the driver should not be required to continuously shift his vision. He needs a readily and accurately recognizable speed deviation signal that creates only minimum distraction from the driving task.

b. Speed information should be provided continuously. Aside from the psychological aspect of positive reinforcement, null zones and deadbands should be avoided for better control and less fatigue.

c. Speed error should be easily assimilated. The direction of the speed error must be obvious and the sensitivity must be high such that errors of only a fraction off the acceptable limits may be recognized.

d. Speed error limits should be clearly distinguished. Since speed control within 1 mph is desired in skid testing, speed excursions beyond this limit should be made obvious to the driver and operator. This has the additional advantage of giving immediate indication when a repeat test may be desired.

A review of the commercial market yielded only one nonvisual speed monitor adaptable to this application. This device, the "MDSH Toneometer," has been employed as an audio speed monitor on road profilometers. It includes a visual indicator and also generates a high or low tone depending on error direction, the amplitude (or loudness) of which is proportional to error magnitude. This device, however, gives no signal either at the desired speed or within its close range. A continuous signal is considered necessary for skid tester application because various background noises incidental to skid tester operation make the variable loudness mode uncertain and the speed error limits difficult to detect.

1.2.2 Penn State Audio Speed Monitor

To fulfill the need for a continuous signal mode, a more suitable design was conceived and constructed to determine whether skid test performance could be improved by such an aid.

The monitor's mode of operation is a pulse-width modulation between a high and a low tone. The vehicle speed signal is obtained from the tachometer-generator of a conventional fifth wheel. A switch on the audio speed monitor selects the desired speed. The monitor is powered from the 12-volt system of the towing vehicle and includes in-

ternal voltage regulation. All solid-state construction allows instant activation of the signal, and a volume control permits its adjustments to the desired listening level.

When the test vehicle is moving at the selected speed, the monitor emits a continuous sound consisting of alternate periods of high and low tone. The periods are of equal duration and total approximately 1 sec. When the speed is slightly high or low, the high or low tone that corresponds to the error direction increases in duration while the other decreases proportionately. Hence, the tone in the direction of error dominates. The error sensitivity is set so that the pulse width of the subordinate tone goes to zero as the error reaches 1 mph. The disappearance of the second tone indicates to the driver and operator that the test speed conditions are out of range. Experience with this operational arrangement indicates that the driver becomes aware of speed error less than ¼ mph, though reaction time and vehicle performance may not permit holding the speed as close as that.

The design also accommodates addition of indicator lights and provides error and out-of-range signals for recording, if desired.

Figure A-4 shows a speed performance comparison on a well-used test circuit with and without the audio speed monitor in operation. Driving this circuit with conventional means of speed indication, the experienced driver was on speed 48 percent of the time. With the monitor, this increased to 65.5 percent which might be interpreted as a 33 percent improvement. The error limit indication also produces a measurable reduction of tests in error by 2 mph.

This test represents a conservative measure of the improvement that can be realized in speed performance when the driver is provided with a suitable aid. The test circuit was very familiar to the drivers (the familiarity requiring less than usual attention to the driving function), and improvements in safety, staying in the wheel track, and peripheral benefits are not measured.

1.3 Measurement

Provided that speed is recorded (which is required by ASTM E 274)*, a speed error will be recognized during data evaluation and, in principle, could be corrected for then. The best way to correct for speed errors is to test at several speeds and plot the mean skid numbers versus the means of the actual speeds, where the mean speed for each skid is taken during the same interval in which the force signal has been averaged. Such tests should be spaced at least 10 mph apart and are best made at three different speeds. To illustrate the problem, Figure A-5 shows a plot of skid resistance (measured by two testers on the same site) versus speed.

The tests were to be made at 30, 40, and 60 mph, but Tester A was consistently below the nominal speed. In Part (a) of Figure A-5, the speed error was disregarded; in Part (b), the data were plotted versus the actual speeds and resulted in better agreement between the two testers. Repeat tests at several speeds, however, are impractical in inventory testing. In this case corrections for speed errors, if they are known, can be applied when the gradient for

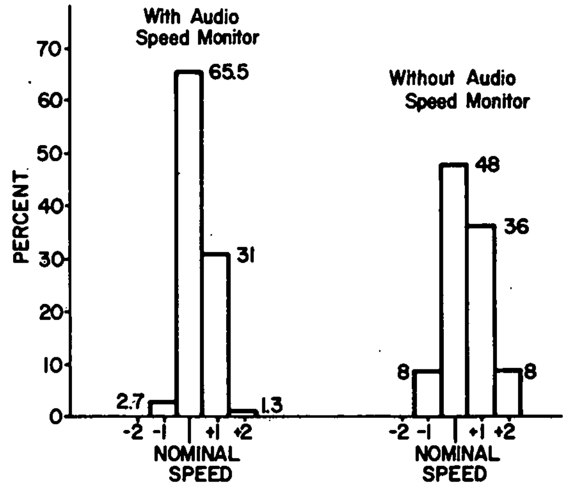


Figure A-4. Comparison of typical skid testing performance with and without the Penn State audio-speed monitor.

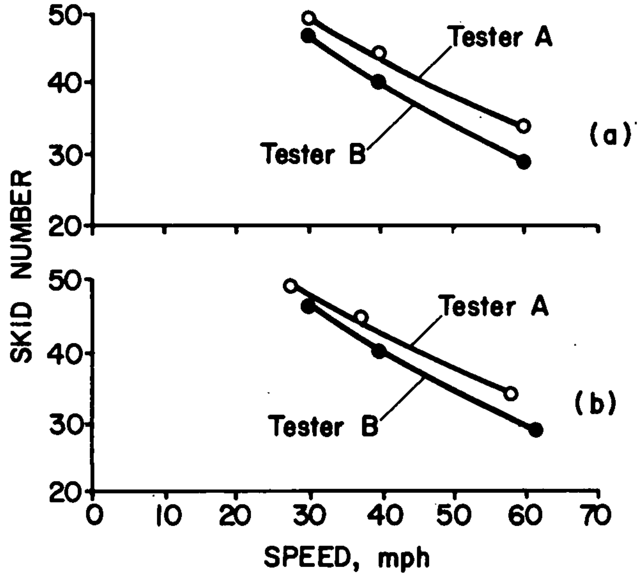


Figure A-5. Plottings of skid number versus nominal speed (a) and versus measured speed (b) (15).

a particular pavement at a given test speed is known or can be estimated from known pavement characteristics, such as texture.

A measurement error caused by a poor or malfunctioning speed-measuring system is not immediately recognized and, therefore, can cause unexpected and unexplainable results in skid testing. How accurate and reliable are the various speed-measuring systems? Those generally used are: (a) speed of towing vehicles; (b) tachometer-generator driven by towing vehicle; (c) tachometer-generator driven by fifth wheel; and (d) pulse generator driven by fifth wheel.

All four systems serve primarily to indicate to the driver actual vehicle speed. Skid testers using only the vehicle speedometer generally obtain no permanent record of test speed. Thus, any deviation from the nominal test speed is likely to go unnoticed, even when the speedometer is ac-

* ASTM E 274-70, par. 3.4.3

curate. The accuracy and reliability of speedometers are limited, however, and frequent calibration is necessary.

Not all error sources can be eliminated by calibration. The SAE Handbook (*16*) lists eleven factors that affect the accuracy of speed measurement. Two of these, design tolerances and the effects of tire construction, can be corrected for by calibration. The effects of centrifugal forces on the tire can also be eliminated if separate calibrations (on the road, not on dynamometer rolls) are made at each speed, and if it is taken into account that these effects also vary with tire wear. Factors that may vary despite calibration and their resulting errors are listed in Table A-2.

It is impossible to predict how these errors may combine. Tire wear and aging progress in parallel but have opposite effects. The greatest possible error would be 8 percent, but a more probable error is of the order of 5 percent. Wheel slip introduces an additional error, which becomes greater the lower the friction of the pavement or the higher the drive torque.

A vehicle-driven tachometer-generator is an improvement over the ordinary speedometer mainly because it can be connected to produce a permanent speed record. It is, however, subject to the same drive system errors as the vehicle speedometer, except that the wheel slip effects are eliminated if the generator is driven by a nondriving wheel.

Typical specifications for tachometer-generators list an accuracy of ±1 percent and temperature effects of 0.1 percent per 20 deg F. Thus a calibrated truck-driven tachometer-generator system will have a somewhat better accuracy than a speedometer. This advantage can be improved further by using a speed indicator of adequate resolution.

TABLE A-2

ERROR SOURCES IN A SPEED-MEASURING SYSTEM THAT VARY BETWEEN CALIBRATIONS (*16*)

FACTOR	MAXIMUM ERROR AT 60 MPH (%)
Drive System:	
Inflation pressure	+1 per 6 psi increase
Tire wear	+3 from new to worn
Tire aging	−1.5
Load	+0.5 for 20% increase
Speedometer:	
Temperature	+1.5 per 10° F increase
Vibration	+1.5
Friction	±0.5

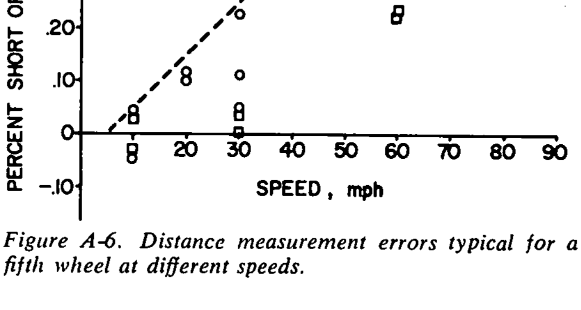


Figure A-6. Distance measurement errors typical for a fifth wheel at different speeds.

1.3.1 Accuracy of Fifth Wheels

A fifth wheel driving a tachometer-generator is capable of an over-all speed-measuring accuracy of ±2 percent, which is about the minimum acceptable accuracy in order to maintain the test speed within ±1 mph. This accuracy can be improved further by using a pulse generator in conjunction with an accurate time base. Tests have shown that an accuracy of ±0.5 percent can be achieved with such a system. Despite frequently observed wheel bounce, the measuring accuracy of a fifth wheel is high; inertia and low losses apparently keep the wheel speed constant during loss of ground contact.

One factor limiting the accuracy possible with fifth wheel speed-measuring systems is the mechanical performance of the wheel running on the pavement. Even though it is assumed that the rotational speed transducer and indicator can be made arbitrarily accurate and the device can be calibrated periodically to compensate for tire wear and aging, the wheel bounce, temperature, inflation pressure, bearing friction, and effective radius can vary during typical use. These variations limit the short-term repeatability and affect the speed dependence of the performance. Tests were conducted to determine the size of these errors by examining the number of tire revolutions per mile.

A commercially available fifth wheel was installed on the test vehicle. The wheel can be used to measure distance because its 5.28-ft circumference makes exactly 1,000 revolutions per mile. Accumulative revolutions are recorded on an electrical counter.

With the inflation pressure at its prescribed value, performance tests were conducted on the fifth wheel both after a short break-in period and after accumulating 5,000 miles of use. The wheel was traversed over a fairly straight and level stretch of highway several times at several speeds. The average of two runs at 10 mph was taken as the fifth-wheel reference mile. The reference miles in both cases were, respectively, 0.18 and 0.27 percent short of a mile measured with a tape measure.

The speed dependence of the fifth wheel is shown in Figure A-6. The repeatability at a given speed is indicated by the spread of data points and is within 0.25 percent at all speeds. Larger errors occur with increasing speed; but the trend indicates accuracy within 0.50 percent over all speeds of interest. This performance is thought to be typical of that expected of any properly maintained fifth wheel.

Speed-measuring systems rarely break down but they may drift. To guard against such drift, frequent calibration is necessary. According to Klaus (*17*), calibration with a stopwatch on a straight and level measured mile is preferable to dynamometer calibrations because the latter introduces errors caused by the curvature of the rollers under the wheels. It is difficult, however, to maintain a

constant speed for a full mile. Shorter calibration runs are preferable but require more precise time measurement than can be obtained with a stopwatch. Such a speed-measuring system was used in the correlation program and is described in the following section.

1.3.2 Speed and Lateral Placement (Correlation Program)

Reliable measurement of test speed was essential for conduct of the skid tester correlation program. An accuracy of 1 percent or better was to be achieved. It was also desirable to monitor lateral placement of the test wheel on the surface during the skid.

A portable speed and lateral placement monitor * was used for this purpose. Electrical sensing elements (contact switches) placed across the test section 200 ft apart (at both ends of each type of pavement surface) were connected by coaxial cables to the remotely located monitor containing the electronic circuitry and readouts. Passage of the front wheel over the sensing elements was used to start and stop crystal-controlled interval timers for speed measurements.

The accuracy in speed measurement was determined by the accuracy of the time and distance measurements. The crystal-controlled interval timer had a digital readout with resolution of 0.01 sec and accuracy of ±0.01 sec. At the shortest traverse time (2.73 sec at 50 mph), the timing accuracy was then ±0.37 percent and was proportionately better at the longer times associated with slower speeds. The sensors were placed at 200-ft intervals with nominal accuracy of ±0.5 ft, corresponding to a worst-case distance accuracy of ±0.5 percent. Hence, the worst-case speed measurement accuracy was taken to be ±0.87 percent.

Simultaneously, the monitor determined the lateral placement of the test wheel by measurement of resistance changes in the sensors and displayed this on panel-mounted meters. The monitor was used in an operational mode in which only the lateral placement of the test wheel was read out. With internal voltage and temperature compensation built into the monitor, and simple daily calibration checks, a nominal lateral placement accuracy of 1 or 2 percent was achieved. The sensors and the monitor operated without failure throughout the tests.

Since the tester operators were instructed to cover the entire width of the surface in testing, lateral placement limits were set up in addition to visual observations to determine when the test wheel had not properly stayed within the confines of the test surface, resulting in an invalid skid test.

2. TEMPERATURE

2.1 General

As with speed, skid resistance generally decreases with increasing temperature. In field tests, temperature can be measured and recorded, but it cannot be controlled. The questions to be answered are: (a) What temperatures should be measured? (b) How should they be measured? (c) How should the data be used?

To answer the first question, the relative effects of several temperatures on skid resistance must be known. These are: (a) tire temperature; (b) pavement temperature; (c) ambient temperature; and (d) temperature of water used to wet the pavement.

With the exception of the water temperature, which is uniform, fairly constant, and relatively easy to measure, these temperatures have no unique value and depend on measurement method and location—and, in the case of the tire, the instance of measurement.

To determine the effect of water temperature, skid tests on several pavements having water temperatures of 140 deg F and at 60 deg F, but otherwise identical conditions, were compared. The difference was about 1 SN (140 deg F, giving the lower values). Because water temperature in skid testing changes far less than the 80-deg temperature difference in these tests, this factor can safely be ignored.

To separate the effects of tire and pavement temperatures, laboratory tests were conducted on the Penn State circular-track apparatus (*18*). The standard ASTM tire was used and tire and track were independently heated—the tire with a radiant heater, the track with installed heating elements.

Temperatures were measured with flexible thermal probes (Section 2.1.1). Smooth and embossed steelplate surfaces represented extremes of pavement texture. Friction was measured at a constant slip of the test wheel. Figure A-7 is a plot of coefficient of friction as a function of tire tread temperature. It shows the slope to be negative in all cases and to decrease with friction level. If temperature affects friction by means of its effect on rubber properties, heating the tire should have a greater effect than heating the surface. This premise was confirmed by the results shown in Figure A-8. When the tire was heated by contact with the hot track, the heating was apparently more superficial than by direct radiant heating, and the effect on friction was less pronounced.

2.1.1 Instruments for Measuring Tire Temperatures

Two instruments were used throughout the project to measure tire temperatures.

Minco Model 100 B Thermal Indicator.—This instrument was used with resistance-type probes, Model SM 1064A, ½-in. square flexible thermal ribbons having 0.5-sec response, which were taped to the surface. Because of their flexibility, the probes can be brought into uniform contact with the surface and, because of their size, they measure a mean temperature over the area of contact. These were considered preferable to the point-type probes, which are often used for surface temperature measurements and which did not prove satisfactory in earlier work. A 12-station multi-point selector switch allows fast successive readings of several probes and was used in taking tire temperatures at up to 12 locations. The probe leads are easily broken during frequent handling and this was found to be the major drawback.

Barnes Infrared Thermometer Model IT-3, Sensing-Head Type A.—This instrument has two response modes and is

* Gillespie, T. D., "Vehicle Placement and Event Monitor." *Report S 68*, Automotive Research Program, The Penn State Univ. (1972).

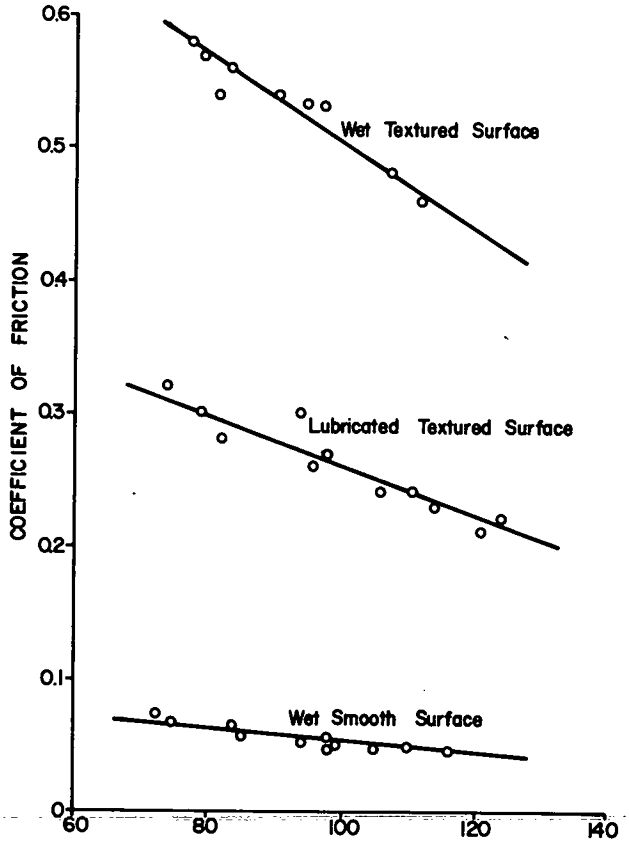


Figure A-7. Tire tread temperature effects on friction using heated tire on circular track apparatus.

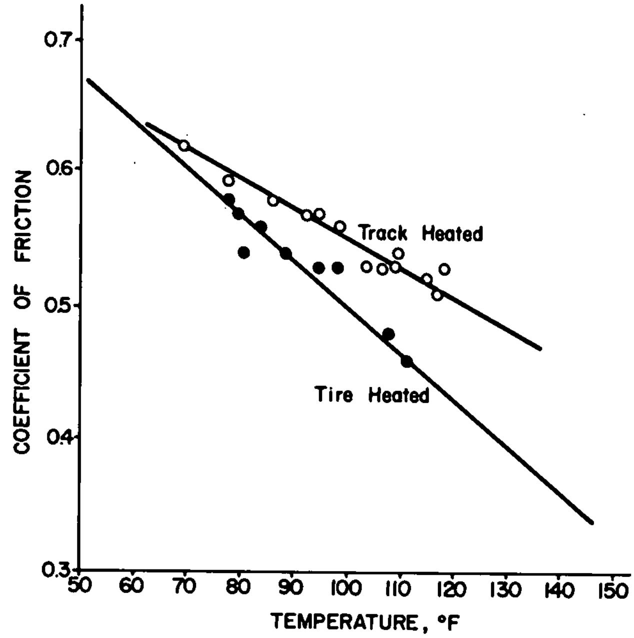


Figure A-8. Temperature effects on friction using tire on circular track apparatus.

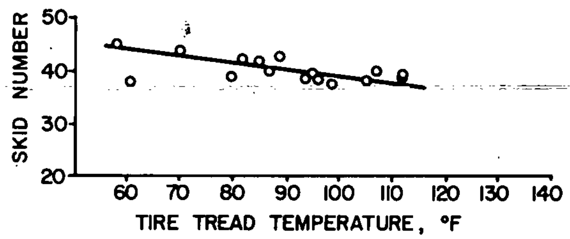


Figure A-9. Temperature effects on skid resistance using heated or precooled tire with constant pavement and water temperatures.

capable of registering hot spots on the rolling tire. Although it was successfully used for temperature measurement on the slipping tire during tests on the Penn State circular track, its performance in field tests was not quite so successful. More rugged instruments are available now that reportedly perform reliably when mounted permanently to a skid tester (*19*).

Temperatures measured with both instruments sometimes differed by up to 10 deg F, which may have been partly due to lack of correction for emissivity. Because of insufficient experience, no final judgment can be made of the performance of the Barnes radiometer or on radiometers in general. There is, however, reason to believe that the proper type of radiometer with correct procedure has great potential in temperature measurements required in skid testing.

2.2 Tire Contact Temperature

Skid tests in the field did not show significant dependence on tire temperature. Because pavement temperature could not be controlled, the tire was cooled or heated (in a temperature control chamber, before mounting) to run at temperatures other than the normal operating temperature. Typical results are shown in Figure A-9. There was at most a 2 percent decrease per 10 deg F (as compared with up to 6 percent in the laboratory). The frictional energy was dissipated in a very thin layer of the running band, generating heat. The tire reached its highest temperature just below its surface with some heat flowing deeper into the tire, but most of the heat was carried away by the water and the pavement (*20*). The temperature in the footprint area during skidding cannot be measured, and its measurement after the skid can be misleading. Figure A-10 shows tire footprint temperatures measured as soon as possible after the skid and continued at intervals thereafter. The temperature rise is proof that the temperature below the surfaces was higher during the skid, and higher still in two consecutive skids. Extrapolation of the two curves back to the beginning of the skid shows that both curves seem to have diverged from a temperature just slightly higher than the pavement temperature.

An experiment was conducted to determine the rate of temperature change when a heated tire is brought into contact with the pavement. The tire was heated to 200 deg F and a temperature sensor was attached to the tire surface. When the tire was brought into contact with the cold pavement (70 deg F) the temperature of the tire's contact area dropped instantaneously. Before the first reading could be taken, the temperature was down to 130 deg F on a wet pavement and to 140 deg F on a dry one (Figure A-11,

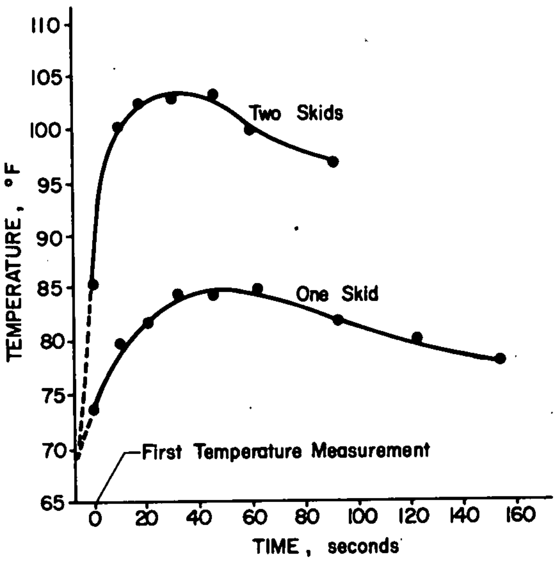


Figure A-10. Temperature of tire contact patch as function of time after skid. (For the upper curve, approximately 1 sec elapsed between skids.)

bottom). Within 60 sec the surface temperature had essentially stabilized at approximately 100 deg F on the dry pavement and 80 deg F on the wet. Because this was measured on a stationary tire, the surface temperature of the pavement's contact spot presumably increased. However, the contact time of a skidding tire at 40 mph is less than 0.01 sec so that no pavement heating is to be expected and the tire will approach the cold pavement temperature faster than the 60 sec measured here. For comparison, the cooling of a tire in still air is plotted in the upper graph of Figure A-11, which shows the temperature continuing to decrease after more than 60 min. The conclusion may be drawn that tire surface temperature, when in contact with the pavement, fast approaches the pavement temperature. Because of the poor heat conductivity of rubber, no inference can be drawn about the rubber temperature below the surface.

A series of field tests over a period of six weeks confirmed the close relationship between different temperature measurements. Figure A-12 shows four temperatures measured during this test series and Figure A-13 shows the corresponding skid numbers on five different pavements. (The five pavements are in the same vicinity and the temperatures were quite similar for all of them.) Obviously, skid resistance is affected by temperature variations, especially when a 6-week period is involved. To better show the temperature influence, the day-to-day changes in skid resistance have been plotted against the corresponding changes of all four temperatures. Figure A-14 shows the plot for one pavement, with the regression lines drawn in. Of 20 regression lines (four temperature plots for each of the five pavements), 18 are negative and vary from —0.019 to —0.290 SN per degree fahrenheit. Table A-3 gives the correlation matrix between the skid number and the four temperatures. Skid number correlates best with tire and dry pavement temperature (correlation coefficient >0.5) for which the regression lines have a mean slope of —0.15.

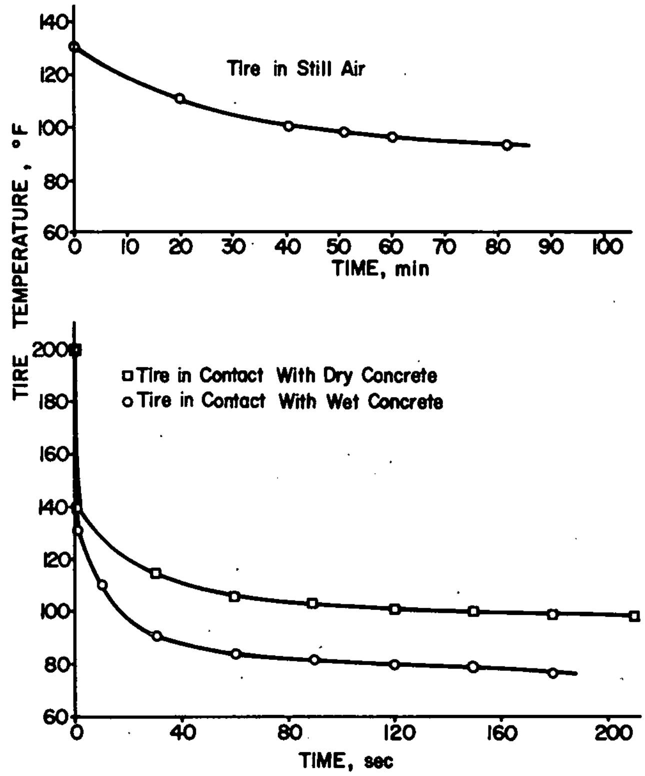


Figure A-11. Tire surface cooling times.

Thus, at the given conditions, a 10 deg F increase in dry pavement or tire temperature caused a decrease of 1.5 SN, or about 4 percent.

2.3 Correcting Skid Resistance Data for Temperature Differences

Laboratory and field test results verified that friction decreases with increasing temperature and that this decrease is approximately proportional to the friction level. Thus, any temperature correction should be made on a percentage basis. Based on skid data over a five-year period, a correction of 3 SN per 10 deg F has been suggested (*21*) although the authors pointed out that the data were taken at intervals too long to be sufficiently reliable. This correction would be approximately 8 percent versus 4 percent found here, and even the latter value turned out to be too high when applied to test data obtained during the correlation program.

Generally the temperature correction may be omitted safely unless a high degree of confidence can be attached to both the skid resistance and temperature measurements.

If pavement temperature is measured with a contact-type probe as used in the project, it is recommended that the temperature of the dry pavement be measured because it is more stable than that of wet pavement. Tire temperatures are nonuniform and, if these are to be measured, an averaging type of instrument (such as a radiometer) should be used on the rolling tire.

A linear regression of skid resistance versus temperature can be obtained as

$$SN = A + S\Delta T = SN_R\ (1 + C'\Delta T)$$

where $A = SN_R$, the skid resistance at an arbitrarily selected reference temperature; and S is the slope of the regression line, which is generally negative.

To apply corrections to skid data taken at different temperatures, the corrected skid number SN_{CT} is obtained from

$$SN_{CT} = SN_{UC}\ (1 + C\Delta T)$$

where SN_{UC} is the skid number measured at temperature T. The correction factor $C = -C' = -S/SN_R$ is obtained from the regression or estimated from previous experience and gives a correction proportional to the level of skid resistance. Its dimensions are (deg F)$^{-1}$, and multiplied by 100 it may be given as a percentage correction.

Based on laboratory results, a correction of 4 percent per 10 deg Fahrenheit was initially applied to all test data in the correlation program. It improved some correlations but made others worse. From regression analyses it became apparent that 4 percent was too large a correction factor and, for best results, different correction factors should have been used for each test site.

Skid numbers, to which all corrections except those for temperature have been applied, versus temperatures are plotted in Figure A-15. The slopes, computed for the second set of data, are plotted in both. Because of the much larger spread in the first set of data, the correction factor based on the same slopes made correlation poorer with temperature correction than without.

The conclusions to be drawn are:

1. Temperature correction factors are small, of the order of 2 percent per 10 deg Fahrenheit. The exact value is difficult to establish and varies with type of pavement.
2. When temperature correction increases the data spread, either the correction factor was too large or the spread of the uncorrected data was such as to result in a positive skid resistance-temperature gradient. In the latter case no correction should be applied.
3. Because of the slight effect of temperature on skid resistance, correction should be attempted only if both skid resistance and temperature measurements are sufficiently reliable.
4. The dry temperature measured on the running band of the rolling tire or on the pavement just before a skid is the most consistent one and should be used for temperature corrections (*20*).

3. PAVEMENT WETTING

3.1 General

The objective in this portion of research was to establish a rate and method of pavement wetting conducive to con-

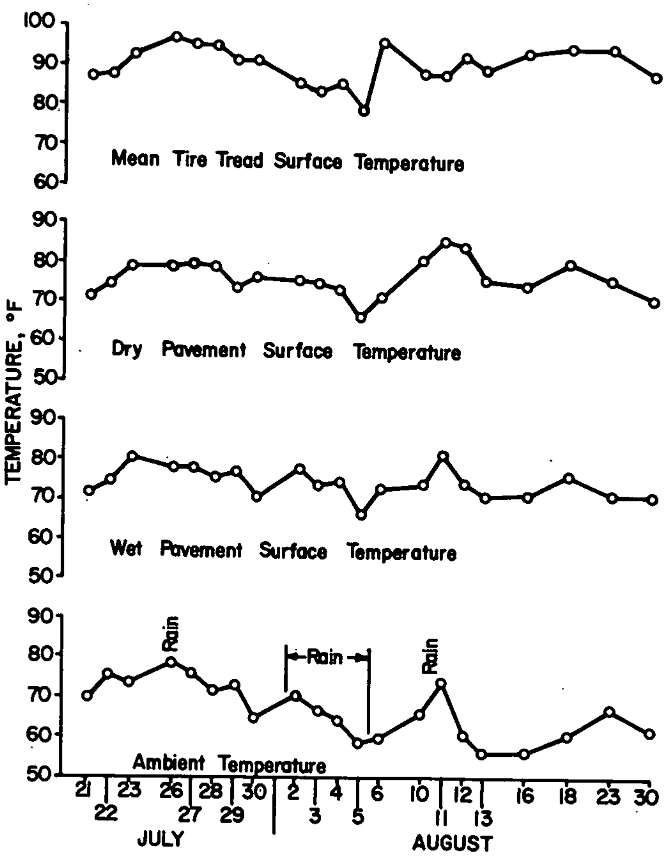


Figure A-12. Mean temperatures during skid testing.

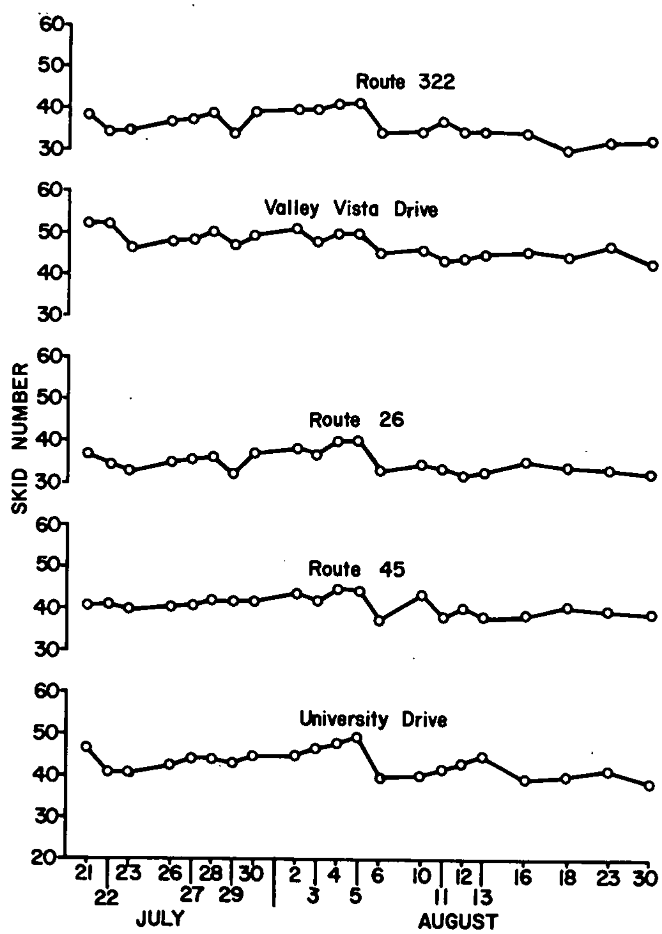


Figure A-13. Skid resistance variations for five pavements over a 6-week period.

sistent skid resistance measurements. The water film between a skidding tire and the pavement is of crucial importance to the development of skid resistance. The film is nonuniform, and there is no direct way of measuring its thickness. To define a water-film thickness on a textured pavement would be even more difficult because of its random surface features. Thus, the term "water-film thickness" refers to a nominal thickness of the water film encountered by the tire and computed from the flow rate, the tester speed, and the wetted width. In order to ensure application of a standardized water film, ASTM E 274 prescribes a flow rate per inch of wetted width. The actual water-film thickness in the contact area depends on the surface features of both the tire and pavement and on operating conditions, as well. Water film is created when sufficient water is applied to the pavement; increasing the flow rate further has no additional effect. A nominal water-film thickness of 0.020 in. has been found to provide sufficient water (*22*) and the ASTM specification is based on it. To ensure uniformity across the whole pavement width, a well-designed water nozzle is required (See Section 3.2).

An extended test series was conducted (*23*) to investigate the effects of varying water-film thicknesses on skid resistance. Tests were made on different pavements and at different speeds. Figure A-16 shows skid resistance on a coarse pavement versus water-film thickness. At speeds between 20 and 50 mph, the curves level out above 0.020-in. film thickness. Figure A-17 shows skid resistance on six different pavements. On five of them, including a longitudinally grooved one, the curves have leveled below 0.020-in. film thickness. The exception is a highly permeable slag pavement on which skid resistance continues to be sensitive to changes in water-film thickness even at the highest flow rate available in these experiments. (This pavement, at the time of measurement, had a total air void content of 15 percent as opposed to that of 3 to 5 percent for most pavements.)

Based on this additional evidence, the specification of a 0.020-in. water film is a good choice. Its merit is that deviations from this value, particularly on the high side, have little if any effect on the measured skid number. This would not be true to the same degree when assessing a highly permeable pavement, but this exception does not justify generally higher flow rates. Increased flow rates would require pumps of higher capacity, possibly larger piping, and more frequent refilling, all of which would add to the cost of skid testing.

In survey testing, permeable pavement should be tested at the same standard conditions as for all other pavements. In a study on rainfall intensity (*24*), an accumulation of 0.020 in. was found to be representative for average rain on most surface courses of most roads. This does not exclude thicker water layers under some conditions, but the object of skid-resistance testing is to obtain a surface characterization under standardized conditions rather than to assess a momentary condition of a road surface.

The preceding discussion was based on results obtained with a single, albeit typical, nozzle. Current use involves different types of nozzles that are positioned differently

TABLE A-3

CORRELATION MATRIX OF SKID RESISTANCE AND FOUR TEMPERATURES

			TEMPERATURE			
		SKID NUMBER	AMBIENT	WET PAVEMENT	DRY PAVEMENT	TIRE
	Skid Number	1	0.24	−0.18	−0.54	−0.58
Temperature	Ambient	0.24	1	0.64	0.34	0.27
	Wet Pavement	−0.18	0.64	1	0.71	0.52
	Dry Pavement	−0.54	0.34	0.71	1	0.57
	Tire	−0.58	0.27	0.52	0.57	1

with respect to the tire. One cannot assume a priori that the 0.020-in. flow rate will be adequate under these conditions. To determine sufficiency of flow rate under test conditions, one would have to perform tests similar to the ones performed for this project (*23*). Another method, though not a simple one, is photography.

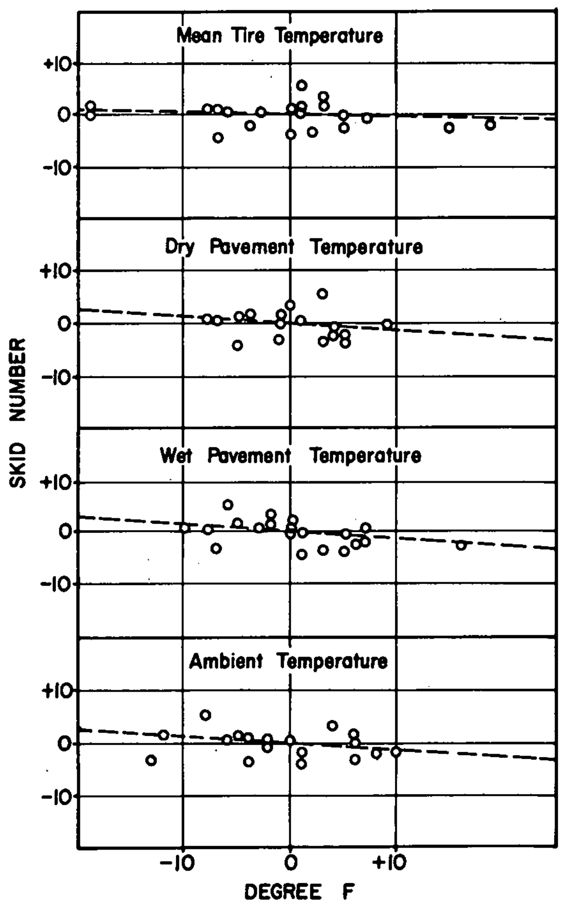


Figure A-14. One pavement's day-to-day changes in skid resistance and temperature.

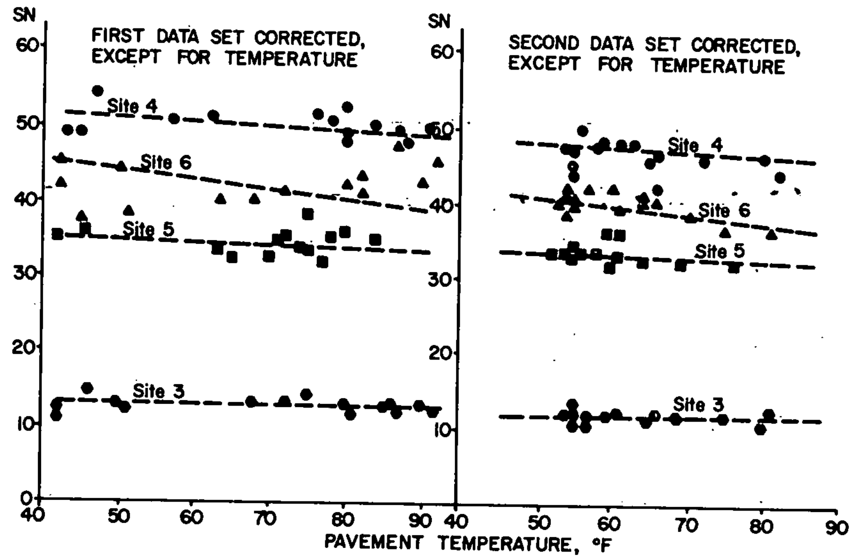


Figure A-15. Mean skid resistance versus temperature trends computed from regression of second data set.

Photographs taken at different flow rates under otherwise identical conditions of skidding show a bow-wave effect in front of a tire. The wave forms apparently when sufficient water is ahead of the tire. The three photographs in Figure A-18 were taken of 0.010-, 0.020-, and 0.030-in. water-film thicknesses respectively, and the latter two show the bow-wave effect. Unfortunately this effect is not easy to observe, but when observed it may be taken as a reliable indicator of water sufficiency.

Insufficient water in skid testing is one of the major variables affecting skid resistance measurements. Figure A-19 shows skid resistance on nine different pavements at three speeds (*25*). One test series was run with external watering, the other with a self-watering skid tester. In the latter case, the water flow rate was constant and not proportional to speed (as it would have to be to maintain nominally constant film thickness). At higher speeds the latter flow was clearly insufficient. The data are replotted in Figure A-20. Self-watering results in higher skid numbers on four surfaces at 40 mph and on all surfaces at 60 mph than does external watering.

External watering, however, is not inherently superior to self-watering. Data from the Florida correlation program (*26*) were analyzed for standard deviations of six skid testers that tested the same sites under conditions of external watering and self-watering. The mean standard deviations per site and speed are given in Table A-4. There is no improvement with external watering and, in fact, the mean standard deviations at the higher speeds were smaller with self-watering.

3.2 Uniform Watering Method for Skid Testers

From observations of a sampling of locked-wheel skid testers and their implementations of the specifications given in ASTM E 274, skid tester watering systems have been found to have major divergences in design. The variations

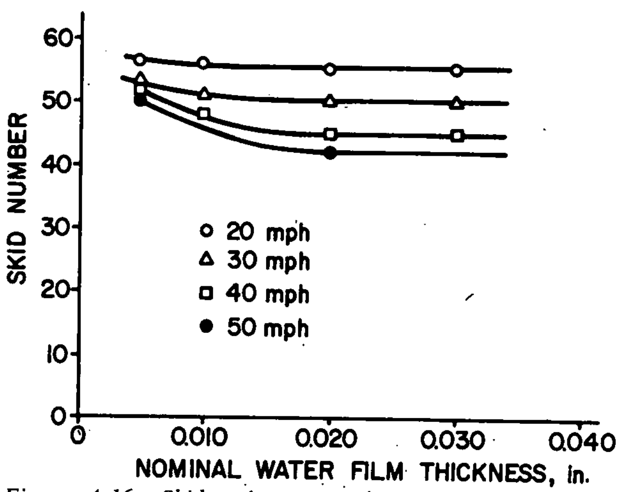


Figure A-16. Skid resistance as function of water-film thickness on coarse bituminous concrete pavement (23).

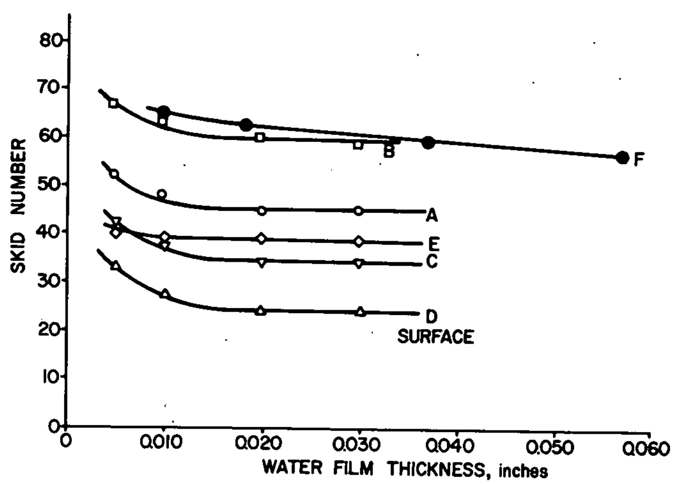


Figure A-17. Skid resistance at 40 mph as function of water-film thickness on various surfaces: A, B—coarse; C—polished PCC; D—fine bituminous concrete; E—longitudinal grooves in PCC; F—permeable slag pavement (23).

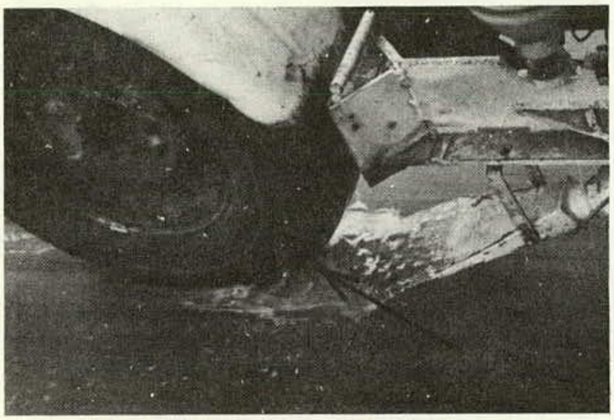
occur both in the flow rate and in the method by which water is applied. Adoption of a uniform watering system will eliminate the need for experimentation with each of the different systems.

ASTM E 274 specifies that water be laid down in front of the skidding tire at the rate of 3.6 gal (±10 percent) per minute per inch of wetted width at 40-mph test speed. The interpretation of the number of inches of wetted width is not uniform among tester operators; and even if it were, it would be difficult to apply to the various designs.

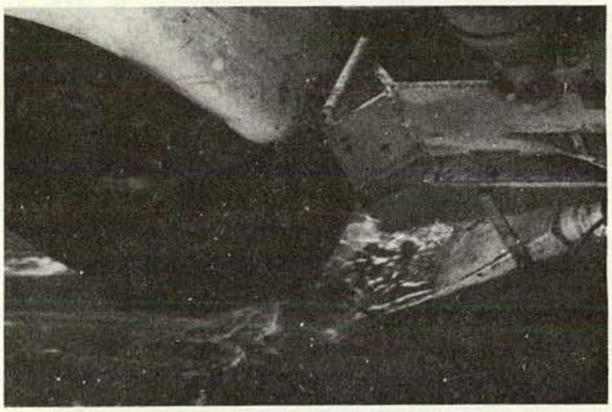
The water application systems observed included spray nozzles, flat jet nozzles, and brush applicators. Spray nozzles are attractive as a commercially available item; however, the advantage is lost when it is realized that for uniformity and consistency of application, the location is very critical, the performance varies with flow (test speed), and aerodynamic effects are more pronounced when water is applied as a stream of droplets.

Brush applicators are also attractive because they offer a means to directly apply and spread water on the pavement. However, again there are too many possibilities for variation. The density and distribution of bristles strongly affect the water distribution with further uncertainty introduced by wear and load against the pavement.

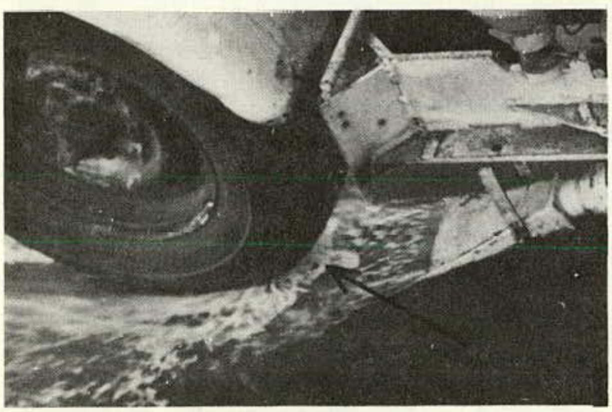
Nozzle location and orientation can have an influence on the water film that the tire encounters. Figure A-21 shows that at low flow rates (or small nominal water-film thicknesses) nozzle location has some effect on the skid number.



water-film thickness, 0.010 in.



water-film thickness, 0.020 in.



water-film thickness, 0.030 in.

Figure A-18. Formation of bow-wave effect.

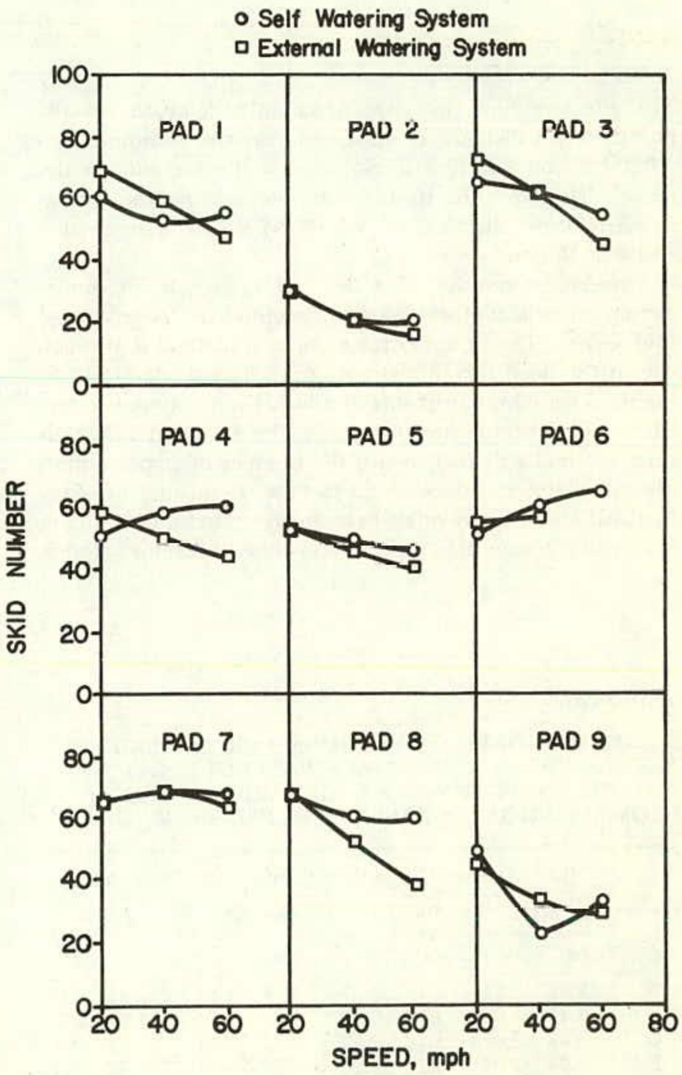


Figure A-19. Skid resistance on nine different surfaces at three speeds (25).

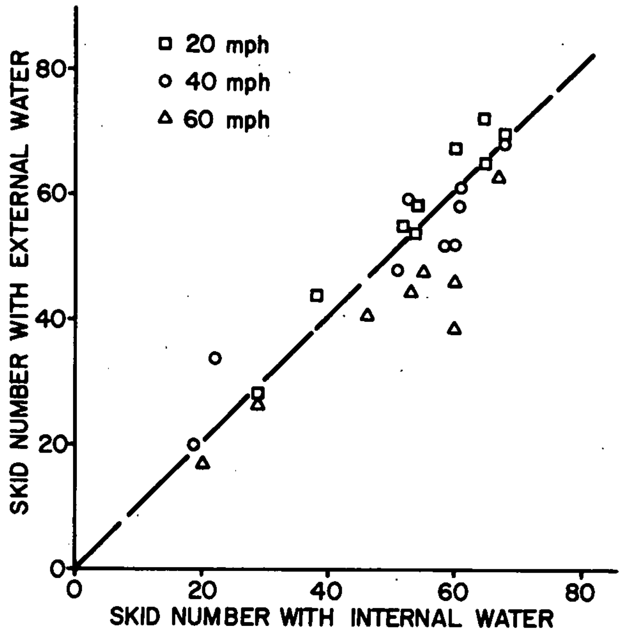


Figure A-20. Poor correlation at higher speeds caused by inadequate watering.

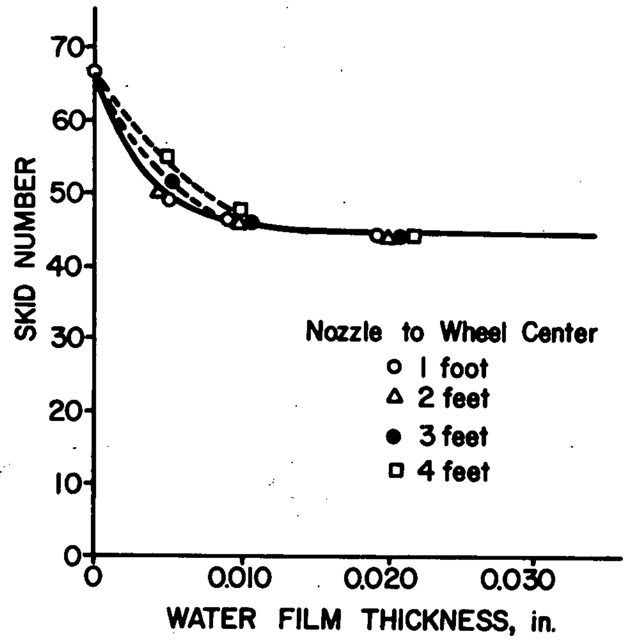


Figure A-21. Effect of nozzle position on skid number.

The effective film thickness apparently decreases as the nozzle-to-tire distance is increased. At the recommended 0.020-in. nominal film thickness, no effect could be detected. Therefore the 10- to 18-in. tolerance for the nozzle-to-wheel-center distance, as per ASTM E 274, is acceptable and well-chosen.

The flat jet nozzles offer the best approach for implementation of a uniform watering method on locked-wheel skid testers. The necessity for a uniform method is as much due to the need for an alternate to individual design as to the need for common points of comparison between testers when correlation is not obtained. The adoption of a uniform method will also reduce the number of opportunities for subtle difference (such as in flow uniformity or aerodynamic effects), provide a base on which to build common experience among the various skid tester operators, and is essential if comparable data are even to be acquired on flow-sensitive permeable pavements.

The simplest possible design was adopted, allowing for the fact that there likely would be considerable variations in the flow regime upstream of the nozzle assembly. The nozzle was tested extensively; its performance was checked by slow-motion photography and found to be satisfactory. Twelve such nozzles were built and used on the testers participating in the correlation program.

Specifications for the nozzle design and watering method require that:

1. The nozzle shall be constructed to the dimensions shown in Figure A-22. It shall be rigidly attached to the test trailer so that the horizontal projection of the nozzle centerline is within an angle of 2 deg of the trailer longitudinal axis and so that the nozzle centerline, projected to the tire tread surface, is within ¼ in. of the tread center.
2. The top surface of the mounted nozzle shall be at an angle of between 20 to 30 deg from horizontal. The nozzle shall be located such that the jet impacts the pavement 10 to 18 in. forward of the wheel center while the trailer is static.
3. In accordance with the flow rate of the water pump, the nozzle shall be located such that the jet width results in 4 gal (±5 percent) per minute per inch of jet width at 40 mph. The jet width is defined as the width at the point of impact on the pavement, measured while the trailer is stationary and level.
4. The water shall be supplied by a positive displacement pump positively driven from either the towing vehicle drive shaft, transmission power take-off, or engine power take-off (except with automatic transmissions).
5. The flow rate for the ASTM E 249 pavement test standard tire shall be between 24 (6-in. jet width) to 30 gpm (7.5-in. jet width) at 40-mph test speed.

TABLE A-4

MEAN STANDARD DEVIATIONS FOR SIX SKID TESTERS WITH EXTERNAL WATERING (σ_E) AND SELF-WATERING (σ_S) AT VARIOUS SPEEDS; FROM FLORIDA CORRELATION PROGRAM *(26)*

	MEAN STANDARD DEVIATION AT SPEED OF:							
	20 MPH		40 MPH		60 MPH		ALL	
SITE	σ_E	σ_S	σ_E	σ_S	σ_E	σ_S	σ_E	σ_S
1-A	1.63	2.31	4.73	3.77	2.56	3.11	2.96	3.06
1-B	2.43	2.89	1.37	2.04	1.66	1.59	1.82	2.17
1-D	2.47	2.69	3.15	2.17	2.22	2.41	2.61	2.42
1-E	3.29	2.05	3.22	3.21	6.26	4.68	4.26	3.31
All	2.46	2.49	3.12	2.80	3.23	2.90	2.97	2.73

6. The pump shall provide flow rates proportional to speed within 5 percent over a speed range from 20 to 60 mph.

7. Using a pump whose performance satisfies the requirements of the previous paragraphs, the following procedure can be used to obtain the specified flow rate per inch of jet width. The flow shall be calibrated with an accuracy of 2 percent at conditions equivalent to a 40-mph test speed and with the flow directed through the nozzle in its mounted position on the trailer. With the trailer stationary and level, the jet width at impact is measured directly and the nozzle location adjusted as necessary to satisfy the requirements of paragraphs No. 2 and 3 above.

8. For purposes of initially preparing a mounting for

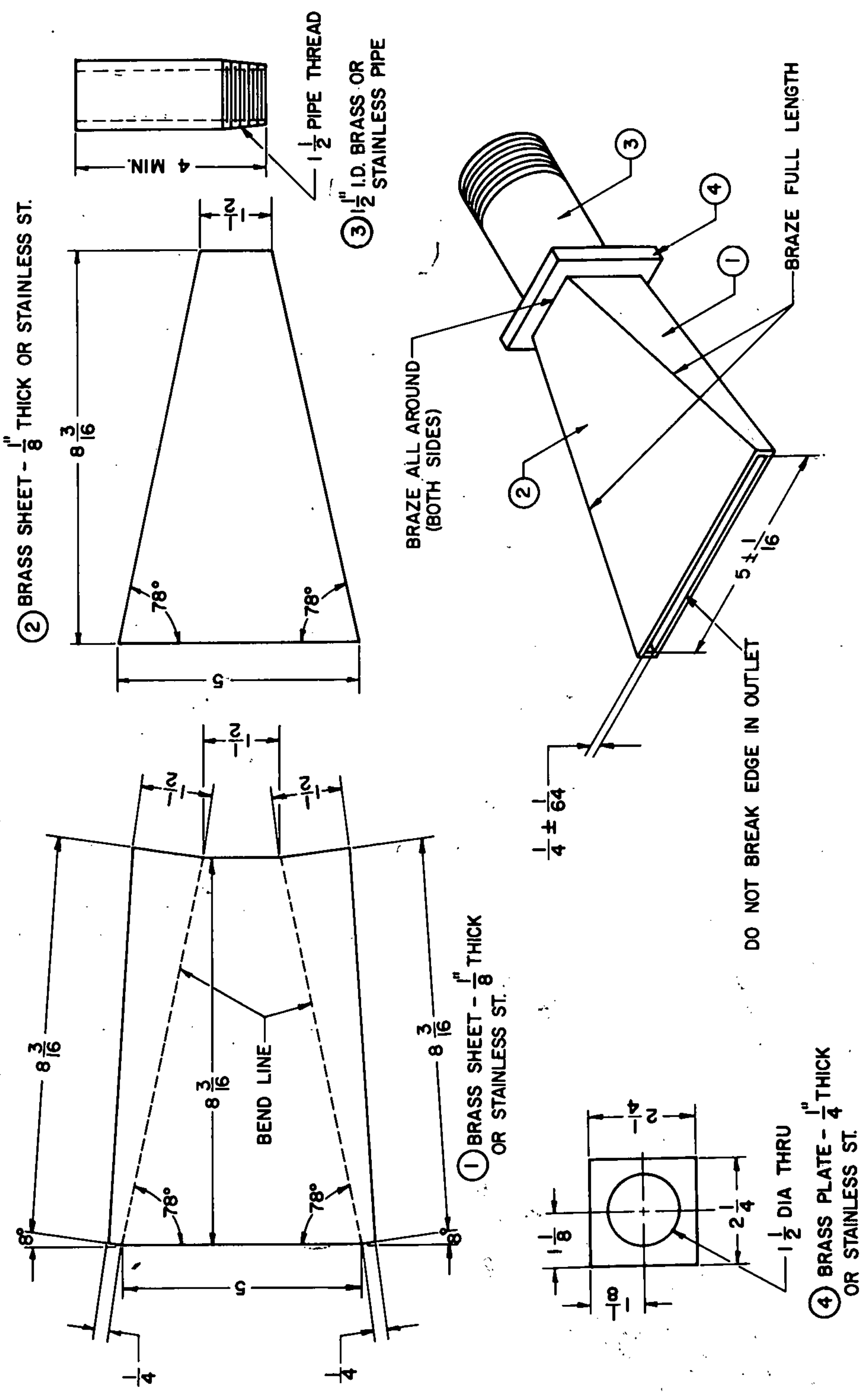


Figure. A-22. Dimensional drawing of the proposed watering nozzle.

the nozzle, the approximate height and forward placement can be determined from Figures A-23 and A-24.

The recommended specifications and nozzle design provide a 20-percent tolerance on the flow rate and achieve uniform wetting by adjusting nozzle position.

The nozzle produces a fairly thick low-velocity water jet to minimize aerodynamic disturbances. The divergence angle combined with sufficient inlet size and decreasing cross section ensure that the flow fills the nozzle and diverges at the outlet so that nozzle location can be adjusted to control the wetted width. The changes in flow area through the nozzle cause the flow to accelerate through a pressure gradient establishing the distribution by all flow accelerating from a common initial pressure rather than by attempting to equalize the flow resistance throughout. No baffles or valves are needed in the nozzle.

The nozzle design has been used extensively with the 5-rib ASTM E 249 pavement test standard tire and found to be suitable over the range of flows and speeds required. From the performance obtained, it is expected that this same design will be adequate for the wider 7-rib tire currently proposed for ASTM acceptance as the successor to the 5-rib design.

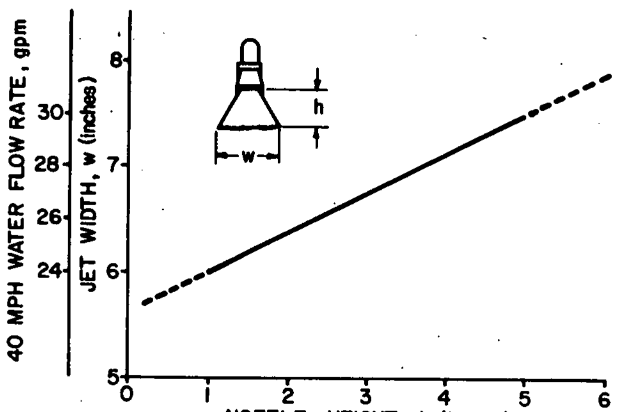


Figure A-23. Approximate jet width as a function of nozzle height.

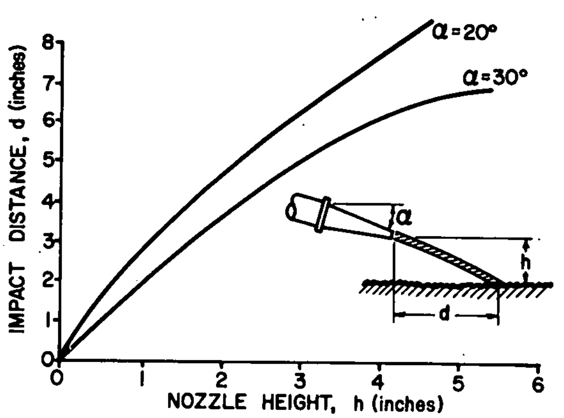


Figure A-24. Approximate impact distance of jet as a function of nozzle height.

Several design alternatives were considered and rejected in the choice of this nozzle. One is that the jet should not be laterally divergent because trailer vertical excursions affect the wetted width. Such a design is insensitive to trailer height but indirect influences are still created by dynamic and aerodynamic effects and precise control of water flow rate is required.

Trailer height changes in testing are of two types—dynamic height changes caused by road roughness and a quasi-static height change caused by load transfer on to the hitch when the friction force is present. High-speed films of tester operation and an analysis of data on trailer spring constants and load transfer effects show that quasi-static changes are only fractions of an inch. Dynamic changes are a function of road roughness and average out in skid testing like so many other factors. It may be argued that the divergent jet, if anything, helps to damp force oscillations due to dynamics by becoming leaner when the trailer is at the top of a bounce (low tire load) and becoming richer when the trailer is at the bottom of a bounce (high tire load).

Another design alternative that receives frequent query is whether the water jet should exhaust at the tester forward velocity so that the water hits the pavement with no relative velocity. This design theoretically simulates the actual case of water lying statically on the pavement. In addition to the problem of generating water pressures up to 100 psig necessary for high-speed testing, many other implementation problems exist because of the accurate dimensional tolerances required. A 5-percent dimensional tolerance on this nozzle translates into 0.001 in. It is not really practical to measure or maintain these tolerances when one considers the severe environment of potholes and stones to which the nozzle is exposed. The problems of water filtering, contaminants, and aerodynamics would be further compounded with a nozzle of this type.

Because smooth tires on cars contribute heavily to skidding accidents, the argument is often made that skid resistance should be measured with smooth tires to reflect the worst possible conditions. Figure A-25 shows that with a smooth tire the skid number continues to decrease with increasing nominal water-film thickness long after it has leveled off with the ribbed tires. This means that in contrast to a ribbed tire a smooth one builds up an increasingly thicker water film at the entrance to the contact area as the nominal film thickness goes from 0.020 to 0.030 in. and more. Figure A-26 shows the same data for a grooved pavement in which the skid resistance for the smooth tire levels off at 0.020 in., just as it does for the ribbed tire. The pavement grooves have the same effect as the grooves in the running band of the ribbed tire. The ribbed tire, because of its lesser sensitivity to water-film thickness, is therefore the preferred choice for skid-resistance measurement, which ideally is insensitive to all operational factors.

3.3 Water System Calibrations

The flow rate of the watering system is determined in calibration. For vehicle-driven systems, calibration should be made at all test speeds to determine whether flow rate remains within specifications. Although the delivery rate

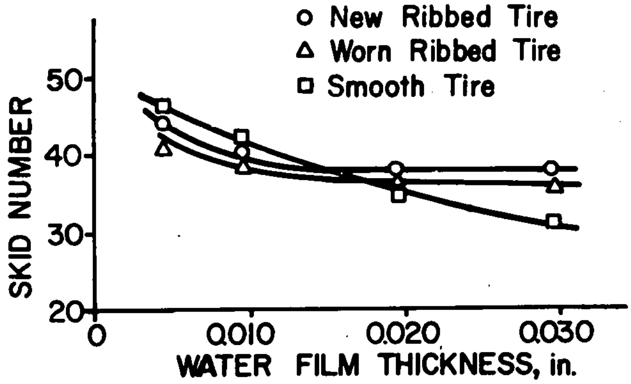


Figure A-25. Skid resistance of different tire treads on coarse textured bituminous concrete pavement.

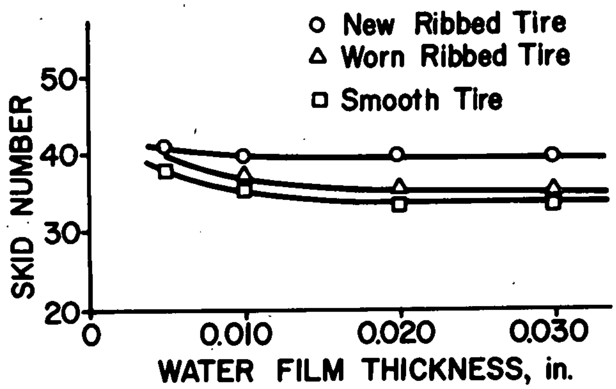


Figure A-26. Skid resistance of different tire treads on longitudinally grooved pavement.

of positive displacement pumps is theoretically proportional to speed, the actual flow rate is affected by the flow resistance of the piping and nozzle, leakage and cavitation. Centrifugal pumps and other systems (such as pressurized tanks) are even more sensitive to flow-resistance variations. For this reason, calibration should be made with the complete system including valves and nozzle in their normal operating positions.

3.3.1 Recommended Method of Calibrating

One objective of the skid tester correlation program was to have portions of the testing conducted by testers having identical watering systems. All participants were provided with identical nozzles (as recommended in Section 3.2.1), which were installed in the period between the first and second correlations. At that time tester flow rates were calibrated and the systems adjusted to meet the specifications for a uniform skid tester watering method (Section 3.2) insofar as possible.

The average flow rate was computed from measured time and volume. A 40-gal submerged receiver tank flush-mounted at surface level in a parking area was provided to capture the effluent flow directly from the water nozzle. A tester was positioned such that its nozzle extended over the tank and the rear wheels of the towing vehicles were raised, if necessary, to allow water pump operation. The water system was started up and stabilized at a rate equivalent to that at the desired speed, at which time the receiver tank was uncovered for a period of 60 sec or until at least 30 gal of water had accumulated. Calibrations were conducted at rates equivalent to speeds of 30, 40, and 50 mph, for which three tests were run at 40 mph and two each at the other speeds. Consecutive tests were always conducted at different speeds so that variability between tests always included both the level of repeatability at which the tester operator could duplicate the desired rate and the influences of water level in the tester storage tank.

After the flow rates were calibrated, the three 40-mph values were averaged and the correct jet width calculated. A cover plate was placed on top of the receiver tank at ground level and the water system was run again at the 40-mph speed. The nozzle position was then adjusted so far as necessary to achieve the correct jet width at ground impact.

The water calibrations, expressed in flow rate per inch of jet width, for the participating testers are shown in Figure A-27. The 40-mph flow rates are also listed. The dashed lines represent the ±5 percent limits of flow rate for jet width permittted by the specifications for a uniform water-

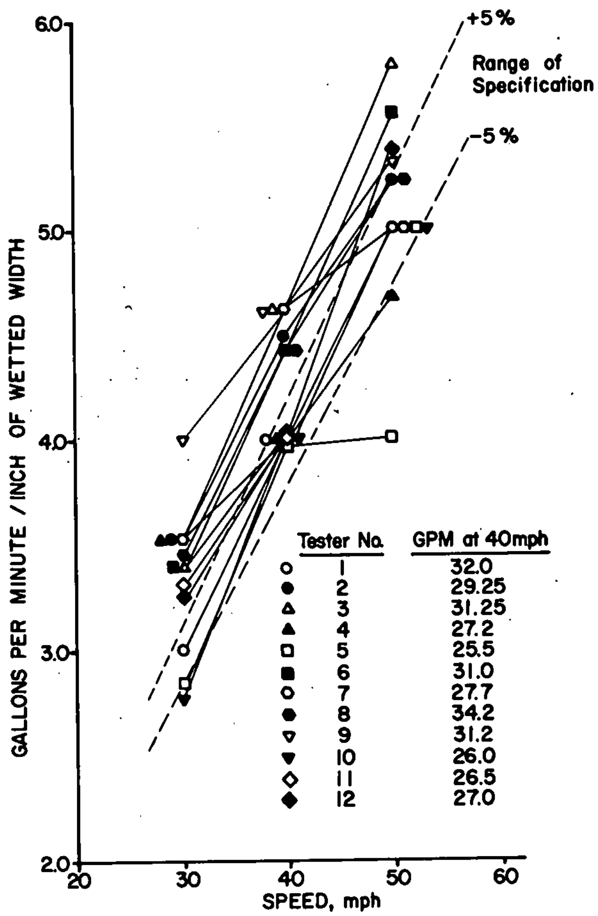


Figure A-27. Water calibration of the correlation program testers.

ing method. The jet width is measured only at 40 mph and assumed unchanged at other speeds.

Figure A-27 data indicate that all testers did not comply with the specifications, because of either excessive flow rate or a limited range for adjusting the nozzle position. Though not to specifications, the spread at 40 mph is just 15 percent and on the rich side. The tendency toward the rich side indicates that the adaptation of the uniform watering method would allow most testers the economy of a lower water flow rate.

Testers No. 1 and 3 produced flow rates significantly higher than those expected by their crews, which indicated some disparity in interpretation of water flow rate. One interpretation, which should be considered incorrect, is to divide the total flow by skid cycle time rather than just by the water flow time in the cycle. Calibrations based on this method are of low accuracy and should be used at most only for periodic checks.

Repeatability of the flow rates during calibration averaged about 3 percent. Tester No. 9, having an air-pressure-driven system, had flow rate variation as broad as 24 percent caused partially by influence of the water level in the tank.

Testers No. 4, 5, 7, and 9 exhibited poor flow rate proportionally to speed. In the case of tester No. 9, the air-pressurized system, the problem was due to the air pressure gage being of inadequate precision and was compounded by the broad flow variation with tank water level. The problem with the other testers was caused by inadequate pumping capacity at higher speeds. The same problem was experienced with a similar tester participating in the open test period of the correlation program.

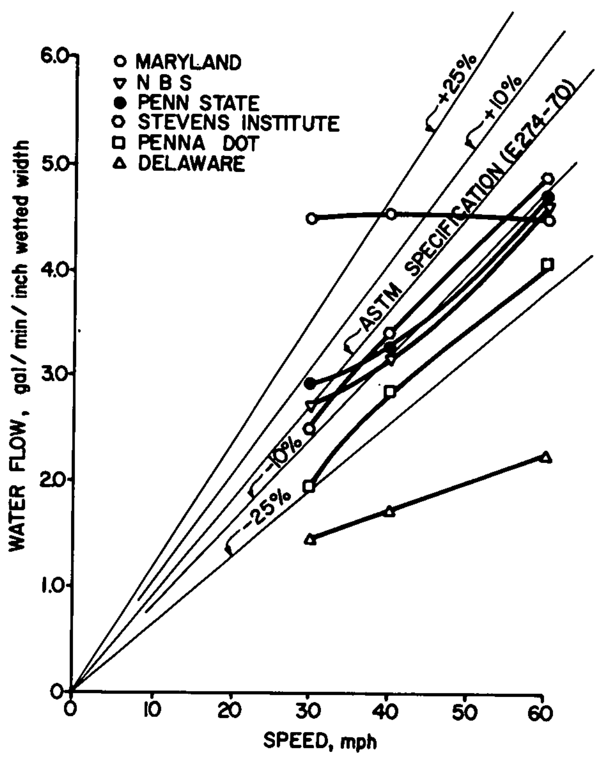


Figure A-28. Waterflow calibration of six testers at three speeds.

Despite the flow capacity limitations, only tester No. 5 fell below the specified flow rate (approximately 20 percent low at 50 mph). Because the specification allowed a generous flow and the correlation program was conducted on prewetted surfaces, this deficiency was not considered to have significant effect on the results.

Figure A-28 shows the results of water flow rate calibrations on six skid testers (*15*) investigated prior to the correlation program. All testers but one had vehicle-driven water systems of different designs and their flow rates should have been proportional to speed. The difficulty of accurately measuring wetted width may be the major reason for the nonlinearity of some of the calibration curves. Three of the six testers were outside the range specified by ASTM E 274.

4. VARIATIONS IN SKID RESISTANCE ACROSS AND ALONG THE PAVEMENT

4.1 General

Pavement itself contributes to the uncertainty in skid-resistance measurement. The pavement surface is not homogeneous initially, and the difference in skid resistance between the wheel paths and the less traveled parts of the pavement increases over the years. In repeat tests, it is impossible to run the test wheel over exactly the same stretch of pavement both laterally and longitudinally; thus, the divergence will be greater if more than one tester participates in such tests. Also, the pavement surface during testing may undergo small changes, which have to be considered in repeat testing.

4.2 Lateral Variations

The extent of lateral variation of skid resistance is shown in Figure A-29. Repeat tests were made on a typical pavement, with the lateral tester position being varied between tests. A total of five such test series were run over a period of approximately three weeks under standard conditions. The data clearly show a lower skid resistance in the center of the wheel track, with a difference of 10 SN between low and high. A deviation of 5 in. to the right from the minimum skid number value can result in as much as 5 SN change in skid resistance. More typically, a mean deviation of 3 SN per 10 in. was found on several pavements.

Thus, a relatively large variation can result should an operator fail to run the test wheel in the center of the wheel track. For example, a correlation program was conducted with six testers (*15*) whose drivers were instructed to test in the most traveled part of the wheel track. Each tester ran 30 test paths which were measured. One tester had a spread of 31 in. and the mean of all testers was 15 in. Although no satisfactory method to aid the driver in tracking has been found, a big improvement can result once the driver is made aware of this error source and he practices testing in a preselected path.

4.3 Longitudinal Variations

Longitudinal variations are more difficult to document because they can include lateral variations as well as other effects. However, in a large number of repeat tests, the

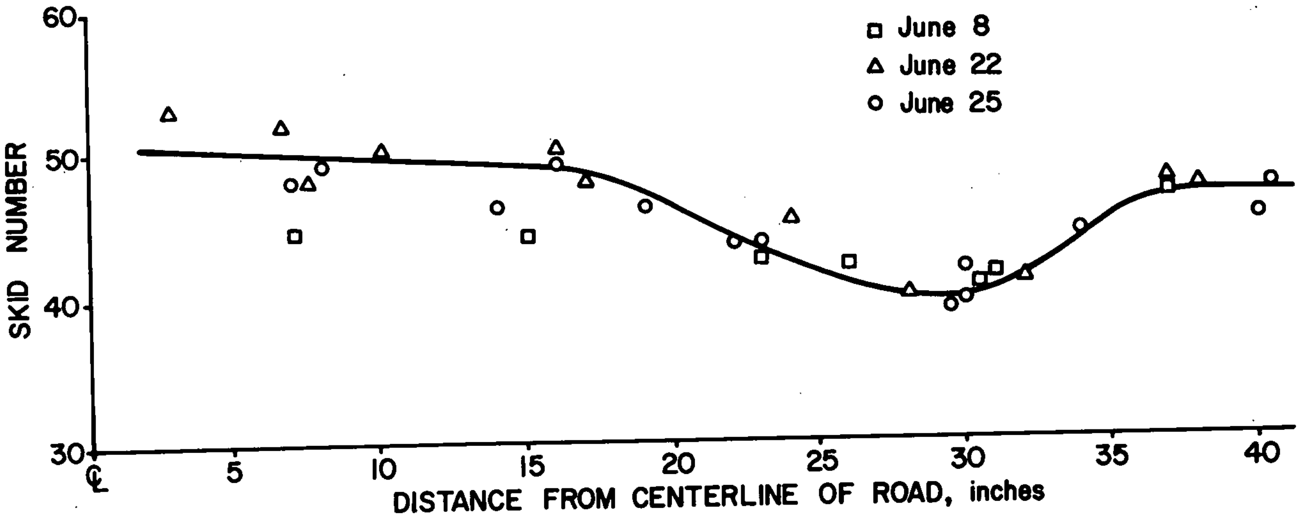


Figure A-29. Variation of skid resistance across wheel track.

latter effects may be assumed to be cancelled and any difference between the means can be attributed to longitudinal variations. Figure A-30 shows the mean skid numbers for each of five wheel lockups on presumably and seemingly homogeneous pavement sections of two highways. Tests were repeated over a period of approximately six weeks for a total of 26 sets of data. The longitudinal variations in 1 mile of Rt. 26 are 3.2 SN and in 2½ miles of Rt. 45, 6.7 SN.

Strictly speaking, longitudinal variations—where they exist—are not errors in skid resistance measurement but rather a manifestation of the variability of skid resistance along a road. Section 4.4 concerns a study of inventory testing that further illustrates road variance in skid testing.

4.4 Inventory Testing Study

A skid tester participated in a 25-day inventory testing study. Skid measurements were repeated at five stations along a segment of roadway. Skid number recordings were analyzed and the data obtained are given in Table A-5.

The chi-square (χ^2) test for normality was applied to both individual station (spot) data and to the composite (over the entire roadway segment) data. Table A-6 shows the results of the test applied to station No. 1 and to the entire roadway length. Both distributions were statistically accepted as being normal.

An analysis of variance was run to test the equality of daily means. The first six days' data were selected for the

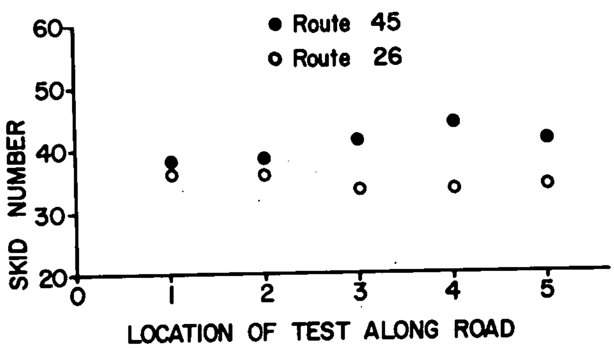


Figure A-30. Longitudinal variation in mean skid resistance. Spacing of skids was approximately 0.2 mile on Rt. 26, 0.5 mile on Rt. 45.

TABLE A-5

SUMMARY OF INVENTORY TEST DATA

STATION NUMBER	SAMPLE SIZE	SAMPLE MEAN	SAMPLE VARIANCE	SAMPLE STANDARD DEVIATION
1	25	31.82	12.84	3.58
2	25	33.20	16.81	4.10
3	25	36.80	11.75	3.43
4	25	34.82	14.79	3.85
5	25	39.10	15.98	4.00
Composite	125	35.15	20.79	4.56

TABLE A-6

NORMALITY TESTS FOR INVENTORY TEST DATA

LOCATION	TEST STATISTIC, χ'^2	CRITICAL REGION, $\chi^2_{k-3,\ 0.95}$	RESULTS
Station No. 1	4.40	5.99	Accept [a] H_0
Road segment (composite of five stations)	12.50	16.92	Accept [b] H_0

[a] Station No. 1 data normally distributed.
[b] Composite data normally distributed.

TABLE A-7

ANALYSIS OF VARIANCE TABLES FOR INVENTORY TEST DATA

SOURCE OF VARIATION	SS	DEGREES OF FREEDOM	MS	MSA / MSW	CRITICAL REGION [a]	RESULTS
Among samples	99.07	5	19.81	1.53	2.62	Accept H_o (Daily means equal)
Within samples	309.9	24	12.91			
Total:	408.97	29				
Among samples	276.72	4	69.18	13.58	2.78	Reject H_o (Station means not equal)
Within samples	132.25	25	5.09			
Total:	408.97	29				

[a] At $\alpha = 0.05$ level of significance.

analysis. From the upper figures in Table A-1, it can be seen that the hypothesis of equality of daily means is accepted.

The analysis of variance was rerun—this time to test the equality of station means over the six-day period. Figures in the lower half of Table A-7 show that this hypothesis is rejected, i.e., there are statistically significant differences among the station means.

We may infer from these results that skid-resistance variations along the road are more significant than the changes that occurred over a 25-day period.

The chi-square test for equality of variances was conducted to compare the variances over the five stations. Data from all 25 days were used. The results of this test, given in Table A-8, show that the hypothesis is accepted. Evidently the system operated in a consistent fashion over all five stations.

4.5 Other Sources

Inconsistent data will result from any project to monitor short-time skid-resistance variations of a pavement if the operator is unaware of the importance of seeking out for repeat tests the same longitudinal and lateral stretch of pavement. ASTM E 274 calls for evaluation of skid data of 1-sec duration. Thus, a difference of 1 sec in triggering the test cycle will result in measurement of the skid resistance of a stretch of pavement other than the intended one. Also, when tests are run at several speeds, each cycle at greater test speeds must be started sooner in order to cover approximately the same stretch of pavement at each speed.

In repeat tests over the same stretch of pavement, the skid number usually drops after the first few skids, as shown in Figure A-31. This "preconditioning" is attributable partly to the tire and partly to the pavement. In repeat tests, the first few tests should be disregarded; in survey testing, when beginning a series of tests or when moving to a greatly differing pavement, it is advisable to run several skids before recording data.

In correlation programs of several testers, an additional potential error source is the difference in test cycle timing between the testers. Also, a degradation of the skid resistance of the pavement may occur as testing progresses. Figure A-32 shows a drop in skid resistance by about four skid numbers during a day of tests, with six skid testers participating. The drop in this example may be the result of the combined effects of temperature changes, some wear and polishing from the large number of skids, and repeated wetting of the test section. Unless the test sequence is randomized, this degradation must be accounted for in the final correlation of test data.

TABLE A-8

VARIANCE HYPOTHESIS FOR INVENTORY TEST DATA

TEST STATISTIC,[a] χ'^2	CRITICAL REGION, $\chi'^2_{4,\ 0.95}$	RESULTS [b]
0.20	9.49	Accept H_o

[a] $H_0: \sigma^2_{sta\ 1} = \sigma^2_{sta\ 2} = \ldots = \sigma^2_{sta\ 5}$
[b] At $\alpha = 0.05$ level of significance.

5. TEST TIRE

5.1 General

The need for a standard test tire had been recognized prior to the First International Skid Prevention Conference in 1958. In conjunction with this conference, a correlation program for several road friction testers first used a standard test tire (*27*). Its successor, the ASTM E 249-65 test tire, was used in the Tappahanock correlation program (*28*). It was, except for the tread design, representative of the size, materials, and construction of passenger car tires in use at that time. The current specifications for the stan-

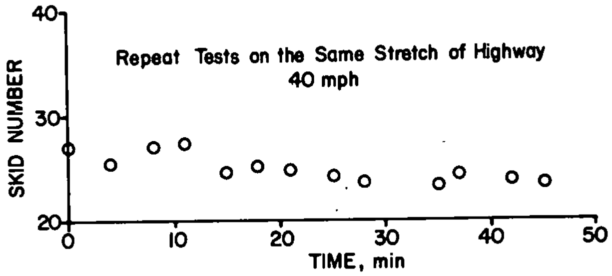


Figure A-31. Drop of skid resistance in successive tests due to preconditioning.

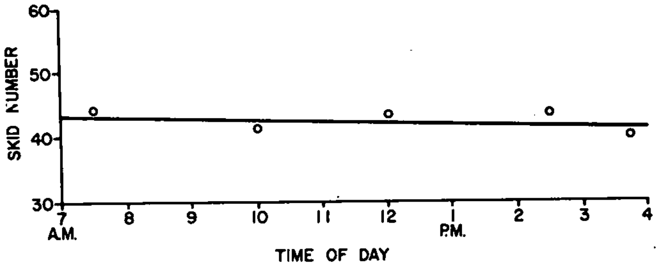


Figure A-32. Degradation of skid resistance during a day of continuous testing.

dard test tire are designated ASTM E 249-66, and are referred to herein simply as ASTM E 249.

Although each standard test tire is certified to meet ASTM E 249 specifications, a tire is a complex structure and a degree of variability is inevitable. The variability can exist between production batches, between tires from the same batch, and in one particular tire because of its changes from aging and use.

Several recent studies were designed to determine the variability introduced into skid testing by changing tires. In one test series (*29*), eight new ASTM E 249 tires were used in repeat tests on a single skid tester. Four tires were tested as received, and four were broken-in according to specifications. Twenty-five repeat tests were run with each tire. Table A-9 summarizes the results and gives for each tire the standard deviations about its mean as well as the standard deviations of the means for both the new and the broken-in tires. The standard deviations for both sets of tires are approximately 2 SN, and the differences are insignificant. Based on these results, one might conclude that breaking-in of new tires can be suspended. However, when the individual skid numbers are plotted in the order they were taken as shown in Figure A-33, the mean drop over the 25 successive tests for the four new tires, is 2.75 SN; for the broken-in tires, 1.5 SN.

New tires seem to give somewhat higher readings than used ones, but no significant differences between the used tires could be found. Figure A-34 gives results obtained in the second week of the correlation program reported in Chapter 2. The tires supplied during the program were alternated with the tires belonging to the skid testers and one new program tire was included. Except on the low-friction surface, new tires measured 2 to 3 SN higher than the used tires. Similar results were obtained on three different pavements, when one new test tire and three well-worn ones were compared with a control tire, which was almost new, having no signs of wear, as shown in Figure A-35. Except for the smooth pavement, the new tire always gave higher skid readings.

In another test series, three ASTM E 249 tires were subjected to 10 repeat tests within a short span to minimize other effects on skid resistance. Two of the tires were new; one was broken-in to ASTM specifications, the other by being run for a comparable time against a steel drum. The third tire was one at an intermediate state of wear. Table A-10 gives the individual results in the order in which they

TABLE A-9

SKID RESISTANCE WITH NEW AND BROKEN-IN ASTM E 249 TIRES, 25 TESTS EACH (NBS)

TIRE	AS RECEIVED MEAN SN	AS RECEIVED STANDARD DEVIATION	BROKEN-IN MEAN SN	BROKEN-IN STANDARD DEVIATION
1	55	1.78	53	1.83
2	54	1.99	56	1.92
3	59	2.74	55	2.42
4	56	2.27	56	1.65
Grand mean:	56	—[a]	55	—[a]
Mean std. dev.:		2.19	55	1.96

[a] Standard deviation about grand mean for new tires was 2.3 SN; for broken-in tires, 1.5 SN.

were run, as well as the means and standard deviations for each tire. The means are within 1.3 SN with a standard deviation of less than 1 SN.

The effect of inflation pressure on skid resistance at two speeds is shown in Figure A-37. Over the range of normal variations (24 to 28 psi), the decrease of skid resistance is about 1 SN at 40 mph and 2 SN at 60 mph. This effect is probably related to the rate at which water can be displaced and semi-dry contact be established and might, therefore, vary with pavement texture.

To reduce the effect of tire variability in the correlation program, 20 standard test tires were purchased from a single production batch. All tires were stored in the same place and were run-in for 200 miles under the same conditions.

The question of what standard deviation in skid testing is acceptable will be discussed in a later section; it is obvious, however, that not all of the variability can be blamed on the tire. There is unfortunately no way of reliably separating the various factors affecting skid-resistance measurement. To estimate the variability that can be ascribed to the tire, comparative tests were conducted with an ASTM E 249 tire and a commercial steel-belted tire, said to be among the best on the market. The tests were run on a public highway and on embossed steel surfaces. Figure A-36 shows the data plotted in the order of measurement. The standard deviations are given on each graph. (The decreasing skid resistance on the steel plates is probably due to polishing.)

To evaluate these results, percent standard deviations are

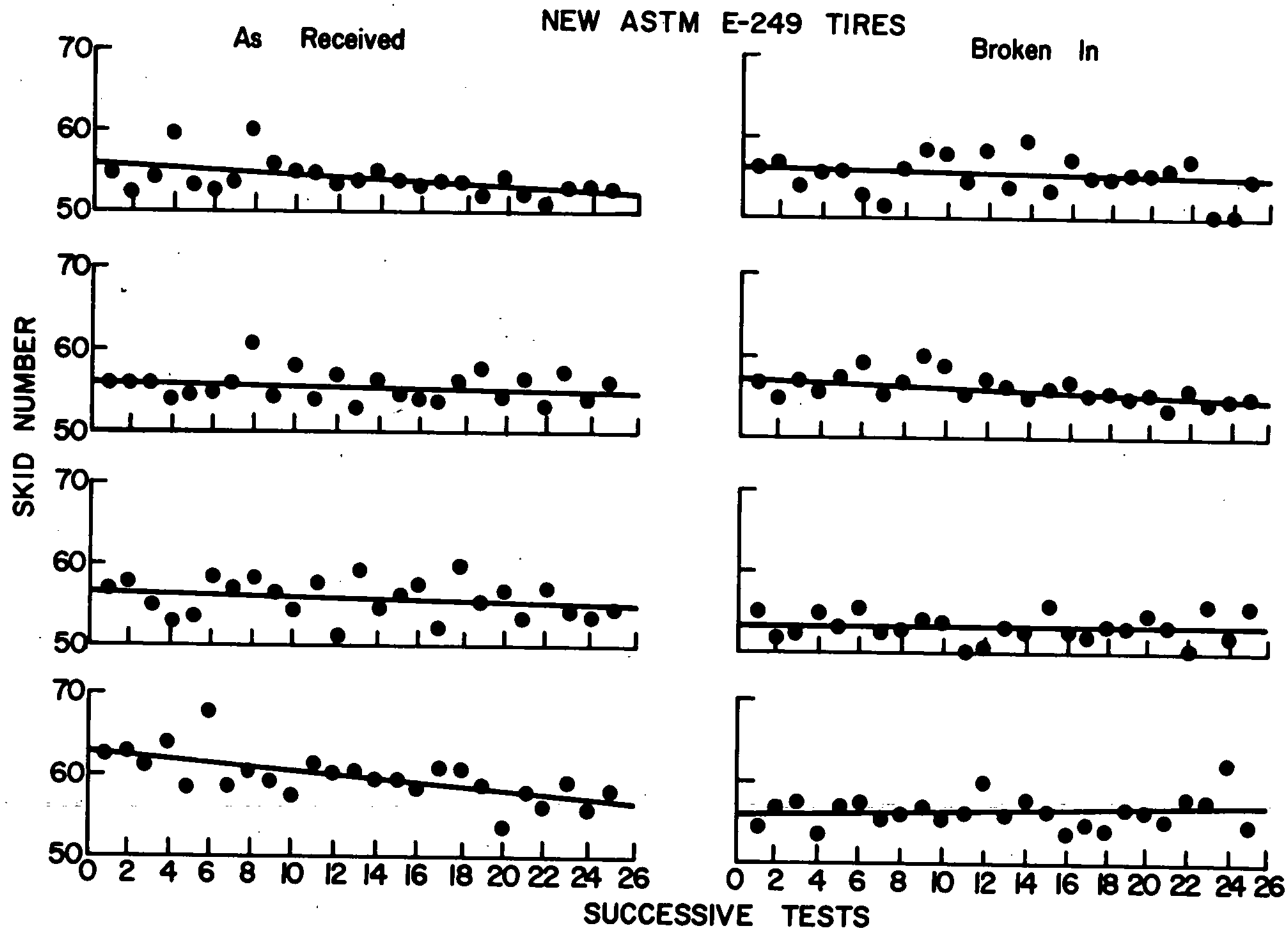


Figure A-33. Repeatability test with new ASTM E 249 tires in both as-received and broken-in conditions.

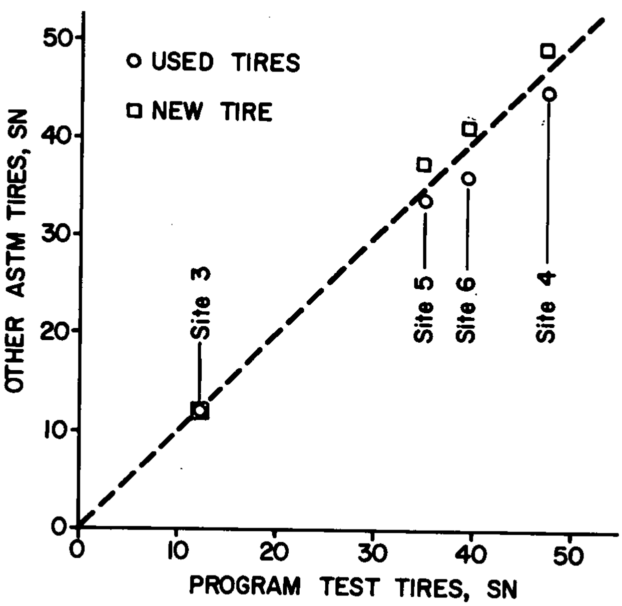


Figure A-34. Skid numbers measured with new and used tires compared to the mean of program tires.

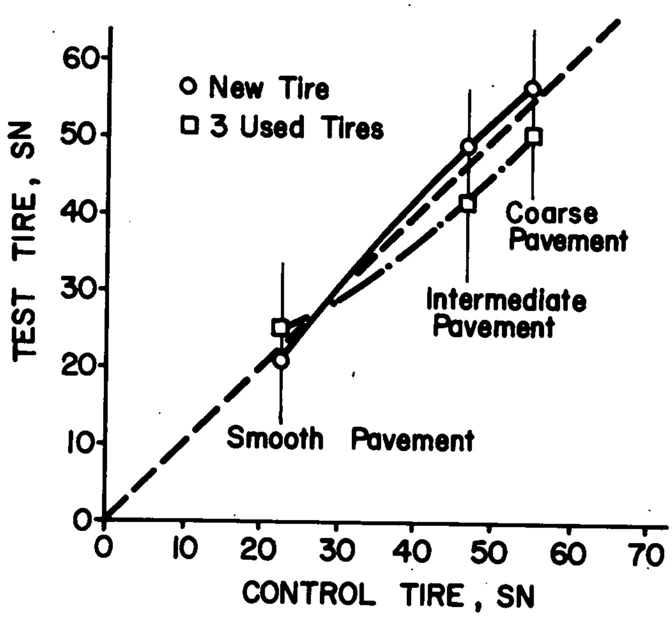


Figure A-35. Skid numbers measured with one new and three worn tires compared to control tire.

used to correct for the differences in skid resistance between the two surfaces (Table A-11). Thus, the data spread is reduced by using Tread Matting instead of a pavement and a radial tire instead of the present standard test tire.

5.2 Comparative Statistical Analysis

In order to gage the effect of tire contributions on skid number variability, a formal statistical analysis was conducted using two different tires: (1) a bias-ply, unbelted ASTM tire in good condition and having approximately 200 miles of break-in use; and (2) a radial-ply, steel-belted Sears Roebuck tire in new condition. The test plan called for 10 runs over each of 10 spot sites with each tire; however, system malfunctions resulted in somewhat fewer measurements being taken. The raw data obtained on these runs are shown in Table A-12.

Statistical tests for the equality of means and variances are derived by assuming that observations are drawn from normal (i.e., Gaussian) distributions. Experimental evidence has demonstrated that while the normality assumption is not crucial in drawing inferences about means, nonnormality of data can significantly affect inferences concerning variances.

Accordingly, each tire-site distribution was subjected to an approximate chi-square (χ^2) test for normality. One such test, outlined by Guenther (*11*), divides the range of the normal random variable into k mutually exclusive intervals and estimates the probability p_i (i=1, 2, . . . , k) of a normal random variable falling in these intervals. The statistic used to test the null hypothesis—H_0: the subject distribution is normal—against the alternative hypothesis—H_1: the distribution is not normal—is

$$\chi'^2 = \sum_{i=1}^{k} \frac{(x_i - n\hat{p}_i)^2}{n\hat{p}_i}$$

(where n = sample size, and $\hat{p}_i$ = estimate of p_i, i=1, 2, . . . , k) which is approximately distributed as χ^2_{k-3} if H_0 is true. A critical region for a test with significance level $\alpha = 0.05$ is given by $\chi'^2 > \chi^2_{k-3;\,0.95}$.

Table A-13 exhibits the results of the normality test applied to the tire comparison data. It can be seen that 17 of the 20 tire-site distributions are accepted as normal on the basis of the test, and that two of the three rejected

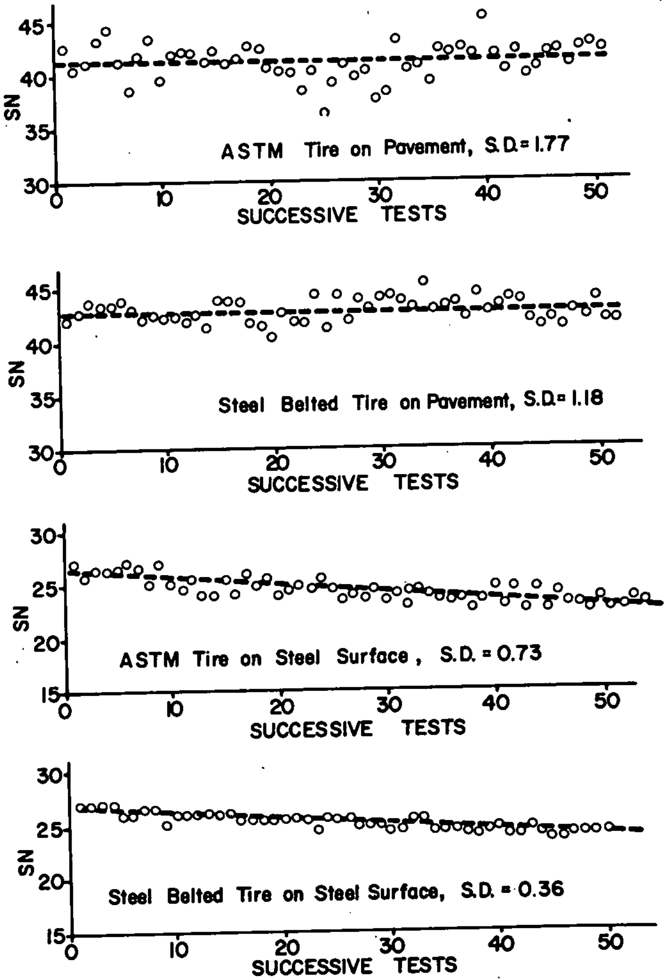


Figure A-36. Repeatability tests with two tires on two surfaces.

TABLE A-10

SKID RESISTANCE WITH ASTM TIRES IN DIFFERENT STATES OF PREPARATION

RUN	SKID NUMBER FOR: USED TEST TIRE	TIRE RUN-IN ON DRUM	TIRE RUN-IN PER ASTM E 274
1	42	44	41
2	43	42	41
3	42	43	40
4	42	42.5	40.5
5	42	41	41
6	40	42	40
7	42	43	40
8	43	41.5	39
9	40.5	40.5	43
10	39	41	42
Mean:	41.55	42.05	40.75
Std. dev.:	1.49	1.092	1.137

Grand mean: 41.44
Mean std. dev.: 0.927 SN

TABLE A-11

PERCENT STANDARD DEVIATIONS AND PERCENT REDUCTIONS FOR TWO TIRES ON TWO SURFACES

TIRE	PAVEMENT	TREAD MATTING	REDUCTION OF STD. DEV. (%)
ASTM E 249	0.0425	0.0284	33
Radial	0.0278	0.0140	50
Percent reduction:	35	50	67

TABLE A-12

TIRE COMPARISON RAW DATA

RUN	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5	SITE 6	SITE 7	SITE 8	SITE 9	SITE 10
					(a) ASTM Tire					
1	37.5	37.5	45.0	44.5	48.0	47.0	43.5	49.0	46.0	46.0
2	38.0	38.0	47.0	44.0	44.0	46.0	42.5	45.0	46.0	44.0
3	38.0	39.0	45.5	40.5	47.0	43.5	42.0	46.0	42.0	43.0
4	36.0	36.5	44.5	43.0	46.5	43.0	40.0	44.0	43.0	40.0
5	35.0	38.0	45.5	41.0	44.5	43.0	43.0	45.0	42.0	41.0
6	33.5	36.0	42.0	40.0	38.5	41.0	42.5	42.0	40.0	38.0
7	31.5	39.0	44.0	40.5	41.5	44.0	43.5	44.5	41.5	45.5
8	35.0	36.0	45.5	39.5	42.5	43.5	43.5	43.0	42.0	43.0
9	35.5	36.5	46.5	40.5	46.5	42.5	43.5	41.5	36.0	—[a]
10	—[a]	—[a]	—[a]	—[a]	—[a]	—[a]	—[a]	—[a]	—[a]	—[a]
					(b) Sears Tire					
1	—[a]	—[a]	—[a]	—[a]	—[a]	45.6	45.2	45.6	45.6	46.0
2	40.8	41.6	45.2	45.6	—[a]	—[a]	44.8	46.4	45.2	44.0
3	41.6	41.6	44.8	42.0	45.6	46.0	43.6	45.2	45.6	44.8
4	37.2	39.6	44.8	43.6	45.2	44.8	44.0	43.6	43.2	43.2
5	37.2	39.2	44.0	41.6	45.6	45.2	44.4	42.8	42.0	41.2
6	—[a]	—[a]	—[a]	—[a]	—[a]	44.8	43.2	46.4	43.6	43.2
7	37.6	38.8	43.2	44.4	43.2	45.6	42.8	45.2	43.6	45.2
8	38.8	41.2	44.4	45.6	44.4	44.4	44.4	43.6	45.2	43.6
9	38.0	41.2	44.8	42.0	42.8	42.8	42.0	44.0	42.4	44.4
10	36.4	38.8	42.8	40.4	44.4	40.4	44.0	45.2	43.2	44.0

[a] System malfunctioned, no data obtained.

(nonnormal) distributions are barely in excess of the threshold value of the critical region.

In applying this test, it is highly desirable to have larger sample sizes than those which were available. Cochran (*30*), for example, talks of sample sizes in excess of 200. Nevertheless, despite the data limitations from these runs, it reasonably can be inferred that the distributions at each site approach normality, and that inferences regarding site-paired means and variances probably can be made without great risk of error.

The bottom row of Table A-13 presents the results of subjecting the composite distribution over all the sites to the normality test. The hypothesis of normality is accepted in the case of the ASTM tire, rejected in the case of the Sears tire. Expectation of normality can be argued to be lower in the composite case than in the case of individual spot-sites because different areas of pavement are included in the composite distribution. Since this test is based upon sample sizes approaching 90, a fair measure of confidence may be placed in its results. Thus, it would be unwise to attempt a statistically rigorous comparison of the composite variances. Inferences about the composite means, however, probably can be made with a reasonable degree of accuracy.

A *T*-test for the equality of two means was conducted on the data. The statistic

$$T = \frac{\sqrt{\frac{n_1 n_2}{n_1 + n_2}}\,(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{(n_1 - 1)s_1'^2 + (n_2 - 1)s_2'^2}{n_1 + n_2 - 2}}}$$

is used to test the null hypothesis H_0: $\mu_1 = \mu_2$ (subscript 1 in this context refers to the ASTM tire, subscript 2 to the Sears tire) against all alternatives (i.e., inequality) at each of the sites. In this expression for T, the n_i are the sample sizes, the $\bar{x}_i$ are the sample means, and the $s_i'^2$ are the unbiased sample variances $\left(\text{i.e., } s_i'^2 = \frac{\Sigma(x_i - \bar{x})^2}{n_i - 1}\right)$. When H_0 is true, T has a t distribution with $n_1 + n_2 - 2$ degrees of freedom. The hypothesis H_0 is rejected at significance level $\alpha = 0.05$ if and only if $|T| > t_{n_1 + n_2 - 2;\, 0.975}$. The results of this test are shown in Table A-14. Rejection of the equality hypothesis occurs at 3 of the 10 sites and on the composite distributions.

In the majority of cases, the skid number distributions tend to cluster about equivalent mean values. There is no clear distinction between the tires in terms of central tendency.

It is logical, then, to seek distinction between the tires in terms of the variability of the results they produce. Under ordinary circumstances, the smaller the variability, the better the results. As a consequence, it is appropriate to test the hypothesis H_0: $\sigma_1^2 = \sigma_2^2$ against the alternative H_1: $\sigma_1^2 > \sigma_2^2$ at each site. The statistic commonly used in such tests is

$$F = \frac{s_1'^2}{s_2'^2}$$

which has an F distribution with $n_1 - 1$, $n_2 - 1$ degrees of freedom when H_0 holds. A test of significance level $\alpha = 0.05$ is obtained by rejecting H_0 when $F > F_{n_1 - 1,\, n_2 - 1;\, 0.95}$.

Table A-15 shows the results of the F test. At 4 of the 10 sites, the variance of the ASTM data exceeds that of the Sears data by a statistically significant amount. At four of the remaining six sites, the ASTM variances are greater than the Sears variances, but by an amount which theoretically may be ascribed to chance. Similarly, at the two sites where the Sears variance was the larger, the differences were also statistically insignificant. On the whole, it is judged that the Sears tire had the advantage over the ASTM tire in terms of variance, although its superiority was somewhat limited.

The last row in Table A-15 shows the composite variances. While the ASTM figure is appreciably larger than that of the Sears tire, statistical significance cannot be defined, as explained earlier.

5.3 Tire Properties and Skid Resistance

Both major components of friction, surface and bulk friction, have been expressed in terms of the modulus and damping factor of rubber (*31, 32*). One of the simplest tests on rubber is hardness measurement, which is related to the modulus (*33*). Hardness and damping were measured on all program tires for the skid tester correlation program to determine uniformity of each tire and among different tires. Hardness was measured with a durometer according to ASTM D 2240.

Damping was determined from rebound tests made with a specially designed pendulum tester. The tire is mounted horizontally on the tester base and is struck by a steel sphere attached to a pendulum. The pendulum is held in

TABLE A-13

NORMALITY TESTS FOR TIRE COMPARISON DATA

SITE	TIRE	TEST STATISTIC, χ'^2	CRITICAL REGION, $\chi^2_{k-3,\ 0.05}$	RESULT [a] NORMAL	RESULT [a] NON-NORMAL
1	ASTM	1.5	3.84	X	
	Sears	1.0	3.84	X	
2	ASTM	0.5	7.38	X	
	Sears	5.0	3.84		X
3	ASTM	1.5	7.38	X	
	Sears	3.0	3.84	X	
4	ASTM	7.5	7.38		X
	Sears	0	3.84	X	
5	ASTM	0.5	7.38	X	
	Sears	0.5	3.84	X	
6	ASTM	3.5	7.38	X	
	Sears	3.5	7.38	X	
7	ASTM	3.5	3.84	X	
	Sears	0	7.38	X	
8	ASTM	3.5	7.38	X	
	Sears	5.0	7.38	X	
9	ASTM	3.5	7.38	X	
	Sears	8.0	7.38		X
10	ASTM	1.0	3.84	X	
	Sears	1.0	7.38	X	
All	ASTM	13.44	14.07	X	
	Sears	22.89	14.07		X

[a] At $\alpha = 0.05$ level of significance.

TABLE A-14

EQUALITY OF SITE-PAIRED MEANS

SITE	TIRE	SAMPLE SIZE	SAMPLE MEANS	TEST STATISTIC,[a] T	CRITICAL REGION, $t_{n_1+n_2-2;\ 0.975}$	RESULT [b]
1	ASTM	9	35.56	−2.949	2.131	Reject H_0
	Sears	8	38.45			
2	ASTM	9	37.39	−4.799	2.131	Reject H_0
	Sears	8	40.25			
3	ASTM	9	45.06	1.367	2.131	Accept H_0
	Sears	8	44.25			
4	ASTM	9	41.50	−1.801	2.131	Accept H_0
	Sears	8	43.15			
5	ASTM	9	44.33	−0.106	2.145	Accept H_0
	Sears	7	44.46			
6	ASTM	9	43.72	−0.808	2.120	Accept H_0
	Sears	9	44.40			
7	ASTM	9	42.67	−2.418	2.110	Reject H_0
	Sears	10	43.84			
8	ASTM	9	44.44	−0.438	2.110	Accept H_0
	Sears	10	44.80			
9	ASTM	9	42.06	−1.804	2.110	Accept H_0
	Sears	10	43.96			
10	ASTM	8	42.56	−1.430	2.120	Accept H_0
	Sears	10	43.96			
All	ASTM	89	41.92	−2.872	1.975	Reject H_0
	Sears	88	43.24			

[a] $H_0: \mu_1 = \mu_2$ vs $H_1: \mu_1 \neq \mu_2$.
[b] At $\alpha = 0.05$ level of significance.

TABLE A-15

EQUALITY OF SITE-PACKED VARIANCES

SITE	TIRE	SAMPLE SIZE	SAMPLE VARIANCES	TEST STATISTIC,[a] F	CRITICAL REGION, $F_{n_1-1,\ n_2-1;\ 0.95}$	RESULT [b]
1	ASTM	9	4.653	1.367	3.73	Accept H_o
	Sears	8	3.403			
2	ASTM	9	1.424	0.892	3.73	Accept H_o
	Sears	8	1.597			
3	ASTM	9	2.153	2.953	3.73	Accept H_o
	Sears	8	0.729			
4	ASTM	9	3.375	0.895	3.73	Accept H_o
	Sears	8	3.769			
5	ASTM	9	9.438	7.550	4.15	Reject H_o
	Sears	7	1.250			
6	ASTM	9	3.257	1.044	3.44	Accept H_o
	Sears	9	3.119			
7	ASTM	9	1.312	1.408	3.23	Accept H_o
	Sears	10	0.932			
8	ASTM	9	5.090	3.329	3.23	Reject H_o
	Sears	10	1.529			
9	ASTM	9	9.153	5.102	3.23	Reject H_o
	Sears	10	1.794			
10	ASTM	8	7.531	4.371	3.29	Reject H_o
	Sears	10	1.723			
All	ASTM	89	13.164	Lack of normality precludes drawing statistical inferences about the composite variances.		
	Sears	88	5.481			

[a] H_o: $\sigma_1^2 = \sigma_2^2$ vs H_1: $\sigma_1^2 > \sigma_2^2$
[b] At $\alpha = 0.05$ level of significance.

a raised horizontal position by a solenoid and released when the solenoid is de-energized. The pendulum strikes the tire when it reaches vertical position. Height of pendulum rebound (h) is measured and the ratio h/h_0 is the resilience, with h_0 being the initial height.

For good repeatability the same tire pressure must be used in all tests, although accurate pressure measurement is not critical. Friction in the test apparatus must be minimized and was achieved by using a pressurized air bearing for the pendulum and a fiber optic-indicating device to measure rebound height.

The damping factors can be computed from resilience by the relationship (*34*)

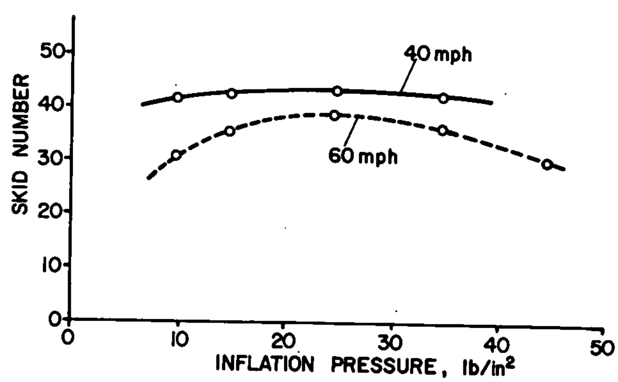


Figure A-37. Skid resistance as function of inflation pressure shown using standard test tire on coarse bituminous concrete pavement.

$$\delta = \frac{4\pi \ln(R^{-1})}{4\pi^2 - [\ln(R^{-1})]^2}$$

This relationship is plotted in Figure A-38.

Measurements were made on the new tires and again after 200 miles run-in. Temperature was measured at the same time. All measurements were made in six positions around the tire running band, three repeat readings in each position. The differences on any single tire were of the same magnitude as differences between tires. This data spread is at least partly due to lack of precision of the measurements. For comparison, similar measurements were made on four randomly selected used tires. All test results are listed in Table A-16. Temperature variations in the measurements were within 10 deg F and could not be related to the measured properties. Run-in affected the properties more than the temperature and generally hardness increased after run-in while damping decreased slightly.

The tires were issued to the participating testers in the correlation program. The mean skid resistance for each tire, as determined from the best corrected data from the program, was regressed against the hardness and damping with the following result

$$SN = 23.5 + 0.49H - 64.25\delta$$

This regression equation shows skid resistance to increase with increasing hardness and decreasing damping. This is contrary to both analytical and experimental results (*31, 32, 35*). No general conclusions should be drawn from this result because only a small range of hardness and damping values were covered here. However, for the range of

TABLE A-16

HARDNESS AND DAMPING OF ASTM E 249 TEST TIRES

TIRES AND CONDITION	HARDNESS		DAMPING	
	MEAN	VARIANCE	MEAN	VARIANCE
20 from same batch:				
Before run-in	62.1	1.40	0.340	0.0020
After run-in	63.0	1.00	0.330	0.0018
4 randomly selected, used	65.4	2.08	0.360	0.0025

variations in these tests, hardness could account for differences of up to 2 SN, damping for 1 SN (Figure A-39).

No attempt was made to correct skid data for hardness or damping. The combined effect was about 1 SN at most because tires of higher hardness also showed higher damping (Figure A-40). Compared to the over-all variability in skid testing, the relatively small variations in tire properties found during this project have no significant effects and no corrections are called for.

6. TEST WHEEL LOAD

6.1 General

The effects of static and dynamic errors in test wheel load are considered. The direct effect of test wheel load changes on skid resistance is relatively small and has been discussed by Kummer and Meyer (*36*). This was confirmed in recent tests and Figure A-41 shows the load dependence of skid resistance as computed from seven tests on different pavements, each test being the mean of 10 lockups. In the range of 885 to 1085 lb (the load range specified by ASTM E 274), the change in skid resistance is about 1.6 SN per 150-lb load change, or about 1 SN per 100 lb. Thus, in the skid resistance range of 30 to 40, a change in the static wheel load of 10 percent will cause a skid number change of about 2 percent. If, however, the wheel load used in computing the skid number deviates by 10 percent from the actual load, the resulting error in skid resistance will also be 10 percent. Errors of almost this magnitude were found during the correlation program.

Reduction of the tolerance on static wheel load from ±100 to ±50 lb is recommended. It will reduce one source of discrepancies in correlation between skid testers from 2 to 1 SN. It is not sufficient, however, that the actual wheel load is within this range; it must be determined with reasonable accuracy so that in computing skid numbers the correct load is used. Scales used to measure wheel load should have at least 0.5 percent accuracy, and wheel load should be checked whenever changes or modifications are made on the tester.

The wheel load during testing is different from the static wheel load. Friction force has an unloading effect on the test wheel, amounting to about 5 percent at a skid number

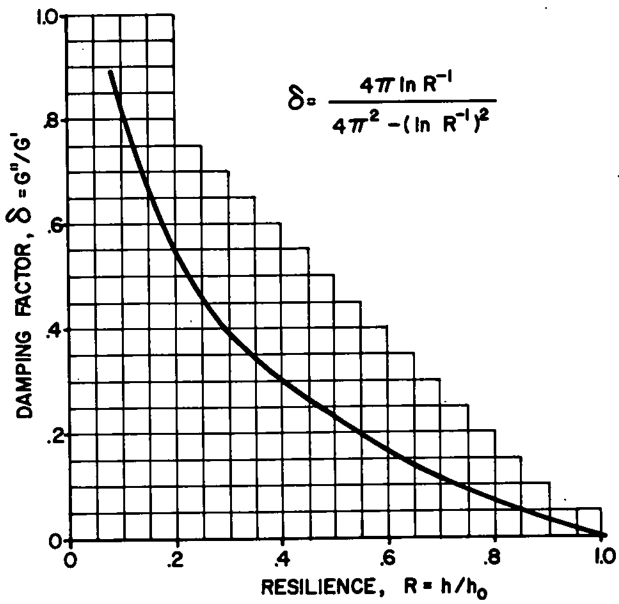


Figure A-38. Damping factor versus resilience.

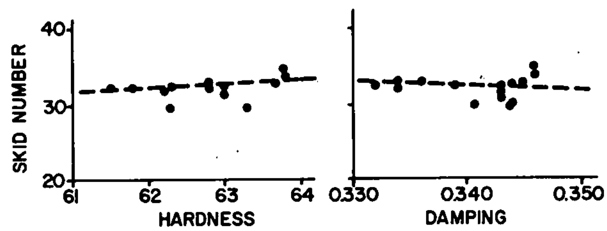


Figure A-39. Mean skid resistance (ANOV–9) versus hardness and damping of the correlation program test tires.

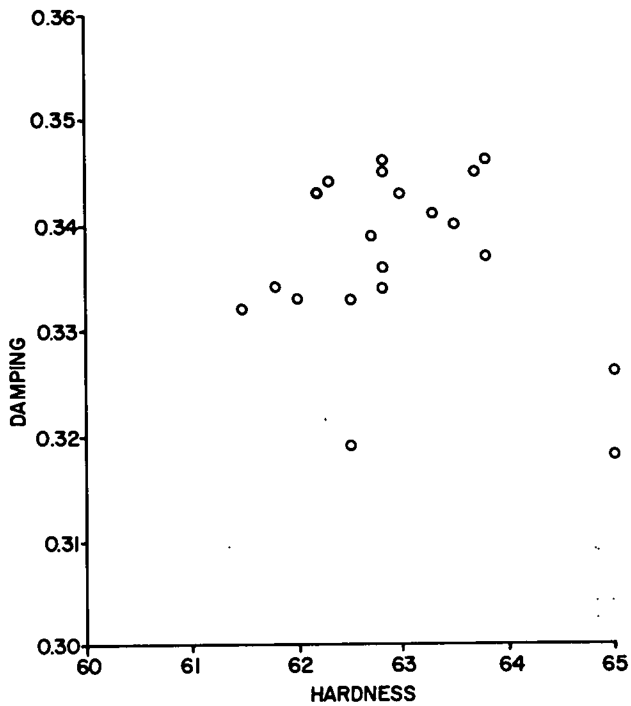


Figure A-40. Damping versus hardness of the correlation program test tires.

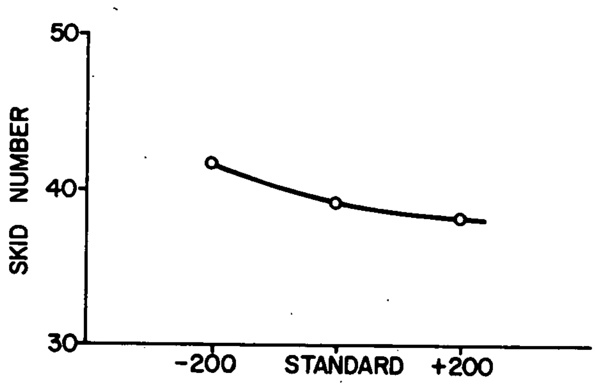


Figure A-41. Effect of wheel load on skid resistance. Standard wheel load is 1,000 lb.

of 50. This effect is corrected for by using the reduced wheel load

$$W = W_o - (H/L)F$$

in which the static wheel load (W_o) and the tester length (L) can be determined quite accurately and do not change in operation. Hitch height (H), however, changes with load changes on the towing vehicle (for instance, emptying of the water tank) and can easily vary by 10 percent. Such a variation is not too critical because it causes only one-half of one percent error in skid number. It is advisable, however, to be aware of the magnitude of this error and not allow larger variation in hitch height to occur without changing the value of H in the computation.

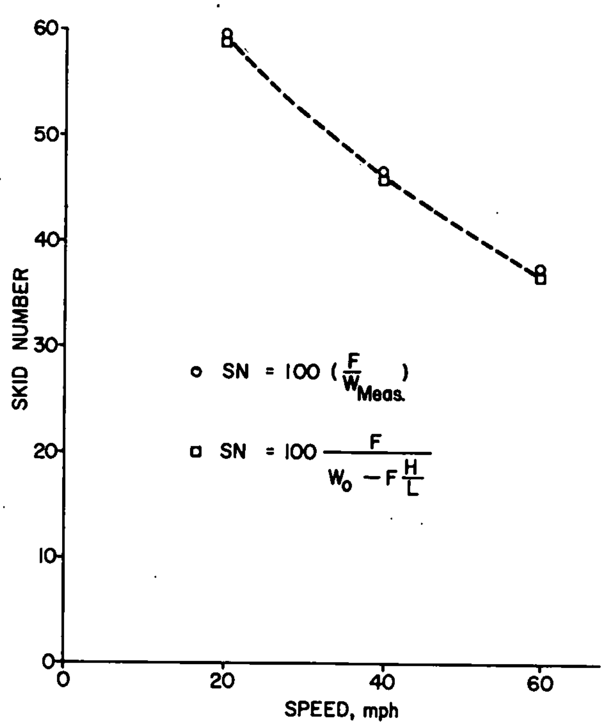


Figure A-42. Mean skid resistance on 24 pavements. The tester had provision for measuring wheel load.

Suspension fatigue can cause a steady lowering of hitch height, which should therefore be checked occasionally.

6.2 Unloading Effects

The unloading effect is caused by the friction force acting on the test wheel in the pavement plane and, strictly speaking, is not a dynamic effect. The same effect is present during calibration on a force platform and has been measured (*37*). In computing skid numbers, the reduced wheel load should always be used. Because the unloading effect differs among skid testers because of their differing geometries, neglect of the correction could be responsible for a difference in the resulting skid numbers of up to 4 percent.

To illustrate, a study of 13 skid testers was made to collect technical data on their individual characteristics for collective comparison. The study showed that trailer length varied between 102 to 122 in. and hitch height between 9.5 to 16 in. (see Appendix 19).

On skid testers equipped with load-measuring systems, skid resistance is computed from measured friction force and simultaneously measured wheel load, which makes correction for the unloading effect unnecessary. Both methods give very close values with practically equal skid numbers when measured wheel loads are used. Figure A-42 shows the mean skid resistance at three speeds on 24 pavements computed from static and measured wheel loads (*38*).

True dynamic effects occur on rough pavements, and the instantaneous dynamic wheel load fluctuates about the static wheel load. The magnitude of these fluctuations depends on the pavement roughness, wheel speed, suspension characteristics, and directional stability. Dynamic wheel load changes on the left wheel of a skid tester were recorded during free-rolling on a level tangent. The records were integrated electronically at 1-sec. intervals. Averaged wheel load changes of 1-sec. or more duration are shown in Figure A-43. The wheel load was off by more than 5 lb nearly 60 percent of the time and by more than 20 lb for 12 percent of the time. The data are for speeds of 40, 50, and 60 mph, with slightly increasing deviations at the higher speeds. The same load changes occur during skidding and, because they may last for the duration of a skid evaluation, a skid number error of the same percentage magnitude as the load error will result, unless wheel load is recorded.

6.3 Aerodynamic Effects

Additional wheel load errors can be caused by aerodynamic effects, especially on trailers having high superstructures or carrying signs, flags, or lights.

In order to measure aerodynamic error, a skid tester having dynamic wheel load measurement capability was fitted with a magnetic tape recorder and driven around the Pavement Durability Facility test track at several speeds. A 30 by 54-in. road sign was installed vertically at the rear of the trailer to act as a spoiler, which simulated the signs and flags used on many test trailers. The spoiler weighed 50 lb and added 37 lb of static load to each test

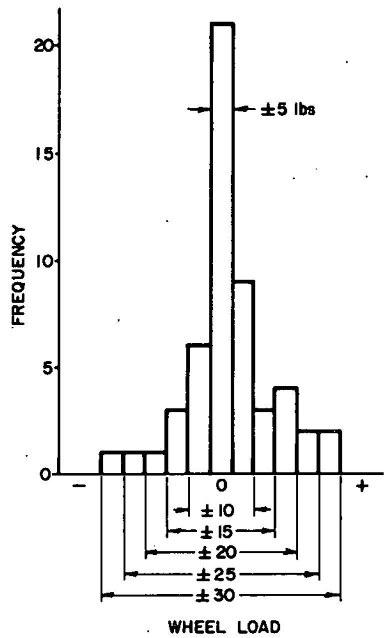


Figure A-43. Histogram (53 measurements) of dynamic wheel load variations from the static wheel load.

wheel. The load instrumentation was zeroed and the tests repeated.

The dynamic wheel load data obtained with and without the spoiler were evaluated in the laboratory by playback of the tape recordings through an electronic integrator. The load was integrated every 1.5 sec for a 1-sec interval. The integrated values for straight travel through one tangent were identified and averaged.

The effective aerodynamic loading as a function of speed is shown in Figure A-44. The estimated accuracy of the load change evaluation is ±5 lb. Without the spoiler this aerodynamically designed trailer body develops essentially no aerodynamic loading at speeds up to 50 mph. With the spoiler added, aerodynamic loads on the test wheel measured to to 40 lb. Aerodynamic loads would be expected to rise with the square of the speed, but the accuracy and precision of measurements were apparently insufficient to show this effect.

The 40-lb aerodynamic load effect would result in a 4-percent error in skid number unless the load change was known and corrected for. It might be expected, for trailers having large-area bodies and especially those pulled by the larger towing vehicles, that errors of this magnitude would occur. The use of flags and signs at the rear of skid test trailers should be avoided wherever possible.

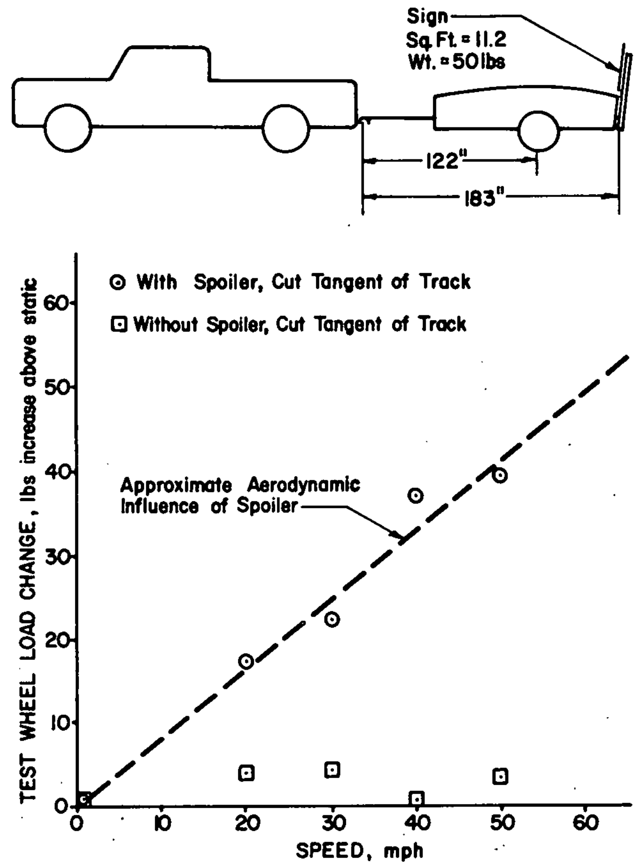


Figure A-44. Aerodynamic loading because of spoiler addition.

7. MEASURING FRICTION FORCE

7.1 General

Obtaining road friction information by means of a locked-wheel skid tester requires measuring a force, torque, or pressure whose value is entered into a computation to arrive at a skid number. Because the force in the contact area of a skidding tire cannot be measured directly, it is the reaction to the force that is measured (*39*). To date this measurement is accomplished in nearly every case by means of a strain-gage-type transducer having power supply, amplifier, and recorder components.

The accuracy of this measurement depends on the level of the transducer signal, relative impedances of transducer output and amplified input, amplifier input configuration, power supply characteristics, transmission line shielding, and level of noise present in the environment of the measuring system.

The transducer is always the most critical element of the instrumentation system. Hysteresis should be well below 1 percent of full scale. Cross-axis load sensitivity, which complicates the calibration and correct use of the transducer, should not exceed 1 percent.

One of the major problems in obtaining accurate strain-gage measurement is noise due to ground loops in the system and electromagnetic interference that can result in a distorted measurement input. This is particularly true when the noise-to-signal ratio is high. To minimize the noise problem, every effort should be made in selecting or designing a transducer that will produce a relatively high-level output. Generally, transducer outputs of 10 mv and above do not present much of a noise problem, and one of several types of amplifiers can be used.

The output of strain-gage sensors on skid trailers, as in most common strain-gage applications, is normally below the 10-mv level. In this case it is not sufficient to select

amplifiers on the basis of type alone. Specific amplifier design characteristics become of major importance. The amplifier for such applications should have:

a. High input impedance that is constant at all attenuator or gain settings, floating with respect to ground and guarded by a floating shield.

b. High gain sufficient for the lowest signal levels.

c. Good zero and gain stability.

d. High common mode rejection, at least 120 db with 1,000-ohms unbalance.

e. Excellent linearity, meaning within 0.2 percent.

f. Low peak-to-peak noise, less than 0.5 percent of full scale.

For rejection of noise, it is also necessary to properly shield lead wires and select the amplifier configuration to be compatible with signal source configuration. For example, a balanced-to-ground amplifier input configuration gives best results when used with transducers that are either balanced grounded or balanced floating. Shielding lead wires should be carried out in accordance with the amplifier manufacturer's recommendations, and the manufacturer's literature and representatives should not be overlooked as sources of guidance in system design.

A choice must be made between a-c and d-c systems. Advocates for each type may be found with the preference usually attributable to an unsatisfactory experience in the past. However, experts with experience in both types will usually claim that good-quality equipment of either type is quite capable of satisfactory performance in this application, and, at best, give only a slight margin of preference to d-c systems. By and large, the choice of a-c versus d-c mode is considered secondary to the choice of high-quality equipment and design.

A recommended feature for any instrumentation system is provision of auxiliary outputs for all signals. A high-level, low-impedance analog electrical voltage available through standard connectors within the tester cab can be a convenience for calibrations and diagnosis.

7.2 Tape Recording Instrumentation

Analog tape recording of skid test data is receiving increasing application. During this project, skid test data were recorded using both a Lockheed Model 416 and a Teac Model R-200 FM tape recorder.

Skid test data were recorded on some of the testers during the correlation program. Though the recorded data were valuable for later diagnosis of certain error sources, particularly zero drift, the over-all data exhibited inconsistencies that precluded conclusive analysis. The inconsistencies were indicative of some of the instrumentation compatibility problems that arise in on-board tape recording of data.

The impedance between the tester instrumentation and the recorder input must be closely matched for accurate signal transfer and reproduction. The transducer signal level input to the recorder must be of the proper magnitude to provide full utilization of the FM recorder range, thereby permitting reproduction to the best accuracy of the recorder.

The recording equipment must be reliable and capable of working on an inverter supply or the standard rotating machine supply without diminishing accuracy and with immunity to power supply fluctuations from other instrumentation going on and off during a skid test.

The recorded signal is no more accurate than the recorded zero and calibration values. These reference values must be recorded in lengths sufficient to allow laboratory adjustments and calibrations during playback.

An accuracy-checking method, which can be employed with recorders that do not have this built-in capability, is to record a reference frequency or voltage, such as transducer excitation, on additional channels. This signal can later be used to check recorder performance and, in some cases, would allow correction of erroneous data.

Magnetic tape recorders may be expected to increase in popularity in the skid tester application. In addition to the advantages of providing permanent records of test programs, allowing laboratory analysis of skid test data, and opening opportunities for computer processing of data, tape-recorded data were found to be a valuable research tool in this project because of their capability for undergoing repeated and varied analyses. Wherever a tape recording method is introduced for routine use, it is critical to choose and use the equipment in a fashion that will not lead to new error sources in skid tester performance. Tape recording of data is not recommended as a substitute for the conventional strip chart recorders because of the subtle errors that can occur in recording and because the strip chart records provide a quick assessment of test validity.

However, inadequate resolution of chart recorders is a frequent shortcoming on skid testers. Among a sample of 20 skid testers, only 5 had chart recorders with resolution better than 10 lb per division. One tester had the gain set as low as 40 lb per division. Poor resolution causes the accuracies of calibration, zero setting, and chart reading to be low, which compounds the potential error threefold.

Good instrumentation does not ensure good results unless proper procedures for its use are followed. Zero setting and calibration checks ideally should be done under no-load conditions, which are, however, almost impossible to obtain in normal operation. Adjustments, if needed, should be made according to specifications. Recommendations for correct use of the instrumentation are given in Section 8.

8. OPERATING PROCEDURES

Accuracy of skid test data depends as much on the operating procedures used with the instrumentation system as on any other factor. The great variety of instrumentation types, designs, and brands used on different testers makes it impossible to specify a common detailed operating procedure applicable to all. Therefore, the tester operators must be knowledgeable about how to use the instrumentation properly and strive to achieve the accuracy required.

There are two categories of operating procedures, one governing the test cycle, the other prescribing all other activities in skid testing. The test cycle is automatically

controlled by the cycle timer and, therefore, this part of the operating procedure normally remains constant for any one agency, although it does vary widely among agencies.

8.1 Skid Test Cycle

The cycle timer controls the instant and duration of water and brake application and fixes the minimum time between two consecutive cycles. Other functions are also controlled by the cycle timer, but these do not affect the performance of the skid tester.

The part of the skid cycle of concern comprises the time from brake application to wheel lock-up and the time during which the locked wheel skids. Lock-up time depends on rate of brake application, brake torque, and the friction force resisting lock-up. Thus, for a given interval of brake activation, as determined by the timer setting, the time of locked-wheel skidding decreases as the lock-up time increases. For this reason brake activation time should be chosen to accommodate the maximum expected lock-up time. Because the former varies with individual braking systems, no time can be specified; it must be determined on a high-coefficient surface. The total length of the braking cycle, according to ASTM E 274, should be not less than 2 sec. The 2-sec cycle has been found to be too short (Section 10) and the duration should be increased. The upper limit is determined by practical considerations, such as tire wear as well as temperature and conservation of water. If the cycle timer is readily adjustable, good practice may be to increase the length of the test cycle when higher accuracy is required, as in a research project or in a correlation program.

The watering cycle should be somewhat longer than the braking cycle. It is important that it begin prior to the brake application. Rolling the tire for a second over the wetted pavement helps to cool any existing hot spots from preceding skids.

In correlation studies it is important to be aware of differences in timing cycles of different testers. Roadside markers that indicate the start of the test cycle should be moved as needed so that all skids at all speeds occur on the same stretch of pavement.

8.2 Other Activities in Skid Testing

Aside from the automatically controlled test cycle, other procedures in skid testing are usually regulated by written or oral instructions to the operator. These concern the selection of test sections, number and spacing of tests per test section, test speed and lateral position on the road, instructions for field calibration checks of force- and speed-measuring systems, and related tasks such as the method of site identification, and recording of weather information and temperature measurement.

Certain instructions often are too flexible and require an operator to make spot decisions. Acceptance, rejection, or repetition of a suspect test during inventory testing is properly left to the operator. Repetition of a test at that time obviates the need to return for repeat tests should the data be found suspect during evaluation at the home office. However, even though a decision may be left to the discretion of an operator, the criteria by which the decision is to be made should be defined and adhered to. Assuming proper calibration and operation of the tester and watering system, the two factors most likely to affect skid resistance are deviations from the desired test speed and from the intended wheel path. The effects of both deviations have been discussed in previous sections.

Field check of instrumentation zero and gain calibration requires a clear understanding of the system operation. A high-resolution readout is frequently considered unnecessary because of the imprecision associated with other aspects of skid testing. However, poor resolution causes systematic errors and adversely affects the consistency with which the instrumentation can be adjusted. In practice the imprecision due to readout resolution leads to equivalent errors in setting zero, setting gain, and reading the friction trace. For this reason, a 5-lb (force equivalent) chart resolution is recommended, and in any case maximum care must be used in adjusting the instrumentation to achieve repeatability and accuracy.

Aside from chart resolution, signal noise is an element in readout resolution. Although noise such as a 60-cycle hum can be visually averaged out, its magnitude should be minimized by good design, particularly in shielding, grounding, and choice of amplifier configuration. Noise in excess of 1 percent of chart full-scale is an indication of inadequate design and is an unnecessary detriment to precision in use.

Setting the *static* zero, corresponding to zero horizontal force on the test wheel, is the most routine and critical task in daily preparation for testing. The mark of a good instrumentation system properly used is a repeatable zero that requires no daily adjustment. Often the system's capability is misused because of improper zero-adjustment procedures or inadequate warm-up time before checking zero, and inherent repeatability is not recognized.

The static zero should be set with the maximum possible accuracy and, in the worst case, within ±5 lb (force equivalent). Many tester operators, when setting zero, are unaware of the magnitude of residual forces that can act on the stationary test wheel because of brake drag, bearing friction, and an uneven surface under the wheel. The recommended procedure for setting zero is as follows:

1. With the instrumentation warmed-up, stop the tester on a clean and level paved surface.
2. Before adjusting zero, roll the tester forward and backward slightly while observing the magnitude of the residual forces in each direction.
3. Adjust the zero, only if necessary, to center the chart base line between the two limits.

The surface condition is especially important with testers having a force-measuring transducer because any unevenness creates a sine-angle force component from the test wheel load. Typically, a 1-degree longitudinal slope will result in a 17-lb residual load because of this effect alone.

Brake drag is potentially one of the largest sources of residual zero force. Since the drag is not usually equal in both directions, it should be minimized by adjustment and, if it exceeds 10 lb (force equivalent), it should be periodically measured in both directions with the wheel raised and the zero adjustment procedure modified appropriately.

An alternate way to determine zero is to raise the test wheel off the ground. Because the transducer is unstressed, this may be called a *true* zero. However, all transducers exhibit a cross-axis load sensitivity that causes an apparent zero shift when the load again rests on the test wheel. If this shift is significant (more than 5-lb friction force equivalent), the true zero should not be used as the reference in testing. Since the true zero is always repeatable, it can serve, however, as a good reference against which to check repeatability of the static zero.

On the highway the friction transducer output takes on a *rolling* zero because of rolling resistance, brake drag, and bearing friction. It is good practice to routinely monitor this value as an indication of zero drift. The rolling zero, even with allowances, should not be used for reference in determining skid friction level. The absence of a rolling zero different from static zero usually indicates insufficient readout resolution or excessive transducer hysteresis.

The next step is to check calibration, which is discussed separately for the three different systems encountered.

a. Strain-gage transducer with shunt resistor for calibration pulse.—In this case the calibration pulse will shift together with the zero and should be checked at the same time. Its position relative to zero is the gain and should remain stable. Adjustments, when needed, should be made by setting the specified value relative to the uncorrected zero signal. When evaluating the chart after testing, zero corrections must be made.

b. Strain-gage transducer with constant voltage as calibration pulse.—In this case the calibration pulse is not affected by residual load. Gain must be checked and adjusted if needed relative to the corrected zero, which is the static zero halfway between the two zero signals. Chart evaluation after testing should be made relative to the calibration signal and no correction need be applied, provided no further drift occurs. (The disadvantage of this system is that it does not test the condition of the strain-gage bridge.)

c. Hydraulic force cell and pressure transducer, with known pressure applied to force cell as calibration signal.—In this system the gain is checked by applying a regulated pressure to the force cell. It is independent of residual load just as system (b) and adjustment, if needed, is made in the same way.

It is advisable to record the calibration pulse of a rolling test wheel before every skid. This can be done automatically by the cycle timer, which can be filtered if it contains too much noise. (When filtering, sufficient time must be allowed for the pulse to reach its full value.) This calibration pulse will read somewhat higher than under stationary conditions, because of rolling resistance, which is, however, likely to remain constant (for any given speed). A continuously shifting calibration signal, therefore, indicates drift.

9. CALIBRATION OF SKID TESTERS

9.1 General

This section deals with laboratory calibration and field checks of the torque or force-measuring system. Speed, water flow, and wheel load calibrations are discussed in the respective sections of this report.

Because skid testers operate at relatively high speeds, the ultimate calibration would be a dynamic one conducted on surfaces of known and invariable friction properties. Such surfaces are not available at present; therefore, a static calibration of the complete system must be made as the next best alternative.

Two calibration methods are presently in use. One method calibrates the system without the tire by applying a known torque to the wheelhub. This calibration is a check on the linearity of the fixed parts of the measuring system, and it should remain stable provided all components are in good condition. The second method includes the tire in the calibration by applying a measured friction force to the tire. Only the latter method calibrates the complete measuring system, including the test tire, and is recommended by ASTM E 274.

In the course of this work both methods were considered, tried, and discussed with proponents of each. The conclusion is that these methods should not be considered as alternatives but rather as complementary, and required, steps in the calibration procedure. A skid tester is a complex measuring system with several components and calibration of the system would not be in order unless all components have been, or are known to be, calibrated. Thus, platform calibration should be done only when the complete system, except for the tire, is known to function properly. This can best be verified by calibrating without the tire.

9.2 Torque Arm Calibration

Calibration without the tire is done by applying a known torque (or known force for force-measuring system) directly to the wheelhub. The torque or force should be applied in the plane of the wheel and as close as possible to the centerline of the tire. This precaution will minimize the effect any bending moment may have on the measuring system. The means of measuring the applied torque or force must be at least as accurate as the one used on the calibration platform and, when dead weights are used in torque application, care must be taken to maintain the torque arm in a horizontal position.

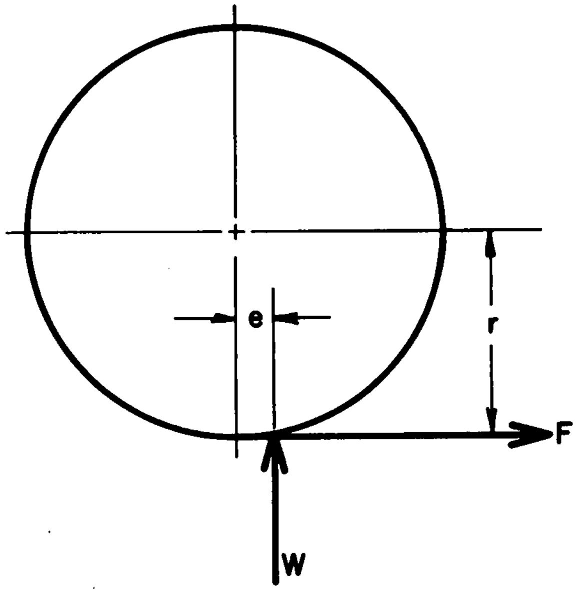
The torque arm device shall consist of the torque arm and a load system. The torque arm shall be designed to attach directly to the hub or rim of the test wheel. It shall provide for load application at points no less than 4 ft (1.2 m) nor more than 8 ft (2.44 m) from the center of the test wheel. One or more load application points shall be located from the wheel center with an accuracy of ±1/8 in. (3.18 mm) and shall allow only for a vertical force direction. The arm shall be counterbalanced, or have provision for counterbalancing, so that a value of zero torque can be achieved.

A load system consisting of an appropriate set of weights or a tension-type force transducer shall be provided to load the torque arm. The system shall have a capacity of at least 100 lb (45.5 kg) for an 8-ft (2.44 m) arm length or 200 lb (91 kg) for a 4-ft (1.22 m) arm length. The

accuracy shall be within ±½ lb (0.227 kg) and traceable to the National Bureau of Standards.

Calibration procedures require that:

1. All instrumentation for the transducer system shall be turned on and allowed to warm-up.
2. If the test tire is to remain installed during calibration, it shall be balanced and be free of excessive dirt.
3. The trailer shall be within 5 deg of horizontal in the longitudinal and lateral directions and shall be supported such that the test wheel is clear of the ground and the transducer unstressed.
4. The torque arm shall be installed and the test wheel brake locked.
5. Torque values from 0 to at least 800 ft-lb (11.7 kg-m) shall be imposed in increments of approximately 100 ft-lb (13.8 kg-m). At all times the load must be within 5 deg of vertical and applied at a point which is within 5 deg of horizontal from the test wheel center. Calibration should be performed with increasing and decreasing inputs in order to detect any hysteresis in the system. At each incremental value, the torque transducer hysteresis shall be determined by momentarily overloading (or underloading) the torque arm by hand, then slowly releasing the overload (or underload) torque to achieve the maximum (or minimum) transducer indication.
6. The results shall be plotted on a rectilinear graph. The input torque is calculated as the product of the force and torque arm length. The calibration is represented as a smooth curve passing through zero and the midpoints of the maximum and minimum output torque values at each increment of input torque.



$$T = Fr + eW \text{ (ft-lb)}$$

$$e = \frac{12\,(T - Fr)}{W} \text{ (in)}$$

$$\text{ERROR} = 100\left(\frac{T/r - F}{F}\right) \text{ PERCENT}$$

Figure A-45. Torque components acting on a test tire footprint.

9.3 Platform, or Force Table, Calibration

Platform calibration should be repeated frequently, while torque or force calibrations need be repeated only when system malfunction is suspected. On a skid trailer having a force-measuring system, both calibrations should be in close agreement. On one having a torque-measuring system, some difference between calibrations is to be expected because of the shift of tire contact patch with the calibration platform (Figure A-45). The difference, for ASTM E 249 test tires, is estimated to average 5 percent (*40*).

The calibration system consists of a calibration platform, a horizontal drive mechanism, and a force transducer.

The calibration platform on which the test wheel is placed shall have a flat top no less than 6 in. (15.2 cm) wide by 10 in. (25.4 cm) long with a high-friction surface. The table shall be supported by an arrangement of bearings permitting longitudinal motion and capable of sustaining a vertical load of 1,500 lb (682.5 kg). If the bearings constrain the table in the lateral direction, they shall be capable of sustaining a 300-lb (136.5 kg) lateral force. While subject to the total vertical and lateral loads, the table shall move in the longitudinal direction with no more than ±10 lb (4.55 kg) of resistance. The longitudinal movement shall be at least 2 in. (5.08 cm), limited only by the stroke of the horizontal drive mechanism.

The horizontal drive mechanism, a force- or displacement-type driving system, shall be capable of developing a force of 80 percent of the wheel load. The force shall be applied along the longitudinal centerline of the table and be as close to the top surface of the table as possible.

The force transducer shall link the horizontal drive mechanism to the calibration platform. The transducer shall have a capacity equal to or greater than 80 percent of the wheel load with resolution and accuracy to ±5 lb (2.27 kg) or better. The transducer shall be mounted in a manner appropriate for its type to ensure that cross-axis forces cannot adversely affect accuracy.

Calibration procedures require that:

1. The test vehicle and calibration platform instrumentation shall be turned on in advance of calibration to allow them to warm-up.
2. The test tire shall be inspected for damage, inflated to its rated pressure, and then operated for 5 miles (8 km) under normal test load at an average speed of 40 mph (64 kph).
3. The test vehicle shall be positioned with the test wheel resting on the center of the calibration platform. When necessary, blocks or jacks shall be placed under other vehicle wheels or the hitch point to bring the test trailer within 1 deg of the normal level attitude in the longitudinal and lateral directions.
4. The calibration platform shall be centered, levelled within 1 deg laterally and 0.3 deg longitudinally, and aligned longitudinally within 1 deg of the trailer axis.
5. With the calibration platform supporting the full

wheel load and with the test wheel brake released, the calibration platform shall be positioned near the beginning of its stroke, and the zeros of the calibration platform and tester shall be set.

6. The table shall be operated several times through its full stroke in order to confirm that no more than 10 lb (4.55 kg) of static force is registered at any point by either the calibration platform or the test wheel instrumentation.

7. With the calibration platform again near the beginning of its stroke, engage the test wheel brake and record the simultaneous readings of the calibration platform and test wheel instrumentation. The test wheel output shall be on the strip chart recorder or other read-out device normally used for friction determination.

8. The calibration platform shall be operated to increase the force on the test wheel in approximately 100-lb (45.5 kg) increments up to at least 80 percent of wheel load. At each increment, the drive shall be stopped to allow the force to stabilize for 1 min or more. While the indicated platform and test wheel forces have stabilized, simultaneous readings of both forces shall be taken. In the event a load increment is exceeded, the force shall be decreased below the desired value, then approached again in the increasing force direction.

9. After reaching the maximum desired force, the applied force shall be returned to zero in the same increments and, using a similar method as indicated in the preceding paragraph, approach each increment in the decreasing force direction. When the calibration platform force has returned to zero, simultaneous readings of both force values shall be recorded both before and after brake release.

9.3.1 Safety Precautions

Nonparticipating personnel should be cautioned to stand clear of the actuated calibration platform. The platform should be constrained to prevent slippage when force is applied, and personnel should be alert in the event the constraints fail.

9.3.2. Interpretation of Results

1. All data shall be plotted on a rectilinear graph that plots the test wheel output (ordinate) versus the indicated force of the platform (abcissa). The points of increasing and decreasing force are connected with straight-line segments forming the calibration hysteresis loop.

2. If at any value of platform force, including zero, the hysteresis exceeds 10 lb (4.55 kg), the calibration must be considered invalid either because of defective equipment, defective procedures, or insufficient stabilization time at each data reading. In this event, the calibration must be repeated.

3. If the hysteresis limit in the preceding paragraph is satisfied, the calibration is considered valid and the calibration curve is prepared by drawing a smooth curve through the midpoints of each pair of data corresponding to increasing and decreasing force.

4. The calibration shall be dated and the test tire identified by serial number. This calibration shall be used in all tire-pavement friction determinations made with this test tire until superseded by another calibration.

9.3.3 Performance Verification of the Apparatus

The calibration platform performance shall be verified at periodic intervals appropriate to its use and maintenance by the following tests:

1. The calibration platform force transducer shall be calibrated for accuracy against a reference transducer traceable to the National Bureau of Standards. The calibration shall be performed with the transducer mounted in the platform by attaching the reference transducer by a fixture such that it opposes motion of the force table through an element having longitudinal stiffness less than or equal to 1,000 lb per inch (179 kg/cm).

2. After each such calibration, the bearing friction of the calibration platform shall be determined by loading the platform with 1,500-lb (682.5 kg) dead-weight vertical load and, if laterally constrained, a 300-lb (136.5 kg) lateral load, and repeating the calibration observing for changes in hysteresis or sensitivity.

3. After each such calibration, the platform cross-axis load sensitivity shall be determined while changing the vertical load by 200 lb (91 kg) and, if appropriate, by changing the lateral load through its full range.

4. Individual or total errors due to bearing friction and cross-axis sensitivity greater than 10 lb (4.55 kg) shall be considered excessive.

9.4 Errors in Calibration

During the correlation program, torque and force calibrations were compared for testers No. 5 and 9. The footprint shift and error were computed and found to be 0.405 in. and 7.6 percent for tester No. 5 and 0.55 in. and 6.25 percent for tester No. 9. These errors result primarily from the additional torque due to shift of the tire footprint, but probably include some other contributing factors. Skid-resistance measurement with a system calibrated in torque only may be in error on the high side and, therefore, platform calibration is recommended.

When the two calibrations fail to agree within an explainable and acceptable difference, errors may be traced to either the tire, the calibration platform, or calibration procedure. Incorrect inflation pressure, out-of-roundness, or other nonuniformities of the tire, including flat spotting, can cause calibration errors. Such errors can be detected by calibrating in several different tire positions and flat spotting can be alleviated by running the tire for a few miles before calibration.

Some slight hysteresis in calibration is almost unavoidable. Figure A-46, a typical calibration chart, shows what must be considered acceptable hysteresis of approximately 10 lb. Such hysteresis may be caused by the tire or the calibration platform, though well-designed air-bearing platforms have negligible hysteresis. (Hysteresis should be absent in torque calibration, unless caused by the measuring system.) In tracing the source of hysteresis, calibration at higher inflation pressure (50 psi) can be used to reduce the contribution of the tire to hysteresis.

Experience has also shown that calibration errors can

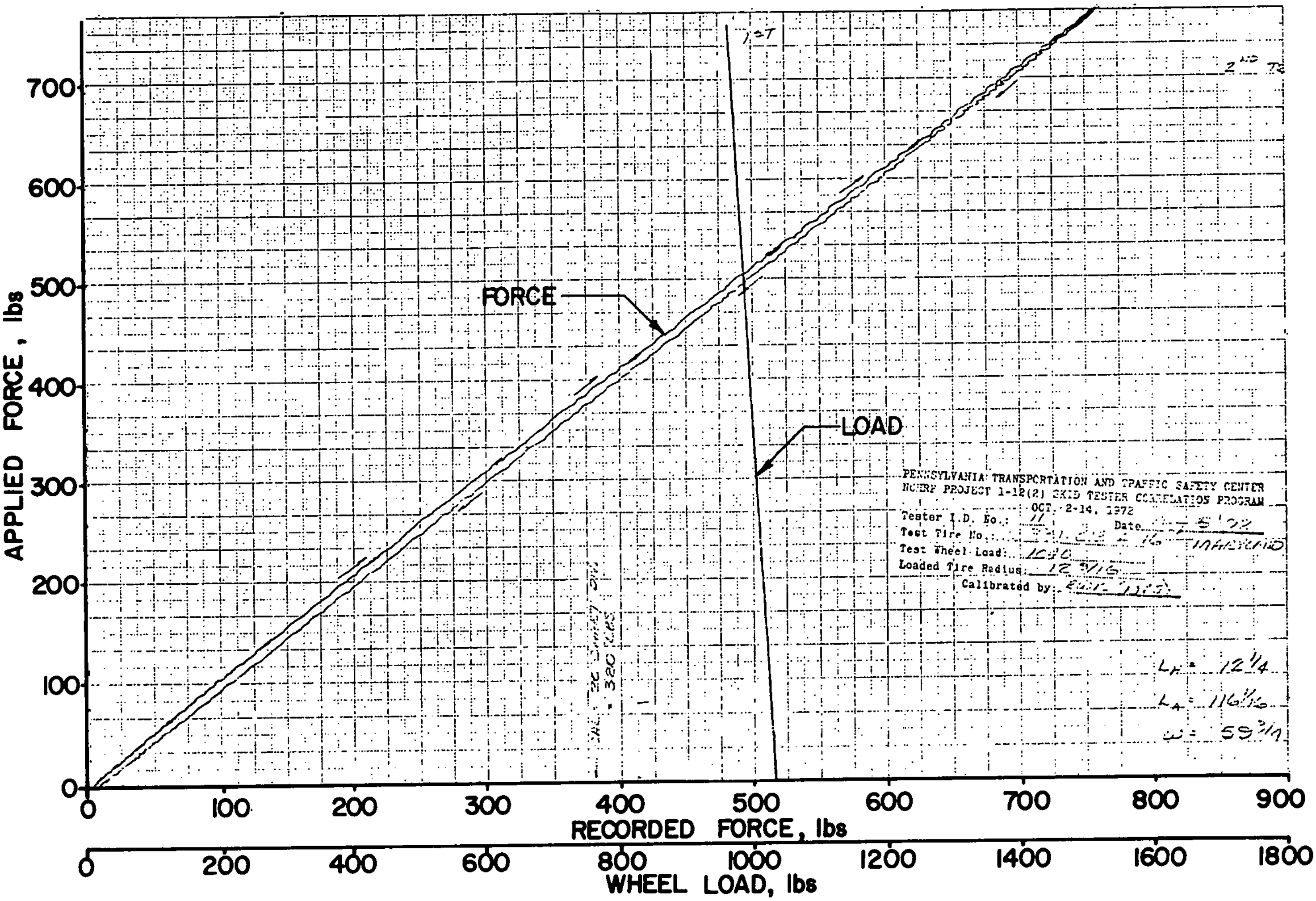


Figure A-46. Typical skid tester calibration curve on air-bearing platform. Also shows load decrease under applied force.

be introduced when braking both wheels during calibration. The explanation most probably lies in the reaction of the suspension system. A rigidly mounted axle or independently suspended wheels would presumably show no interaction between the wheels. With present systems it is important, however, to brake only the wheel being calibrated.

The desired over-all accuracy for torque calibration is ±0.5 percent or ±2 lb (equivalent friction force), whichever is smaller; and for platform calibration, ±2.0 percent or ±5 lb (equivalent friction force), whichever is smaller.

These accuracies cannot be determined directly. For the purpose of skid tester users, accuracy may be defined as "the greatest difference between a certified calibration (such as certified by the FHWA Field Test and Evaluation Centers or the manufacturer) and any other calibration performed on similar calibration equipment." This definition presupposes that the accuracy of the calibration equipment has been verified. (It is beyond the scope of this report to deal with accuracy of calibration equipment. It should be checked in a qualified laboratory. A simpler check, sufficient for detecting gross error, is to compare such equipment against equipment available at the FHWA Field Test and Evaluation Centers.)

Field checks of calibration equipment should be performed regularly as specified in ASTM E 274. Strain gage systems use either a shunt resistance across the strain-gage bidge or a fixed reference voltage. The former method is preferable because it has less potential for error. With hydraulic systems a known pressure can be applied to the system. All these "calibration" methods are incomplete in that they check only the condition of the instrumentation system.

A good check on gross malfunctioning is to run control tests before and after every test series on a surface that is known to have consistent skid resistance.

10. DATA EVALUATION PROCEDURE

10.1 General

To determine a skid number from the recorded signal requires several procedures, each of which is a potential error source. The first step is to find a mean value of the signal, that is, reading the chart relative to a reference value, which may be zero or the calibration signal. Both

may be in error as discussed in Section 8. This value is then converted into force or torque, depending on the calibration method used. From this the skid number is computed, using the static or measured wheel load (Section 6). Calibration and wheel load errors have been discussed in the respective sections. In this section only the problems connected with averaging the recorded trace will be discussed. Skid testers with wheel load recording systems have two traces to evaluate for every skid and the following discussion applies to both, but not to speed and other recordings.

The most widely used method of trace reading is by visual averaging ". . . from a point of approximately 0.2 sec after wheel lock-up to a point 1.2 seconds after . . ." as specified by ASTM E 274. Wheel lock-up is defined as "the start of steady-state friction." Averaging and fixing the point of start of steady-state friction will clearly suffer from subjective errors.

To determine the typical magnitude of subjective error, the traces shown in Figure A-47 have been evaluated by four men, all experienced in skid-data evaluation. The difference in evaluation was 1 SN for the four traces of the first set and the last trace of the second set, and 2 SN for the remaining three traces. When one of the men reevaluated the same traces a week later, differences between his two sets of evaluations were about the same as those between the four men. Thus typical skid-resistance traces will be read within 1 or 2 SN, either by different operators or by the same operator at different times. The difficulty in trace evaluation increases with trace noise, as would be expected.

10.2 Electronic Methods of Data Evaluation

Electronic integration of skid resistance data has three basic advantages over the human evaluation method still employed by most users: the skid data are available immediately, it involves less personnel-time expenditure, and the data can be obtained with much higher accuracy. These advantages have been recognized and several organizations are already using or are planning to establish automatic data processing systems.

Electronic data integration systems generally take the form of signal-integrating circuits that are actuated over the desired evaluation interval in the skid test cycle to produce an analog and/or digital indication of average friction level. The systems can have high resolution and accuracy, but their added complexity offers opportunities for additional error sources in locked-wheel skid testers. From the experience gained in using automatic data integrators in this research and from observing some of the

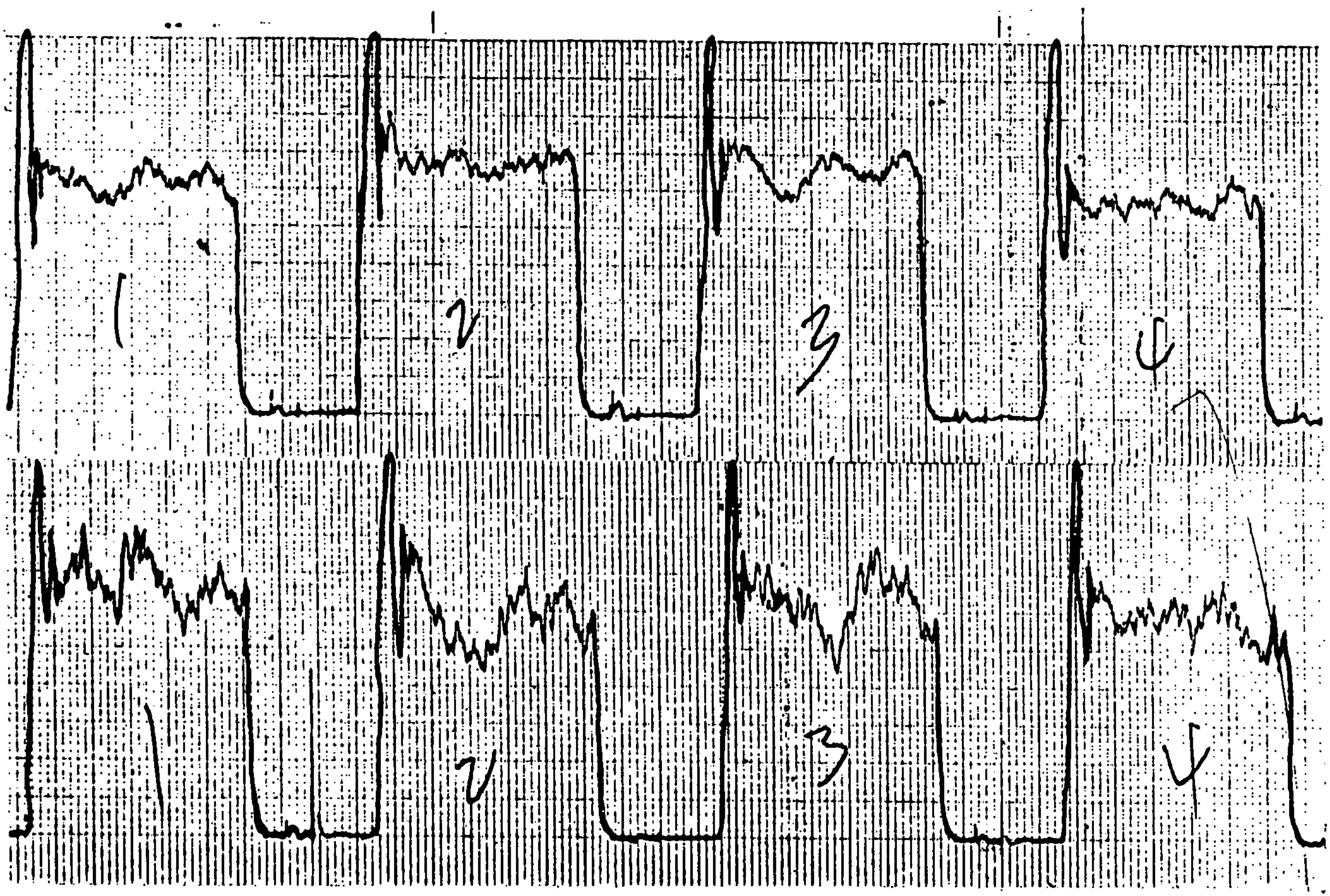


Figure A-47. Typical skid-resistance recordings from a two-wheel tester running at 40 mph and whose chart speed is 20 mm per second.

other users, design and operation considerations formulated as a guide to avoid unsatisfactory applications are:

1. An electronic integrator should supplement rather than replace the conventional strip chart recording of skid test data. Ideally the integration interval and integrated value should be displayed on the strip chart. Until absolute confidence in the consistent performance of the integrator is obtained, the integrated value should be routinely compared against the strip chart record.

2. Few of the commercially available integrating digital voltmeters are suitable for integrating skid records. Except for the more expensive models, integration times of 1 sec or more are not available. Sampling and display rates on such instruments can also be misleading because the integration time is only a fraction of the time implied by the sampling rate. Averaging of consecutive readings over 1 sec is erroneous.

3. Triggering of the integration must be externally controlled. Operation from the cycle timer is the simplest method although it does not comply with ASTM E 274. The ideal system would trigger (with a delay) from a transducer that detects the test wheel lock-up. With any system, it is essential that the triggering point be sufficiently delayed that under the worst conditions of brake fade and high coefficient it does not occur prematurely.

4. The electronic integrator must be suitably chosen to operate in the shock and temperature environment of typical skid testers. The accuracy must not be dependent on the voltage and frequency stability of the power source.

5. Procedures for the set-up and use of the integrator should be well defined. The integrator should be calibrated in a torque or force plate calibration of the tester. The system zero and calibration references should display on the integrator.

10.2.1 An Example

In the absence of a commercially available integrator of the required capabilities, an integrator was constructed to facilitate certain portions of the research in this project (*41*).

The integrator, shown in Figures A-48 and A-49, was based on the operational amplifier type of integrator. A crystal clock provides the precise timing required for the selectable integration interval and delay times. Triggering is selectable by a manual, remote, or internal mode. The latter triggers on an input signal level that detects the brake actuation point and allows the integrator to be used automatically with tape-recorded data. Input signal conditioning amplifiers with a vernier gain adjustment allow precise and repeatable adjustment of the system gain. The integrated value is displayed and stored on a 3½-digit panel meter. An analog integration output is available for entry on the strip chart record.

The integrator was used routinely on the Penn State road friction tester for skid data averaging. The system was found to reduce significantly the time required for data reduction, and the instant availability of data was an advantage in many of the research test programs. The digital indication also proved a convenience and increased the precision with which the instrumentation systems could be adjusted.

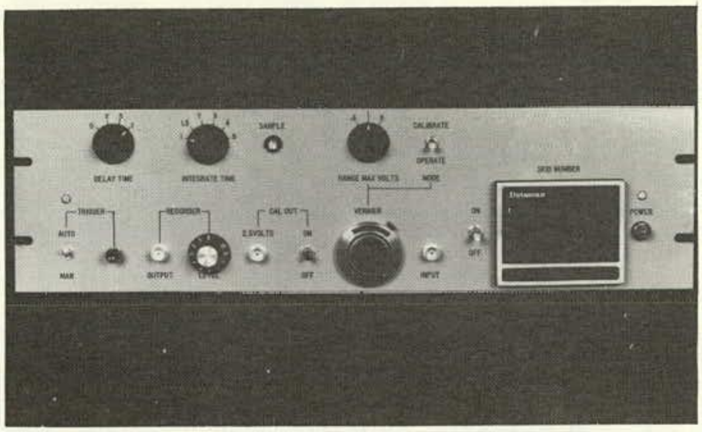


Figure A-48. Penn State data integrator.

10.3 Other Considerations

The integrator in combination with an FM magnetic tape recorder proved an invaluable tool in conducting research. From a large number of skid tests recorded on tape, investigations into human evaluation errors and instrumentation filtering were conducted. One extensive test to determine typical errors in skid-trace evaluation was conducted by simultaneously recording more than 100 skid tests on both a vehicle strip-chart recorder and a magnetic tape recorder. The taped signal was averaged by an electronic integrator and the charts were evaluated by three experienced men. Using the electronically integrated values as references, the error in each man's individual evaluation was determined and plotted in an error histogram, which is shown in Figure A-50. Errors are as large as 7 SN. One evaluator (c) showed a strong bias on the negative side. The mean error over all evaluations is 2.3 SN.

To make visual averaging easier and more accurate, the signal is often filtered. Excessive filtering, however, introduces other errors through attenuation of part or all of the signal. To find the smallest acceptable bandwidth, tape-recorded skid test signals were repeatedly integrated by the electronic integrator through a third-order, low-pass filter. The cut-off frequency was successively reduced until attenuation of the signal became noticeable below 10 Hz (Figure A-51). The frequency response, therefore, should be from 0 to 10 Hz minimum. A bandwidth of 0 to 20 Hz, recommended by ASTM E 274, is a good choice.

To test the frequency response of the skid testers participating in the correlation program, a special test section 2 ft wide and approximately 50 ft long was prepared on test site No. 1. A regular pattern of plastic pavement marking sheets ("coefficient stripes") was installed at intervals so that a skidding wheel experiences periodically alternating friction. The skid resistance of the pavement and stripes is approximately 40 and 10 SN, respectively. The spacing of the plastic stripes is such that a skidding wheel traveling at 40 mph successively excites frequencies of 4, 8, and 16 Hz.

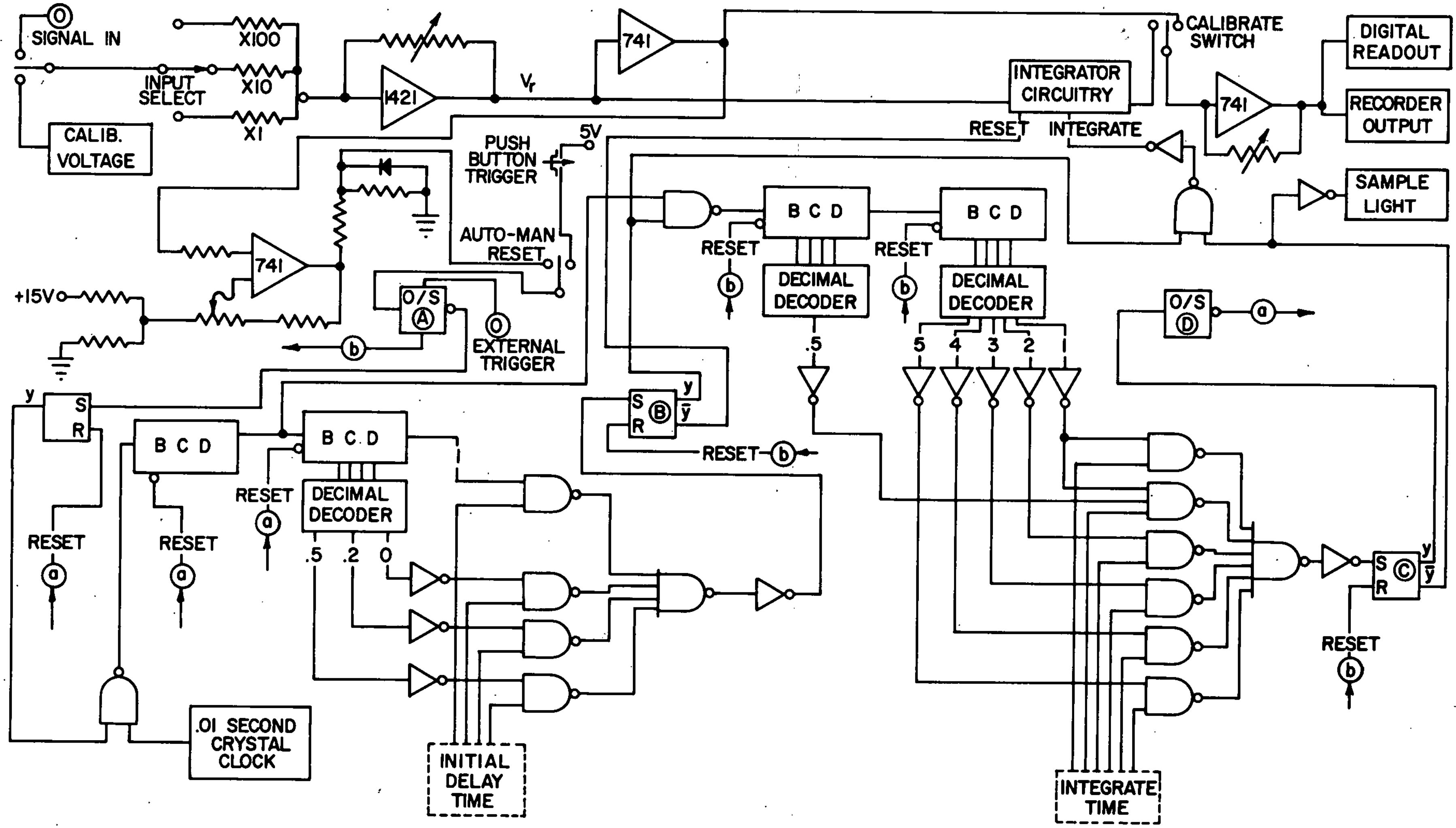


Figure A-49. Schematic diagram of integrator.

Several tests were conducted on this striped section, and the recorded traces were examined. The analysis is given in Table A-17.

A tester with perfect fidelity should record a skid trace oscillating exactly between the two levels of skid resistance (range: 30 SN). In practice, the oscillations of the trace were different for every tester, depending on its dynamic response characteristics. Signal amplitudes for testers No. 1, 6, 9, and possibly 10 remained unchanged with increasing frequency; those for testers No. 2, 7, 8, and 11 increased indicating resonance; those for testers No. 3, 5, and 12 decreased indicating the effect of damping. Resonance should be avoided because it makes chart evaluation more difficult. The effect of damping, which has been discussed, is useful in visual chart evaluation. Tester No. 12 had a 10-Hz(the lowest acceptable cut-off frequency as shown in Figure A-51) filter installed. Because damping for testers No. 3 and 5 was about the same as for tester No. 12, it was concluded that frequency response for all testers is 10 Hz and above and that no attenuation of skid resistance is expected.

In addition to the errors inherent in averaging a noisy trace or in extreme filtering, selection of the part of the trace to be averaged tends to vary between operators. Many highway departments provide templates, or similar means, to make evaluations more uniform, but some degree of operator judgment still enters the evaluation.

Start of steady-state friction is not a well-defined point. The instant of brake application initiates several transient effects, which are discussed in Section 11. These effects are felt beyond wheel lock-up and their duration depends on the frequency response and the degree of damping of the tester suspension and of the instrumentation system. Skid-resistance records, from magnetic tape, were recorded on a strip chart without filtering and through filters of three different cut-off frequencies. The results are shown in Figure A-52. Even on the record of the most heavily filtered signal (6-Hz bandwidth), the end of the transient effects and start of the steady-state friction cannot be determined uniquely. Transients caused by wheel load transfer may typically last for one second.

Evaluation accuracy depends not only on the choice of start of averaging but also on the length of trace averaged. Length of evaluation time and its effect on accuracy was investigated experimentally and in the computer simulation given in detail in Section 11. Evaluation or integration error is defined here as the difference between a result obtained in integrating over a short period and the result obtained in much longer integration of the same steady-state signal. By testing the simulation model on a surface of sinusoidal roughness, the minimum integration times in which the dynamic effects average out to a specified degree were determined. Table A-18 lists integration times for accuracies of 1 and 2 percent for different frequencies of

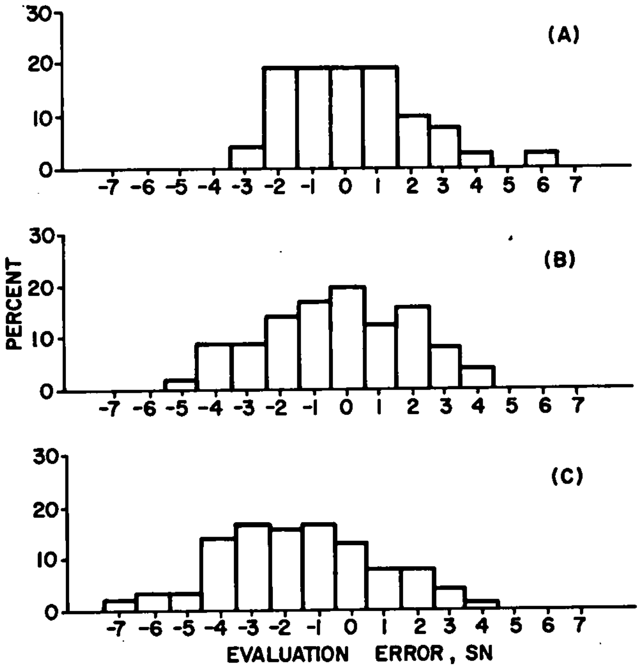


Figure A-50. Error histogram of three evaluators relative to electronic evaluation of 100 skid traces.

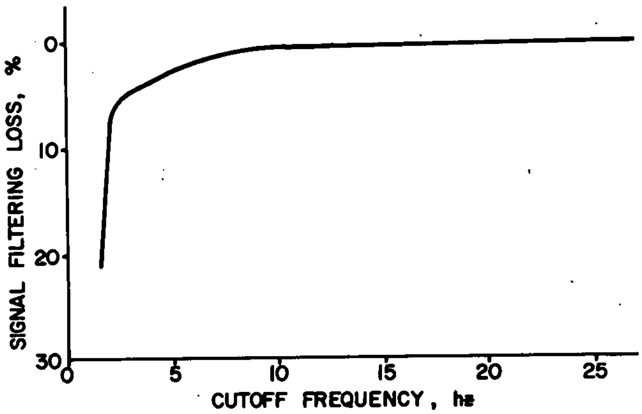


Figure A-51. Attenuation of typical skid-resistance recordings by filtering.

TABLE A-17

ANALYSIS OF TESTER RESPONSE TO COEFFICIENT STRIPES

TESTER NO.	APPROPRIATE SN RANGE OF OSCILLATIONS ON RECORDER CHART FOR FREQUENCIES OF 4 HZ	8 HZ	16 HZ
1	40	40	40
2	45	45	60
3	24	8	1
5	25	18	2
6	50	50	50
7	45	55	L, H[a]
8	40	55	70
9	45	45	45
10	L[a]–70	L[a]–65	L[a]–65
11	60	70	O–H[a]
12	25	10	1

[a] Off scale; L indicates low side, H indicates high side.

road roughness. The longer times near the 1-Hz frequency reflect resonance effects, because the natural frequency of most skid testers was found to be between 1 and 2 Hz (see Section 6.2). At normal travel speeds, road roughness frequencies are between 1 and 15 Hz and in this range integration over 1 sec will on the average be in error by 2 percent.

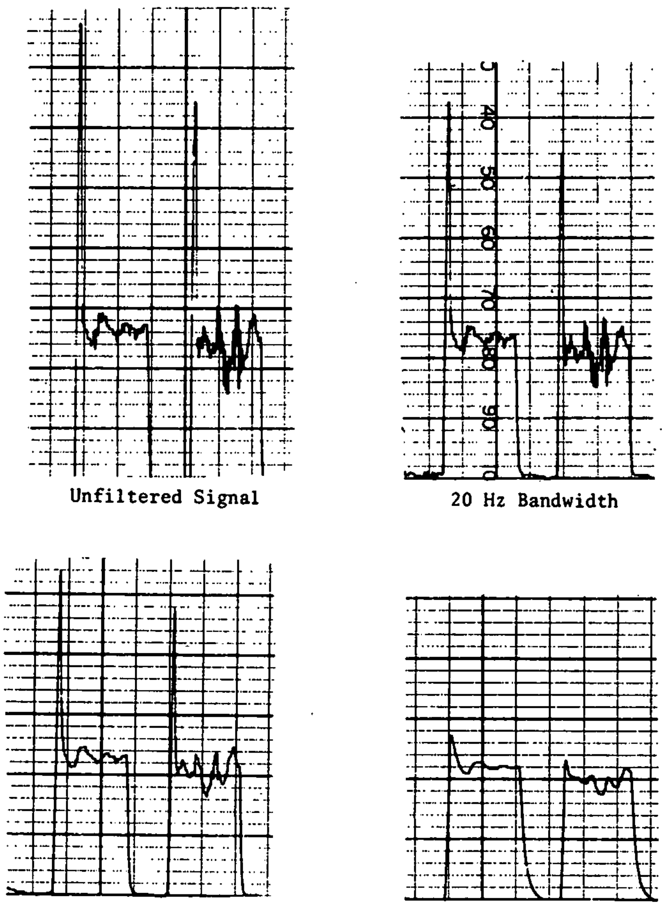


Figure A-52. Typical skid-resistance record unfiltered and filtered at three different bandwidths. The chart speed was 0.25 in. per second.

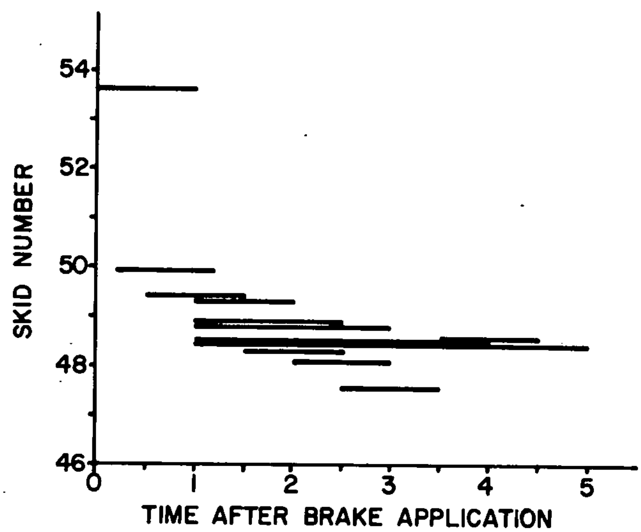


Figure A-53. Skid resistance integrated over several time intervals and after different delay times.

The effects of delay and integration times on evaluation accuracy were also determined by means of repeated integration of skid data. Fifty tape-recorded skid tests were electronically integrated with different settings of delay and integration times. The 50 skid numbers were averaged, to reduce random error effects, and are plotted versus time, as shown in Figure A-53. When integration starts 1 sec or more after brake application and continues for 1.5 sec or more, the results agree within 0.5 SN. The spread increases to 2 SN when integration is stopped after 1 sec because the average portion of the trace is too short to be sufficiently representative. When delay time is reduced below 1 sec, the error increases rapidly because the braking transient has not decayed sufficiently.

These results are based on data from one two-wheel skid tester and can be somewhat different for other testers. It can be concluded, however, that delay and integration times longer than those specified in ASTM E 274 will increase accuracy in data evaluation. The minimum delay after wheel lock-up should be 1 sec with a 1.5-sec minimum evaluation time. Allowing approximately 0.5 sec between brake application and wheel lock-up, a 3-sec braking cycle should be considered the minimum. Longer cycles may improve accuracy further, but practical considerations set the upper limit (Section 8).

Automated data-processing equipment, similar to the electronic integrator used in this project, has now come into use, or is being considered. Such equipment, installed on the tester or used in the laboratory on tape-recorded signals, offers advantages in time saving and precision of the averaging operation. However, in order to acquire accurate skid-resistance data certain precautions must be taken. Errors in zero or calibration signals may affect automatic evaluation to the same degree as they affect manual evaluation. A human evaluator can use judgment and increase signal delay time or omit part of the signal if he considers it suspect for any reason, but an electronic integrator always averages the same preset part of the signal. For this reason longer delay and integration times are especially

TABLE A-18

INTEGRATION TIME AND INTEGRATION ERROR DETERMINED IN COMPUTER SIMULATION

ROAD ROUGHNESS INPUT TO TEST WHEEL (CYCLES/SEC)	TIME OF INTEGRATION (SEC) FOR ERROR OF	
	2%	1%
0.0	0.408	0.814
0.057	0.619	0.927
0.2857	0.207	1.143
0.571	0.451	1.648
1.000	1.012	2.856
2.857	0.712	3.408
15.000	0.925	1.747
50.000	0.608	1.164

important with automated data processing. When integration is started simultaneously with brake application, allowance must be made for the time it takes to lock the wheel. With an effective braking system, delay times should be no less than 1.5 sec with at least the same time allowed for integration.

Skid testers with wheel load transducers should integrate the wheel load signal in the same way as the force signal. The two integrated values can then be processed to give the skid number directly. Another way would be to divide the instantaneous force signal by the instantaneous load signal and integrate the result, thus requiring only one integrator. Visual averaging of wheel load signals adds error sources. With electronic integration some of the dynamic wheel load errors (Section 6) will be reduced.

Visual chart evaluation accuracy depends in part on the resolution of the recording chart (Section 7). Inadequate resolution also reduces the accuracy of calibration, zero setting, and the reading of calibration pulses. For adequate accuracy, one chart division should be no more than 10 lb of force or 10 ft-lb of torque, depending on the calibration method used.

11. ROAD ROUGHNESS AND TESTER DYNAMICS

11.1 General

The typical skid trace exhibits oscillations reflecting a broad spectrum of frequencies. The indirect effect of dynamics on data evaluation has been discussed in Section 10. Now the direct effects of road roughness and tester dynamics on skid resistance will be examined.

At the instant of brake application, a friction force between the tire and pavement develops and tries to keep the tire rolling, opposing the braking torque. It reaches a peak value between 10- and 20-percent wheel slip. At higher slip, friction drops off and the wheel goes rapidly into skidding. The recording system records this transient peak before the trace settles down to the steady-state friction of the locked wheel (skid resistance). With a torque-measuring system, the inertia of the decelerating wheel contributes to the transient effect by adding to the recorded torque.

Another transient effect during wheel lock-up is the load transfer from the test wheel to the trailer hitch over and above the steady-state unloading effect caused by tester geometry (Section 6.2); also, two-wheel testers have load transfer between the wheels. Actual friction force is reduced in proportion to the unloading. Trailer yaw is another transient effect, which recovers partly after wheel lock-up.

Friction has dropped to its steady-state value when the effects of the transients become negligible, that is when the recorded force trace has assumed random oscillations of more or less constant amplitude. These oscillations can be caused by dynamic wheel load changes and nonuniform skid resistance during the skid.

The transient and steady-state dynamics of skid testers and their effects on skid resistance were explored by experiments with single- and two-wheel testers and by a computer simulation (Section 11.2).

Except for the yaw motion, the dynamics of a skid tester moving at high speed canont be readily observed. High-speed photography was employed to obtain qualitative information on tester dynamics under free-rolling and skidding conditions. To determine suspension characteristics, a drop test was devised. Appendix H gives details and data for 13 examined skid testers. The drop test records for all testers showed fast decay of the vertical motion, indicating close-to-critical damping. The natural frequency was computed from the drop test results and, for the examined testers, was found to be between 1.1 and 2.6 Hz.

To determine whether the frequency of oscillations in a steady-state skid trace is related to tester dynamics or caused by the disturbance input of the pavement, skid tests were run at 10 and 40 mph over the same test sections. Chart speeds were selected proportional to test speed, so that equal lengths on the chart represent equal lengths of pavement. Figure A-54 shows records of these tests. The number of peaks over the same length of pavement (1 in. of chart) is about four times greater at 10 mph than at 40 mph. Thus, the oscillation frequency of approximately 10 Hz, which is the same at both speeds, does not reflect a characteristic of the pavement.

The same frequency is found in skid traces of different skid testers under various testing conditions. For instance, the records reproduced in Figure 47 are from another tester and the number of peaks is again about 10 per sec. This frequency is several times higher than the natural frequency of tester suspensions and apparently unrelated to it, but nearly equals the natural frequency of passenger car tires (*42*). The oscillation in the skid trace may well be caused by tire vibrations, but such a determination was beyond the scope of this project.

On the single-wheel skid tester, the wheel load is obtained partly by dead weight and partly by a pneumatic load cylinder. By changing the ratio between dead weight and pneumatic load, the dynamic characteristics can be changed. This was done in several steps, but no discernible effect on the skid traces or mean skid resistance was found.

Repeated skid tests were run with a two-wheel tester on a pavement of average roughness and over bridge joints. Testing was done with the suspension system in normal condition and with the suspension blocked. The frequency of the skid-trace oscillations remained unchanged, although their amplitude increased. The mean skid resistance, however, remained unchanged.

Vertical acceleration of a skid tester was measured simultaneously with skid resistance at 30, 40, and 60 mph. Figure A-55 is a typical recording; the number of peaks of both traces is again about 10 per second. Dynamic wheel load changes with vertical acceleration and causes a corresponding change in instantaneous friction force. These are plotted in Figure A-56 for all three speeds. The high and low fluctuations in friction force are approximately equal and the resulting effect on mean skid resistance is negligible.

Experiments on tester dynamics were also made in the second week of the correlation program when additional testers were on hand. Artificial bumps of 0.5 in. height were placed on one test site at 50-ft intervals. This arrange-

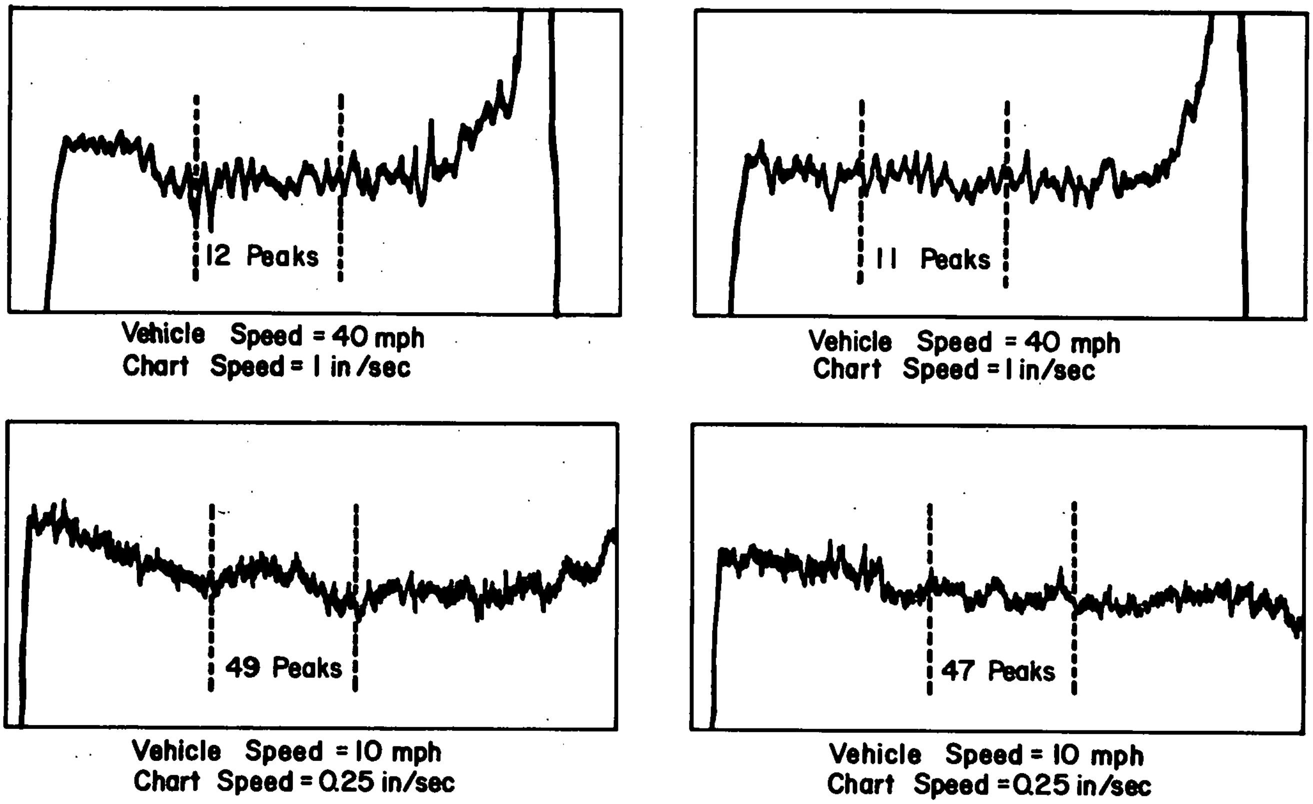


Figure A-54. Typical skid records on the same pavement segments at 40 and 10 mph. The number of peaks is proportional to time and independent of distance travelled.

ment corresponds, at 40 mph, to an excitation at about 1 Hz, which is of the order of the tester natural frequency and should therefore have the strongest effect, if any. The same test site was tested with and without the bumps by four testers. The differences in the results of the tests with and without bumps were within 2 to 3 percent. These differences are within the normal variability in skid testing.

To determine whether trailer yaw affects mean skid resistance, the single-wheel tester was used with the trailer being either free to yaw or restrained to run at 0- or 5-deg yaw. The results showed no effect on mean skid resistance.

11.2 Hybrid Computer Simulation Model of a Skid Trailer

A hybrid computer simulation model of a generalized locked-wheel skid test trailer was developed to investigate the influence of road roughness on measured skid resistance and, in particular, the influence on trailer performance that would affect correlation among testers. The simulation model exists in two forms—a physical model and the mathematical description of the physical model. Only the physical model is discussed here, although mathematical model details are available elsewhere (*43, 44*).

The physical model is a generalization and geometric simplification of the actual vehicle. To keep the complexity of the mathematical representation within manageable limits, the physical model was kept as elementary as possible while still including the major features that account for the performance under investigation. Use of a simulation model allows many otherwise impractical methods of investigation to be employed. Three of the major advantages are that:

1. A generalized model's parameters can be selected to simulate a particular tester, and individual parameters may be varied over a broad range to determine performance sensitivity without need for actual hardware.
2. Any number of trailers can be put through the same tests wherein conditions of road roughness, coefficient profile, and test tire characteristics are duplicated to a far higher degree of accuracy than can be accomplished experimentally in field testing.
3. Actual or artificial road roughness can be used to excite the tester dynamics while specifying an idealized friction characteristic (constant or variable coefficient) to avoid masking the dynamic effects as occurs in physical tests.

The model was implemented at the Hybrid Computer Laboratory of The Pennsylvania State University. The systems used in the simulation are a PDP 10 digital computer, an EAI 680 analog computer, an EAI 693 data conversion system, and a Digital Equipment Corporation Tu 20 magnetic tape drive.

An examination of numerous trailers showed them to consist basically of a main frame pinned at one end (the hitch) and sprung at the other, with a suspension system, axle, brake assembly, and test wheel. A skeletal representation of these components became the physical model

and is shown in Figure A-57. The model is a multi-degree of freedom system operating in the confines of planar motion. Consequently, roll and yaw freedom are not included in the model (though some simulation of these effects can be added when desired).

The simulation is generalized by the use of "black box" type of suspension system and tire models to allow application to many different trailers with quick conversion of the suspension system parameters that characterize coil and leaf springs. A rigid suspension combined with several other changes converts the model to the one-wheel trailer type.

The model selected for the test tire is shown in Figure A-58. It includes elements that simulate the torsional and radial stiffness and damping of an actual tire. This representation includes effects that simulate the tire contact patch motion in skidding, with the associated additional torque components.

In operation, the inputs to the simulation include the hitch-point motion, road profile, and the coefficient of friction. As with its physical equivalent, the test is initiated by actuation of the brake that carries the wheel through a coefficient-slip curve modeled after real performance data until the tire at lock-up reaches the programmed value of skidding coefficient.

The output of the simulated test includes a time record of the wheel torque and any or all of the other variables in the simulation that may be desired. The tests are conducted in real time, and the data printout may be furnished in analog or digital form. To facilitate run-to-run comparisons of tester performance, integration subroutines were included in the digital portion of the program. From a designated starting point, the subroutines would compute the cumulative integral value at real-time intervals of one hundredth of a second during the test. The integration subroutines determined test wheel average torque, force, and normal load values.

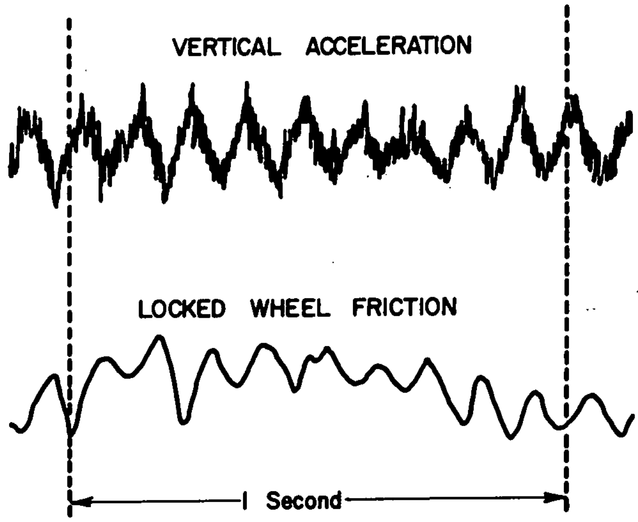


Figure A-55. Oscillations of friction force and vertical accelerations on the test wheel of a skid trailer during lock-up at 60 mph.

11.2.1 Verification of the Model

The model contains 21 parameters, many of which are not readily measured on a particular trailer. Typically, it is

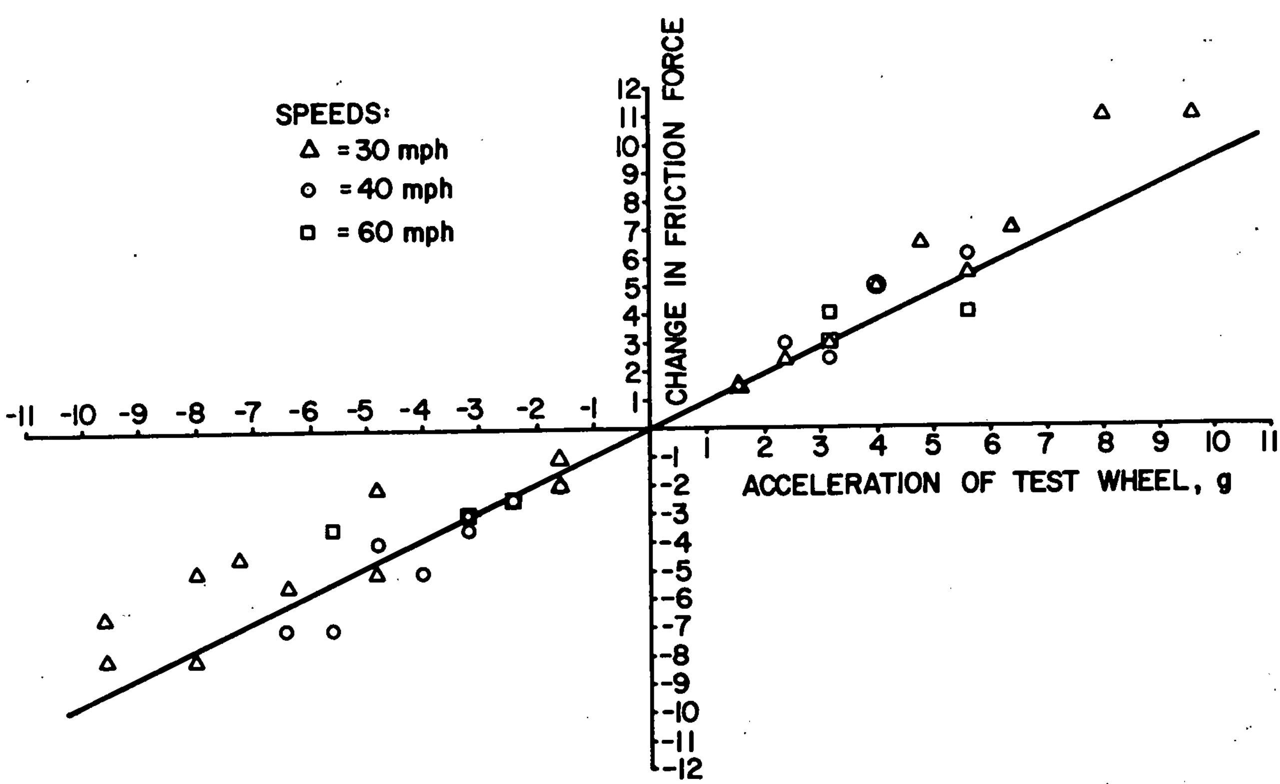


Figure A-56. Instantaneous changes in friction force as function of vertical wheel accelerations.

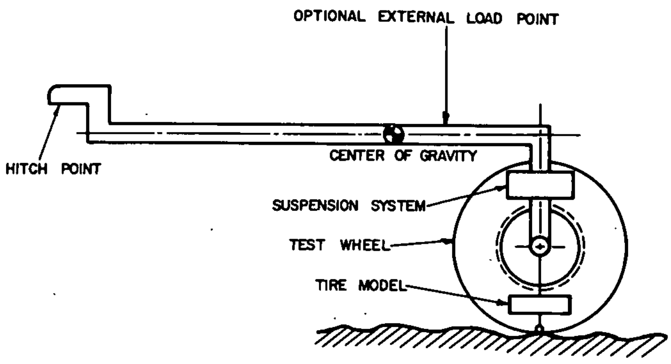


Figure A-57. Generalized skeletal model of skid test trailers.

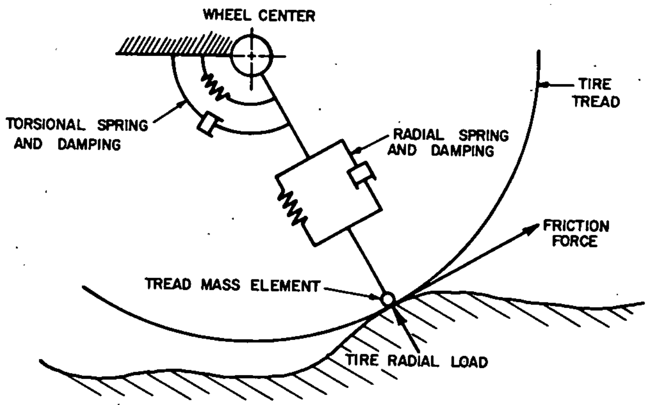


Figure A-58. The test tire model.

necessary to know the moment of inertia of the trailer when rotated in pitch about the hitch point, or the weight of the axle assembly, or the moment of inertia of the wheel-brake assembly. Hence the two-wheel trailer used in other research under this project was selected as a reference and the many required parameters were measured or estimated. This trailer was then implemented in the simulation with all tests based on modifications of individual parameters from this reference.

Verification of the model was attempted only with the reference trailer simulation and followed three avenues. First, the dynamics of the trailer were studied in drop tests (Appendix H) and compared with the same tests conducted on the simulation model. Close similarity in performance was obtained as shown in Figure A-59. Second, the simulated skid tests on flat roads, real roads, and roads with artificial roughness were examined to verify that the wheel torque and trailer motion compared with what was expected based on the experience and knowledge of project personnel. And last, with all variations of model parameters, the changes in trailer performance were examined to rationalize their cause.

A meaningful comparison between the computer simulation skid force record and that of the actual skid test trailer

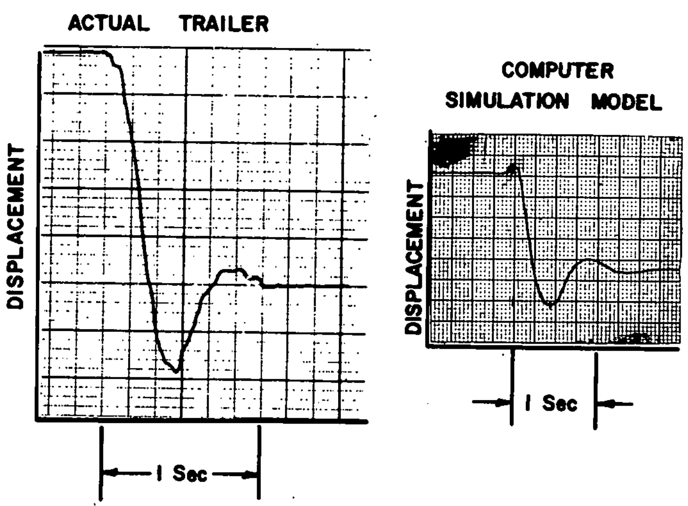


Figure A-59. Drop test recording of actual trailer and computer simulation of trailer.

was not attempted because of the variable and unknown coefficient characteristic along actual highways. Verification was attempted by comparing the vertical acceleration record of the actual trailer with that of the simulation trailer running over the same road profile. However, the method did not succeed because the low-amplitude and low-frequency accelerations produced by the roughness are heavily masked on the actual and simulation trailers by higher frequency noise accelerations that made comparison inconclusive.

11.2.2 Methods of Investigation

Aside from the studies conducted to build confidence in and to verify the model, three types of studies were conducted to determine direct effects of road roughness on skid-resistance measurement. Initially the model was operated on flat and sinusoidally rough surfaces to investigate the transient dynamics produced at the beginning of a skid test and averaging times required to obtain repeatable test results in the dynamic situation. Actual road roughness profiles were then used with the model to determine whether skid resistance measurements were significantly affected by road roughness when the programmed coefficient is held constant. After these were completed, 17 major parameters of the model were varied over their maximum appropriate range to determine whether, at any combination of values, a significant road roughness influence on skid resistance would be indicated.

During operation of the simulation and analysis of its performance, emphasis was placed on using the same methods and outputs as used with real testers by typical users. That is, the outputs routinely scrutinized were the torques and forces generated at the axle-wheel attachment point as the most common transducer location on real trailers. Likewise, the force plate calibration method was assumed in determining the reference against which trailer performance changes were compared. The flat surface test in steady state was exactly analogous to the force plate calibration so that a dynamic error was indicated if the average torque, force, or load for any profiled surface differed from the value on a flat surface under corresponding conditions.

Three actual road profiles were selected on which to operate the simulation trailer. The profiles were obtained

on local highways with the Pennsylvania Department of Transportation Road Profilometer. A single skid test covers only a small sample of highway and a large number of tests would be required to sample a representative portion of the profile. For reasons of economy this could not be incorporated practically in the simulation studies. As an alternate approach, representative sections of the profiles were selected to provide smooth, intermediate, and rough surfaces on which to run the simulation skid tests. The three profiles, with the approach and skid test sections indicated, are shown in Figure A-60. The smooth surface was taken from an interstate highway of concrete slab construction having an RMS roughness value of about 0.1 in. The intermediate and rough surfaces were taken from different sections of an older and noticeably deteriorated concrete slab highway having an RMS roughness value of 0.2 in. The roughness values are obtained from an independent report on the road surfaces (*45*).

11.2.3 General Results

The first studies with the model were conducted on flat surfaces. Figure A-61 shows an example of the strip chart recording of the test wheel torque and trailer pitch motion during a skid test on a flat surface of constant coefficient. The trailer pitch record shows the transient dynamic motion that occurs at the start of a skid. The motion appears dominated by trailer suspension characteristics with excitation caused by the friction force generated in the skid test. Other factors that were found to influence the amount or duration of the motion were hitch height, pitch moment of inertia, and any other parameter that in one way or another had influence on the pitch-mode oscillation frequency or damping.

The model was operated on surfaces having sinusoidal roughness of ½-in. peak-to-peak amplitude and frequencies from 0 to 50 Hz. The trailer pitch motion was recorded and the test wheel torque was integrated in a cumulative manner starting at 0.2 sec after lock-up. The pitch motion tended to reflect low-frequency roughness up to about 1-Hz frequency, the suspension natural frequency, at which damped resonance occurred. At higher frequencies road roughness was absorbed in the tire and suspension. The cumulative integral of the torque was examined to determine the minimum integration time that would yield an average close to the final value obtained after 6 sec. The results are given in Table A-18.

When actual road profiles were introduced, simulation tests were conducted on a flat surface and smooth, intermediate, and rough road surfaces over a range of coefficient values. A 3-sec integration period, which started 1.5 sec after brake actuation, was selected to determine average values for test wheel torque, force, and normal load throughout all testing. The model was operated on all surfaces with constant friction coefficient values ranging from 0.2 to 0.6. The average torque, force, and load values, shown in Table A-19, varied less than 1 percent from the flat surface value over all road profiles. The small variation that is observed is credited to computation accuracy and variance associated with the 3-sec averaging period.

Finally, an investigation into variation of the model parameters was made using the same methods as those discussed but limited to flat and rough surfaces of 0.4 coefficient. The 17 major parameters of the model were varied individually and in combinations while the flat and rough surface values for average torque, force, and load were compared. The 17 parameters and their range of variation are listed in Table A-20.

As all parameters were changed, the flat surface values changed much as expected. However, in each case the rough surface values changed in the same manner and by the same amounts, thus indicating no significant influence due to road roughness.

11.3 Comments

Because of higher than anticipated demands on time and computer charges in accomplishing the computer studies, the investigation was not carried out to the comprehensive degree originally planned. In particular, the tests with hitch-point motion, coulomb-type suspension damping, and one-wheel trailers were not accomplished. However, because it became apparent from the investigations that were accomplished that no skid-resistance measuring errors induced by real-road roughness were generated by the model and the dynamic phenomena represented therein, it is considered unlikely that errors would have been observed in the unaccomplished tests.

The simulation model developed for this work allowed study for the first time of the complex interaction of sprung

TABLE A-19

AVERAGE TORQUE, FORCE, AND LOAD VALUES OF SIMULATION REFERENCE TRAILER

	$\mu=0.2$			$\mu=0.4$			$\mu=0.6$		
SURFACE	TORQUE	FORCE	LOAD	TORQUE	FORCE	LOAD	TORQUE	FORCE	LOAD
Flat	2880	206	1031	5612	403	1008	8203	590	983
Smooth road	2866	206	1027	5574	401	1001	8194	589	986
Intermed. road	2884	207	1026	5630	406	1011	8264	595	991
Rough road	2880	208	1033	5616	404	1008	8198	590	952

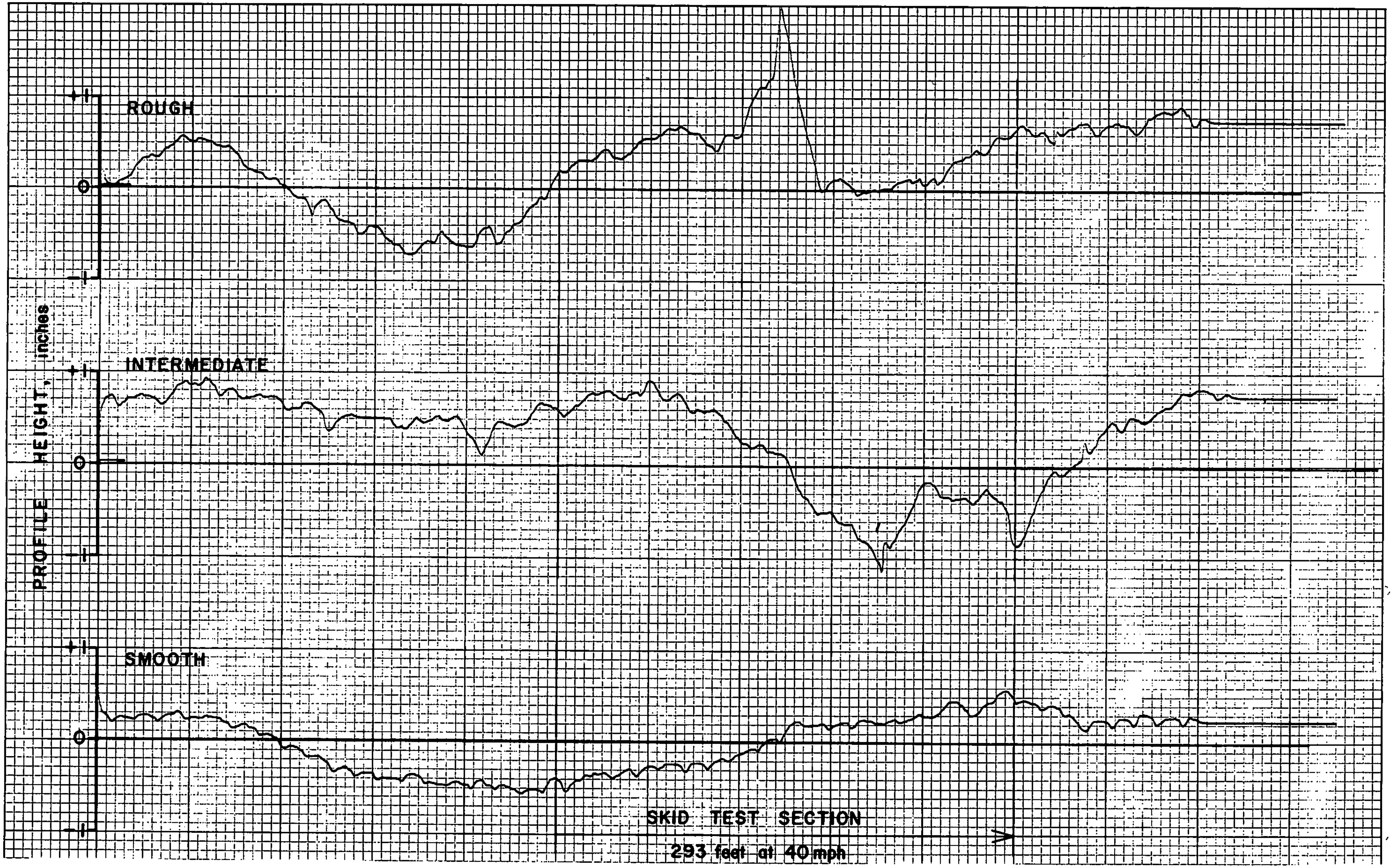


Figure A-60. Actual road roughness profiles used in computer simulation studies.

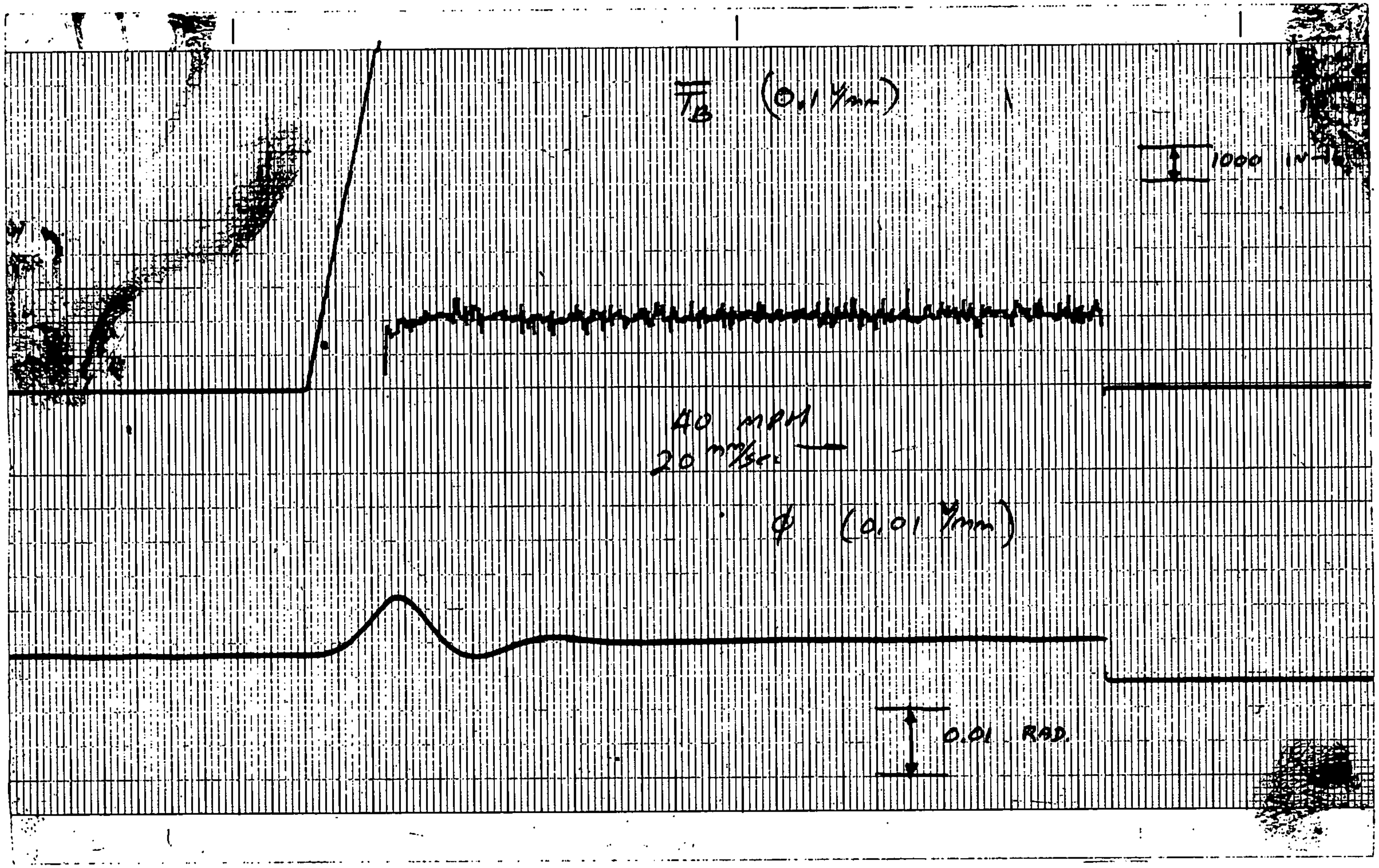


Figure A-61. Strip chart recording of computer simulation skid test showing wheel torque ($\overline{T}_B$) and trailer pitch angle (ϕ).

TABLE A-20
RANGE OF SEVENTEEN PARAMETER VARIATIONS

PARAMETER	STANDARD VALUE	RANGE OF VARIATION (%)	
Hitch height, in.	24.19	+16,	−34
Length of the frame, in.	103	+22,	−22
Mass of the frame, lb	1,850	+50,	−50
Moment of inertia of the frame, in.-lb-sec ^{2}	35,309	+42,	−43
Center of gravity location behind hitch, in.	100	+20,	−20
Center of gravity level below hitch, in.	5.19	+93,	−100
Suspension spring constant, lb/in.	400	+150,	−75
Suspension damping coefficient, lb-sec/in.	44.3	+99,	−50
Suspension static length, in.	6.4	+88,	−69
Mass of brake-axle assembly, lb	100	+50,	−50
Mass of the wheel and brake drum, lb	50	+100,	−50
Rotational inertia of wheel and brake drum, in.-lb-sec ^{2}	10.8	+57,	−54
Tire radial spring constant, lb/in.	11.65	+72,	−57
Tire radial damping, lb-sec/in.	12.5	+140,	−52
Tire torsional spring constant, in.-lb/RAD	140,000	+64,	−64
Tire torsional damping, in.-lb-sec/RAD	630	+90,	−68
Mass of tire tread element, lb	1.0	+250,	−75

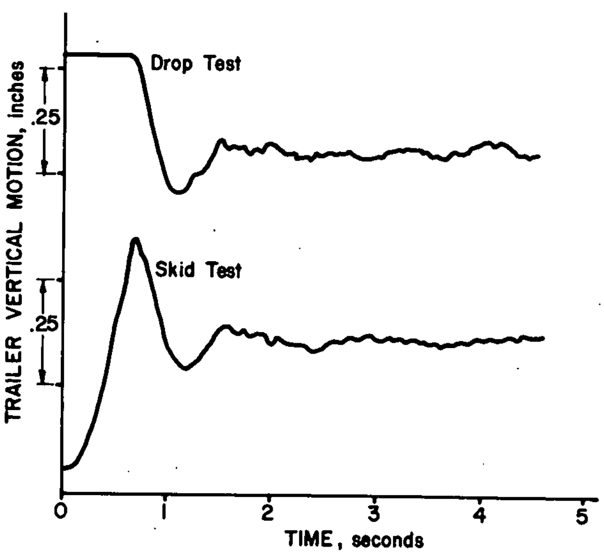


Figure A-62. Simulation of skid and drop test for typical set of tester parameters.

and unsprung vehicle dynamic systems during braking. The tire model forming a part of these systems included the torsional as well as radial stiffness and damping parameters that were most suspected of creating dynamic skid-resistance measuring errors. All aspects of the model were retained in their nonlinear forms to allow opportunity for the nonlinearities to combine in the dynamic situation and generate unpredictable errors. No such errors were observed.

One shortcoming of the simulation model selected for this work was the lack of the roll or yaw degree of freedom. For the degree of complexity that would have been added to the model and the compromise in accomplishments that would have resulted, the exclusion of this degree of freedom is justified. The dynamics of yaw motion in skid testing were observed experimentally and the yaw influence, within the scope of error types studied here, would have been reflected in the lock-up transient dynamics. Since the solutions required to eliminate lock-up transient dynamic errors cover the effects of yaw as well, the exclusion of this degree of freedom in the model is not considered to significantly compromise the validity of the simulation results.

Some of the parameters in the computer model were varied over as large a range as could practically be encountered. Torque, force, and wheel load were computed for the skidding wheel and averaged over a specified interval, as used in evaluating skid traces. The coefficient of friction was held constant at three levels and pavement roughness was varied from perfectly flat to rough. Recorded pavement profiles were used as inputs. Thus any variation in the computer quantities must be the result of varying pavement roughness. Table A-19 shows computed results for one set of tester parameters and similar results were obtained for other values of the parameters. All variations are within 1 percent and show no consistent pattern. Thus, the conclusion that mean skid resistance is not affected by road roughness is supported by the computer simulation.

The computer simulation was also used to compare tester transient response in the drop test and during lock-up. Figure A-62 shows typical recordings of the vertical motions and proves that the drop test is a simple and adequate method of measuring the important dynamic characteristics of a skid trailer. The transient, which typically lasts for 1.5 sec, causes wheel load fluctuations. Their magnitudes depend on tester suspension and rate of lock-up and may be two to three times greater than the steady-state unloading effect. When the load fluctuations have decayed to approximately 10 percent of their initial value, their effect on normal load may be neglected. For all but one of the 13 testers mentioned in Appendix H, the time to settle at 10 percent of the initial displacement amplitude was estimated from drop tests and was between 0.6 and 1.0 sec, which is in good agreement with Figure A-62. To avoid errors caused by these transient effects, longer delay times have been recommended (Section 10).

All evidence from the experiments with several skid testers of different design (including single- and two-wheel testers) and the results of the computer simulation leads to the conclusion that road roughness and tester dynamics

have no direct effect on mean skid resistance. This has been verified over a wider range of conditions than would normally be encountered. The only effect is indirect, which is to cause oscillations of the skid test signal. Longer delay times reduce errors caused by transient oscillations; longer integration times reduce errors in the steady state caused by random oscillations.

12. METHOD OF ANALYZING SKID-RESISTANCE DATA

12.1 General

The reasons for variance in skid testing have been discussed in Sections 1 through 11. Even if all possible improvements in equipment and procedures are made, a certain amount of data spread is unavoidable. For this reason it is necessary to be able to apply some measure of confidence to the data obtained. Confidence increases with the number of repeat tests, but the number of tests that can be justified is limited because skid testing is costly and time-consuming. Also the pavement may change while tests are being made because of polishing and sometimes because of repeated wetting. In addition the temperature does not remain constant during the time it takes to make a large number of tests.

In practice, therefore, skid resistance generally is based on a relatively small sample size. The significance of the results can be tested by statistical methods. In the course of this project some of the test data were so analyzed, and methods and results are described in Sections A-4 and A-5. These methods are relatively simple and all computations can be made on a desk calculator. The objectives of the statistical tests were to:

1. Compare the performances of several testers.
2. Compare the performances of a single tester using two different tires.
3. Investigate the correlations between skid numbers and associated temperature measurements.
4. Investigate inventory testing and to contrast it with single-spot testing.

12.1.1 Tester Comparisons

A comparison experiment (*15*) was conducted for one week in June 1971 in which each one of six skid testers made 10 runs over a single spot at speeds of 30, 40, and 60 mph. The testers (from The Pennsylvania State University, Stevens Institute of Technology, National Bureau of Standards,* and Delaware, Maryland, and Pennsylvania) were found to differ significantly from one another in terms of mean skid numbers at all three speeds. They were also found to differ significantly in terms of data variability (viz., variances) at the two lower speeds, but had reasonably similar variability at 60 mph. A data summary of these runs is given in Table A-21 (a loss of some data points resulted from tester malfunctions).

The first item of interest was to compare the sample means at each speed to determine if they were statistically equivalent. The analysis of variance permits testing the null hypothesis

$$H_0: \mu_1 = \mu_2 \dots \mu_6$$

against all alternatives (i.e., $\mu_i \neq \mu_j$ for some i and j). The statistic used in this test is

$$F_{k-1,\, n-k} = \frac{\sum_{j=1}^{k} \sum_{i=1}^{n_j} (\bar{x}_{.j} - \bar{x}_{..})^2 / k-1}{\sum_{j=1}^{k} \sum_{i=1}^{n_j} (x_{ij} - \bar{x}_{.j})^2 / n-k}$$

where k = number of populations (testers);
n_j = sample size of the jth population;
$n = \sum_{j=1}^{k} n_j$ = total sample size;
x_{ij} = ith measurement taken from the jth population;
$\bar{x}_{.j}$ = sample mean for the jth population; and
$\bar{x}_{..}$ = mean of all observations (over-all k populations).

When all k means are equal, it can be shown that this statistic has an F distribution with k–1 and n–k degrees of freedom. The null hypothesis H_0 is rejected at significance level α if

$$F_{k-1,\, n-k} > F_{k-1,\, n-k\,;\, 1-\alpha}$$

The term $\sum_{j=1}^{k} \sum_{i=1}^{n_j} (x_{ij} - \bar{x}_{.j})^2$, often referred to as the *within-sample sum of squares*, represents a measure of the variation within the samples. It is usually designated SSW.

TABLE A-21

SUMMARY OF SKID DATA FROM SIX TESTERS

TESTER	SPEED (MPH)	SAMPLE SIZE	SAMPLE MEAN [a]	SAMPLE VARIANCE [b]	STANDARD DEVIATION	SAMPLE RANGE $x_{max} - x_{min}$
PSU	30	10	47.8	11.03	3.32	11.0
	40	10	40.2	0.73	0.86	2.5
	60	10	29.6	7.40	2.72	9.0
Delaware	30	10	57.4	2.42	1.56	4.4
	40	8	49.1	2.66	1.63	5.3
	60	— [c]	— [c]	— [c]	— [c]	— [c]
Maryland	30	10	52.4	0.49	0.70	2.0
	40	10	46.5	7.39	2.72	10.0
	60	9	39.7	1.25	1.19	4.0
NBS	30	10	56.0	2.60	1.61	5.2
	40	10	46.5	4.30	2.07	5.6
	60	10	36.6	5.00	2.24	4.4
PennDOT	30	10	56.5	3.96	1.99	5.0
	40	10	50.5	4.62	2.15	7.0
	60	10	36.9	3.38	1.84	6.0
SIT	30	10	51.3	5.34	2.31	8.0
	40	9	45.1	8.90	2.98	8.0
	60	8	34.8	1.93	1.39	4.0

[a] Data corrected for calibration.
[b] $s'^2 = \Sigma(x_i - \bar{x})^2/n-1$.
[c] System malfunction; no data acquired.

* Tire System Section, Office of Vehicle Systems Research, which has since been reorganized and is now a part of the National Highway Traffic Safety Administration.

If the observations within each sample vary greatly, then SSW will be large.

The term $\sum_{j=1}^{k}\sum_{i=1}^{n_j}(\bar{x}_{.j}-\bar{x}_{..})^2$ is referred to as the *among-samples sum of squares*. For the sake of brevity, it is designated SSA. It represents a measure of the variability of the sample means (specifically, the deviation of the sample means $\bar{x}_{.j}$ from the grand mean $\bar{x}_{..}$).

If we set $SSA/k-1 = MSA$, called the *mean square for among-samples*, and $SSW/n-k = MSW$, the *mean square for within-samples*, the test statistic can be more conveniently written as

$$F_{k-1,\,n-k} = \frac{MSA}{MSW}$$

That is, the test statistic $F_{k-1,\,n-k}$ is merely the ratio of the mean variation among samples to the mean variation within the samples.

The analysis of variance was applied to each of the 30, 40, and 60 mph samples, using $\alpha = 0.05$ as the level of significance. As shown in Table A-22, the equality of means hypothesis is rejected for each population group. Thus, at each speed, the skid number means varied among each other at a statistically significant level.

Table A-21 shows that the Penn State mean at each speed is the minimum such value of the set. No such pattern is observed for the maximum values among the means: at 30 mph, Delaware has the highest mean; at 40 mph, PennDOT; and at 60 mph, Maryland. It is reasonable to wonder if there is equality of means among the testers when the Penn State tester data is removed. The analysis of variance figures in Table A-23 tests this new hypothesis. As in the original test, however, equality is again rejected at all speeds.

Having demonstrated that the testers are unable to show agreement within statistical tolerances among themselves as

TABLE A-22

ANALYSIS OF VARIANCE TABLES FOR SIX TESTERS

SPEED (MPH)	SOURCE OF VARIATION	SS	DEGREES OF FREEDOM	MS	MSA[a] / MSW	CRITICAL REGION[b]	RESULT
30	Among samples	695.90	5	139.18	32.29	2.43	Reject H_o
	Within samples	232.56	54	4.31			
	Total:	928.46	59				
40	Among samples	616.83	5	123.37	24.19	2.41	Reject H_o
	Within samples	259.89	51	5.10			
	Total:	876.72	56				
60[c]	Among samples	536.02	4	134.00	34.01	2.60	Reject H_o
	Within samples	165.52	42	3.94			
	Total:	701.54	46				

[a] H_o: $\mu_{PSU} = \mu_{Delaware} = \mu_{Maryland} = \mu_{NBS} = \mu_{PennDOT} = \mu_{SIT}$.
[b] At $\alpha = 0.05$ level of significance.
[c] No data from Delaware tester.

TABLE A-23

ANALYSIS OF VARIANCE TABLES FOR FIVE TESTERS (PSU TESTER EXCLUDED)

SPEED (MPH)	SOURCE OF VARIATION	SS	DEGREES OF FREEDOM	MS	MSA[a] / MSW	CRITICAL REGION[b]	RESULT
30	Among samples	293.38	4	73.34	24.75	2.59	Reject H_o
	Within samples	133.32	45	2.96			
	Total:	426.70	49				
40	Among samples	162.40	4	40.60	6.73	2.60	Reject H_o
	Within samples	253.33	42	6.03			
	Total:	415.73	46				
60[c]	Among samples	106.53	3	35.51	11.84	2.90	Reject H_o
	Within samples	98.90	33	3.00			
	Total:	205.43	36				

[a] H_o: $\mu_{PSU} = \mu_{Delaware} = \mu_{Maryland} = \mu_{NBS} = \mu_{PennDOT} = \mu_{SIT}$.
[b] At $\alpha = 0.05$ level of significance.
[c] No data from Delaware tester.

to what the correct skid number is, it is appropriate next to consider if the variability in their data shows some consistency. Specifically, the equality of variances among the testers was investigated.

A method of testing the equality of k variances is given by Hoel (*46*). The test statistic in this case is

$$\chi'^2 = \frac{-2 \ln u}{1 + \frac{1}{3(k-1)}\left(\sum_{j=1}^{k} \frac{1}{n_j - 1} - \frac{1}{n-k}\right)}$$

where

$$u = \frac{\prod_{j=1}^{k} (s'^2_j)^{(n_j-1)/2}}{\left[\frac{\sum_{j=1}^{k}(n_j - 1)s'^2_j}{\sum_{j=1}^{k}(n_j - 1)}\right]^{\sum_{j=1}^{k}(n_j-1)/2}}$$

When the variances are equal, the statistic χ'^2 has a distribution which is approximately χ^2 with $k-1$ degrees of freedom. The rule for rejection is:

$$\text{Reject } H_0 \text{ if } \chi'^2 > \chi^2_{k-1\,;\,1-\alpha}$$

Table A-24 shows the results of applying this test at the $\alpha = 0.05$ level of significance to the hypothesis

$$H_0 : \sigma^2_{PSU} = \sigma^2_{Delaware} = \ldots = \sigma^2_{Stevens}$$

Rejection of variance equality occurs at 30 mph and 40 mph; however, at 60 mph, the hypothesis of equality is accepted. In view of the small sample sizes involved, caution should be observed in analyzing these results.

The data in Table A-24 suggests that there are substantial differences among the testers in terms of variability (at least at the two lower speeds). It seems reasonable to wonder if each tester exhibited consistent performances over the range of speeds. The same χ'^2 statistic may be used to test the hypothesis

$$H_0 : \sigma^2_{30\ mph} = \sigma^2_{40\ mph} = \sigma^2_{60\ mph}$$

for each tester. Table A-25 shows that for four of the testers, the variances over the range of speeds were reasonably the same. The other two systems (Penn State and Maryland), however, experienced significantly different variations with speed. It is interesting to note that in each case it was the 40-mph variance that upset the equality hypothesis. Curiously, though, the Penn State tester achieved its best results at 40 mph, while the Maryland tester experienced its poorest results at that speed.

TABLE A-24

VARIANCE HYPOTHESES OVER SIX TESTERS

SPEED (MPH)	TEST STATISTIC,[a] χ'^2	CRITICAL REGION,[b] $\chi^2_{k-1,\ 0.95}$	RESULT
30	16.25	11.07	Reject H_0
40	12.64	11.07	Reject H_0
60	7.13	9.49	Accept H_0

[a] H_0: $\sigma^2_{PSU} = \sigma^2_{Del} = \sigma^2_{Mary} = \sigma^2_{NBS} = \sigma^2_{PennDOT} = \sigma^2_{SIT}$.
[b] At $\alpha = 0.05$ level of significance.

TABLE A-25

VARIANCE HYPOTHESES OVER THREE SPEEDS

TESTER	TEST STATISTIC,[a] χ'^2	CRITICAL REGION,[b] $\chi^2_{k-1,\ 0.95}$	RESULT
PSU	11.43	7.38	Reject H_0
Delaware	0.02	5.02	Accept H_0
Maryland	15.15	7.38	Reject H_0
NBS	0.94	7.38	Accept H_0
PennDOT	0.21	7.38	Accept H_0
SIT	3.67	7.38	Accept H_0

[a] H_0: $\sigma^2_{30mph} = \sigma^2_{40mph} = \sigma^2_{60mph}$ vs. H_1: $\sigma_i^2 \neq \sigma_j$ for some i, j.
[b] At $\alpha = 0.05$ level of significance.

APPENDIX B

THE 1972 SKID TESTER CORRELATION PROGRAM

GENERAL

One of the project objectives was to conduct a regional correlation program involving a representative number of skid testers in order to verify the findings of the first year of research.

The NCHRP informed all state highway departments of the planned program and invited them to send their equipment or representatives. Twelve testers were to be selected to obtain a representative sampling of makes, suspension types, transducer types, and geographic location of the home base. Twelve affirmative replies were received and accepted. Just prior to the program, two cancellations were

received and one substitute tester arranged for. Participating testers and other pertinent information are given in Table B-1. A general invitation to observers was extended, resulting in about 20 visitors in addition to the project Advisory Panel. Participating personnel and observers are given in Table B-2. An open test period was scheduled for those testers that were unable to participate directly in the program. Two testers attended.

During the time leading up to the correlation program, close contact was maintained with the participants. Each was provided a standard electrical cable set with instructions for its installation on the tester and a Penn State water nozzle with instructions, which was installed mid-way through the program. The program began on Monday, October 2, 1972, and ended on Thursday, October 12. The Open Test Period program was held on Wednesday, October 25.

In preparation for the program, the test surfaces (Appendix C) were installed, broken-in, and pretested to select the primary surfaces for use in the correlation. Twenty ASTM test tires were procured from a single production batch, run-in 200 mi, tested for hardness and rebound, and stored under identical conditions for use during the correlation program. All instrumentation and equipment was acquired and checked out in practice tests to assure proper function. The responsibilities of each staff member were assigned and their jobs practiced before the program. Alternate plans were prepared and substitute equipment located for all critical aspects of the testing or data acquisition in the event of unforeseen problems.

Electronic and mechanical service shops were alerted to provide support on short notice if needed to repair breakdowns of the participating testers. Though a number of malfunctions occurred (Appendix G), the repairs accomplished permitted more than 90 percent completion of the planned tests.

The correlation program was planned around two weeks of activity. The first week was dedicated to obtaining the correlation between all testers in their arrival condition as they would be used in routine testing; calibration of the testers, adoption of a uniform watering method, and installation of a new tire; and retesting the correlation between all testers after these changes.

The second week, for which five testers were on hand, was dedicated primarily to additional correlation and diagnostic testing.

SCHEDULE OF ACTIVITIES

A rigid schedule, shown in Figure B-1, was set up for the first week of the program in order to obtain a maximum

TABLE B-1

CORRELATION PROGRAM PARTICIPANTS

TESTER NO.	SPONSORING ORGANIZATION	TESTER CREW	PARTICIPATION 1ST WEEK	PARTICIPATION 2ND WEEK	TESTER MAKE	YEAR	TRANSDUCERS FORCE	TRANSDUCERS TORQUE	TRANSDUCERS LOAD
1	Kentucky Dept. of Transportation	Frank Forester, Larry Warren	X	X	K. J. Law	1968 1969	X		X
2	Georgia Dept. of Transportation	Dale Morris, Jerry Stone	X		Soiltest	1969		X	
3	Pennsylvania Dept. of Transportation	Thomas Leitzel, Richard Rumberger	X	X	Soiltest	1969		X	
4	Florida Dept. of Transportation	S. L. Fuller, S. J. Cullen	X		Homebuilt	1966		X	
5	West Virginia Dept. of Highways	Don Tincher, John O'Leary, Bob Ward	X		Soiltest	1969		X	
6	Michigan Dept. of State Highways and Transportation	Paul Schafer, Philip T. Luce	X		K. J. Law	1971	X		X
7	Nassau County (N. Y.) Dept. of Public Works	John Canecky, Frank Klepper	X		Soiltest	1971		X	
8	University of Tennessee Highway Research Program	Howard Young, Mike Armstrong, Alex Moore	X		Homebuilt	1968		X	
9	North Carolina Dept. of Transportation and Highway Safety	Lee Webster, Richard Isley, Bob Hawkins	X	X	Homebuilt	1969		X	
10	Colorado Dept. of Highways	Phil McCabe, Lou Steere	X	X	Soiltest	1968		X	
11	Maryland Highway Administration	F. J. Stromberg, W. A. Fredericks	X		Homebuilt	1966		X	
12	Pennsylvania State University			X	Homebuilt	1970		X	

amount of data in the available time. The program started with an 8:15 AM meeting the first day at which the participants were acquainted with the objectives, instructed about their own activities, provided with name tags, and assigned tester identification numbers.

Immediately after the meeting the crews affixed the ID numbers to their testers, turned in a spare rim on which the prepared program tire was mounted, and toured the facilities.

At noon of the first day, the first correlation testing was started at the test track of the University's Pavement Durability Facility. The testers reported to the site in groups for a sequence of tests that took approximately one-half day. During the full days, two groups were run through to completion.

Each group conducted a sequence of tests alternating between two testers on the track simultaneously while the two others were standing by or preparing. While on the track each tester made a complete series of tests on a separate pair of the four primary surfaces. The complete series on each surface consisted of five tests each at speeds of 40, 30, 50, and 40 mph. At completion the testers would leave the track, stand by while the other pair of testers ran similar tests, then return to run their remaining two surfaces.

Five tests were considered the minimum number from which a reasonably accurate mean value could be determined. By running the four speeds indicated, the coefficient-speed gradient could be determined, and the second tests at 40 mph provided two data sets at that speed plus allowing study of the two 40-mph data sets for statistical differences. The crews were instructed to space each of the five tests equally across the surface both to minimize the development of a lateral profile and to average over what profile did exist. Though 60 mph was preferred for the high-speed test, 50 mph was selected because of the possibility that all testers might not be able to accomplish 60 mph at the site.

The testing pattern, by groups of four, was selected for efficiency and to allow comparisons within each group and among groups. Though the tests are not randomized due to practical considerations with 12 testers, the order of running was largely random. A different tester always ran two sets of tests either as a member of two consecutive groups or the first and last groups.

Five valid tests were required at each speed. Either the tester crews or the test site controller, who observed the skid placement and tester operation from the sidelines, could declare a test invalid. When that occurred, the test in question was immediately voided on all data records and was repeated in its proper sequence.

Upon entering the track, the test tires were inspected and checked for proper pressure. On leaving the track, tire temperatures were measured and other minor checks made. Before leaving the test area, the crews evaluated their test results and handed over all data to the program staff.

After completing the designated tests in the first correlation, each tester was taken to the garage area for calibrations and modifications. By prior arrangement, personnel of the National Bureau of Standards had set up a force plate and load calibration station in the garage area. Each tester was given precise wheel force and load calibration tests (Appendix F) in accordance with the latest NBS-prescribed procedures. Pertinent data such as the hitch height, trailer length, tire radius, and tire serial number were recorded. Each tester was fitted with a program test tire, which had been obtained from the same production batch and had been subjected to the same run-in as the others, and a nozzle built to Penn State specifications (Appendix A, Section 3.2). The water system was calibrated (Appendix A, Section 3.3) for flow rate at the equivalent of 30-, 40-, and 50-mph speeds and the nozzle position was adjusted as close as possible to match the uniform watering method specification.

After completing all calibrations and modifications, the testers participated in a second correlation program essentially identical to the first with the exception that the tester

TABLE B-2

LIST OF PARTICIPANTS AND ATTENDEES

I. Participating staff of the PTTSC:
- W. Meyer, Co-Principal Investigator, NCHRP Project 1-12(2)
- R. Hegmon, Co-Principal Investigator, NCHRP Project 1-12(2)
- T. Gillespie, Project Coordinator, NCHRP Project 1-12(2)
- W. Benson, Test Site Controller

M. Adams	T. Napp
B. Bright	W. Sellitto
J. J. Henry	R. Slavecki
T. Matsumoto	J. Tung
D. McCloskey	L. Wilson
P. Woodring	

Participating staff of the National Bureau of Standards:

B. Kearns	J. Ward

II. Observers:
- F. W. Barton—Safety Systems Laboratory, NHTSA-DOT
- F. E. Behn—Ohio Dept. of Transportation
- B. Brown—Iowa State Highway Commission
- Larry M. Cook—Federal Highway Administration
- C. Crumpton—State Highway Commission of Kansas
- L. R. Dreihaup—Federal Highway Administration (Region 15)
- M. W. Gallogly—Ohio State University
- John Hopkins—Pennsylvania Dept. of Transportation
- Don Ivey—Texas Transportation Inst., Texas A & M Univ.
- J. L. King—Ford Motor Co. (Western States Field Test Center)
- Ken J. Law—K. J. Law Engineers
- G. Musgrove—Ontario Ministry of Transportation and Communications
- R. M. Nicotera—Pennsylvania Dept. of Transportation
- W. Piotrowski—Federal Highway Administration
- Don Raisanen—Minnesota Department of Highways
- H. Smith—NCHRP
- A. J. Stocker—Texas Transportation Inst., Texas A & M Univ.
- S. D. Teaster—Federal Highway Administration
- John Watson—Federal Highway Administration
- E. A. Whitehurst—Ohio State University

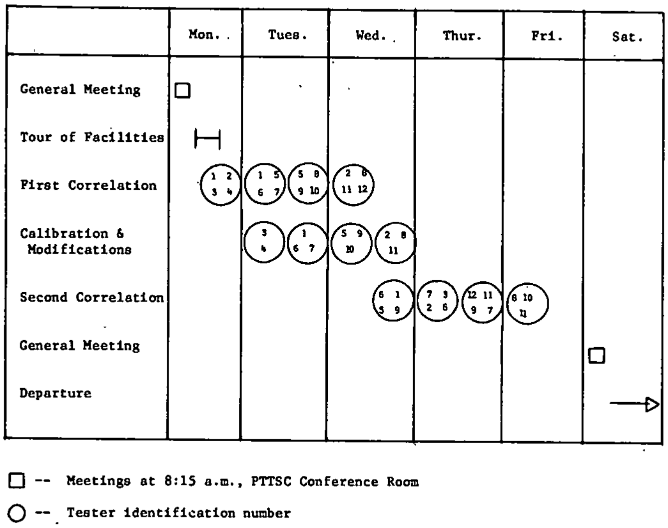


Figure B-1. General activity schedule for October 2 through 7, 1972.

grouping was changed. The testing activities were completed around noon of the fifth day.

Before departure of the one-week participants the next morning, a general meeting was held, and the preliminary results of the correlation program were presented. Each crew was given a copy of the calibration for their tester, a copy of their test results, and a summary of the results from all testers.

The activities during the second week of the correlation program were conducted on a less formal schedule and ended on the fourth day. Using the five testers on hand, the tests were conducted in the following predetermined order of priority:

a. Determine the differences between the original tester tires used in the first correlation and the program test tires used in the second correlation.
b. Run correlation tests on three additional surfaces.
c. Study lateral profiles measured by different testers.
d. Test for dynamic and aerodynamic loading.
e. Calibrate torque for diagnosis of two testers.
f. Make dynamic tests.
g. Make additional water flow rate calibrations.

EQUIPMENT AND FACILITIES

The preparations for conduct of the correlation program included acquiring and coordinating the use of equipment and facilities not normally on hand. Those considered necessary and provided for this program were:

1. Test site—The University's Pavement Durability Facility provided the test site. Parking space and an observation area were available along with office space and telephone. Nine test surfaces (Appendix C) were installed in an exclusive area. A power broom was procured for cleaning the test surfaces, as well as a water tanker for servicing the testers. The speed and lateral placement instrumentation and associated power supplies were installed at the site.

2. Garage area—A convenient garage with ample surrounding parking area was used for calibrations and general work on the testers. Electronic equipment in the form of voltmeters, oscilloscopes, power supplies, and a multitude of electrical cables, connecters, adapters, and components were on hand. Torque arm and water flow rate calibration equipment was provided. Wheel force and load calibrations, as well as the associated equipment, were contributed by the cooperating personnel of the National Bureau of Standards. Jack, chocks, blocks, and other miscellaneous materials were required.

3. Communications—A two-way radio link was established at the test site using military squad radios having an exclusive frequency. The radio link allowed the test site controller to have direct communications with the program staff and the tester crews, facilitating a very efficient test operation. A megaphone was available for other communication in the test area. An up-dated schedule of activities was maintained in the meeting room so that tester crews could remain informed of the progress in all phases of the program and anticipate any changes that would affect their individual schedules. A message center was maintained at the meeting room to ensure that all participants and visitors received outside messages.

4. Meeting room—A convenient meeting room was reserved for exclusive use by program personnel and visitors. The room was employed for general meetings and informal assemblages. Brochures and local information of general interest were displayed.

DATA ACQUISITION AND PROCESSING

Comprehensive data were recorded throughout the correlation program. Tester crews operated their own equipment at the test track to accumulate all skid data in routine fashion. At the completion of their runs, the crews took their skid data to the track office and immediately evaluated and converted them to skid numbers. All records were turned over to the program staff member present and the crews stood by to explain calibration values, zeros, chart speeds, and other factors needed for a staff evaluation of the same records. The tester crews were asked to indicate their evaluation interval on the skid record but not the value, to avoid biasing the staff evaluator. A magnetic tape recorder was used periodically to directly record data pertinent to individual testers for later evaluation.

At the site observation platform, the measured speed (traverse time) and lateral placement were recorded for each test along with the clocked time of each run. Wheel lock-up locations, indicated by the clock position of a paint mark on the test tire, were visually observed to detect any units having defective brakes that would cause a preferential lock-up position. The lateral and longitudinal placements of the skid on the surface were observed and any questionable tests were immediately voided and repeated. Weather and surface temperature data were periodically recorded.

A staff member at the service area where the testers entered the track inspected each test tire and recorded its serial number and pressure. At the periodic stops, the hitch

height, tire radius, and tire temperature, measured by a radiometer, were recorded.

For the water calibration, all water flow tests were recorded and converted to readings in gallons per minute at each speed. After adjusting the nozzles to match the specification as closely as possible, the 40-mph jet width was measured and recorded along with the nozzle height, angle, jet impact point, and other details about the water system design.

The force plate and load calibrations were recorded on an 11 x 17-in. X-Y plotter. The tester and force plate calibration values were entered on the plot to provide the proper scaling factor. The date, test tire number, static tire radius, hitch height, and trailer length were likewise recorded.

At a convenient point in the program, each tester crew completed an information sheet providing details on the design of their tester and associated equipment, their cycle timing, and data evaluation methods. The latter item provided the pertinent data such as hitch height, trailer length, and test wheel load used in routine crew interpretation of skid test data.

The crew-evaluated data was converted to skid numbers by using their routine procedures. The program staff evaluation of the skid traces was recorded in chart units and converted to skid numbers in the computer program used for data analysis. The force conversions, wheel loads, and unloading effects were variously based on the factors provided by the crews or by the force and load calibration data, depending on the form of data correction being analyzed. The correlations of the testers were studied (a) using the original data; (b) using the data corrected for procedural errors in interpretation, force and load calibration, lateral position, and temperature; and (c) after installation of standard nozzle and new tire. An estimated correction for surface deterioration diminished the correlation and was abandoned. Similarly a correction for speed errors, which were generally very small, made no improvement on the correlation.

During the second week of the program, all data were evaluated by the tester crews, and corrections based on the force and load calibrations were applied to the data. The way in which the data were reduced for analysis depended on the individual test objectives.

The tester crews also evaluated their own data during the open test period with corrections for the force and load calibrations conducted and with allowance for any procedural error encountered.

TESTER DIAGNOSTICS

An important facet of the correlation effect was the diagnosis of and correction for tester error sources. Diagnosis implies an analysis of the tester performance to identify error sources. The scheduled program calibrations of the water system, test wheel force, and test wheel load provided performance evaluations of these subsystems as the most likely sources of errors. Other formal tests represented additional efforts to identify suspected factors that produced errors or disparities in performance. The third element in the diagnosis was the review of tester design and operating procedures by the program staff. In several cases the detailed review of the test records, methods of data reduction, and operating procedures by independent and knowledgeable personnel revealed errors that could not be identified by other means.

The test wheel force plate and load calibrations were major contributions to the diagnostic work. The results, presented in Appendix F, indicate that none of the testers had both force and load calibrations within 1 percent. The errors averaged over all testers were 4.65 and 1.90 percent for force and load, respectively. Force system hysteresis of 10 lb or more was observed in 5 of the 12 testers.

The water calibrations (Appendix A, Section 3.3) tested the flow rate at different speeds and compliance with the uniform watering method specification when the common nozzle was installed. No effort was made to judge compliance of the testers' own nozzles with ASTM E 274 because of the variations in nozzle performance and their interpretation. Two testers had flow rates significantly higher than those expected by their crews. Three testers had flow that was not proportional at high speeds because of inadequate pumping capacity. An air-pressure-driven water system had poor repeatability linked to water tank level. With one exception all testers had sufficient or excess water flow. The exception was not expected to affect correlation because testing occurred on prewetted surfaces.

Torque calibrations were conducted on two testers to verify proper functioning of their transducer and instrumentation systems. One tester's calibration revealed a 10-percent nonlinearity in the strip chart recorder that was in addition to the force calibration error.

Several significant diagnostic discoveries resulted from a close examination of the skid records and procedures for determination of skid numbers. Two testers exhibited zero errors that adversely affected correlation. The magnetic tape-recorded data were used in determining corrections for these problems by integrating the zero values between the tests.

The instantaneous wheel load on tester No. 1 was recorded on magnetic tape for later analysis (Appendix A, Section 6.3). Though the results were not usable for identifying errors on any particular testers, they indicate the magnitude of dynamic and aerodynamic wheel load errors on many testers.

Tests were conducted to diagnose the reasons why different testers did not measure the same lateral friction profiles. When all testers ran simultaneously with a sufficient number of tests in identical order, the same lateral profile was observed by all, indicating that the profiles are partially determined by the method of test on the surface (Appendix C).

Tests were conducted which showed there was no significant difference between the two tires used by each tester in the program. Dynamic tests which were conducted indicated that the introduction of a small amount of roughness to the test surfaces did not influence the skid number obtained.

APPENDIX C

SKID TEST SURFACES

For conduct of the skid tester correlation program, test surfaces with a broad range of characteristics had to be prepared.

The test track at The Pennsylvania State University Pavement Durability Facility was selected as the site. The facility offered an exclusive nonpublic area in which the testing could be conducted. The 1-mile oval track allowed the testers to lap continuously, skid testing with each pass over the surfaces. This mode of operation avoided the need for testers to stop or turn around, allowed two or more testers to run simultaneously without interference, and facilitated controlled and consistent testing rates, which ranged between 1 and 2 min between tests.

GENERAL LAYOUT

The test surfaces were installed on a separate internal test lane alongside a level tangent of the track, which is shown in Figure C-1. The test lane provided a straight section approximately 1,150 ft in length with an approach allowing speeds above 50 mph.

The test surface lane was 12 ft wide and directly abutted the 15-ft wide track. The lane's cross slope was 0.25 in. per foot, which is typical of public highways, and was a compromise between attaining good water runoff during testing without subjecting the testers to excessive lateral slope.

The test lane was divided into 10 sites, each 6 ft wide by 200 ft long on which the surfaces were installed. The 6-ft widths conveniently allowed the surfaces to be appraised by five tests spaced laterally across the surface. This length of site translated into a 3.4-sec traverse time at 40 mph, which allowed adequate time for a skid test cycle and for the tester lock-up dynamics to decay.

TEST SURFACES

Nine surfaces were selected with consideration given to materials, construction methods, texture, and expected skid characteristics. With the exception of the special surfaces on sites 1 and 9, the choices were to reflect typical surfaces existing on public highways. The spectrum of surface types considered includes:

a. New portland cement concrete.
b. Worn portland cement concrete.
c. Coarse texture bituminous concrete.

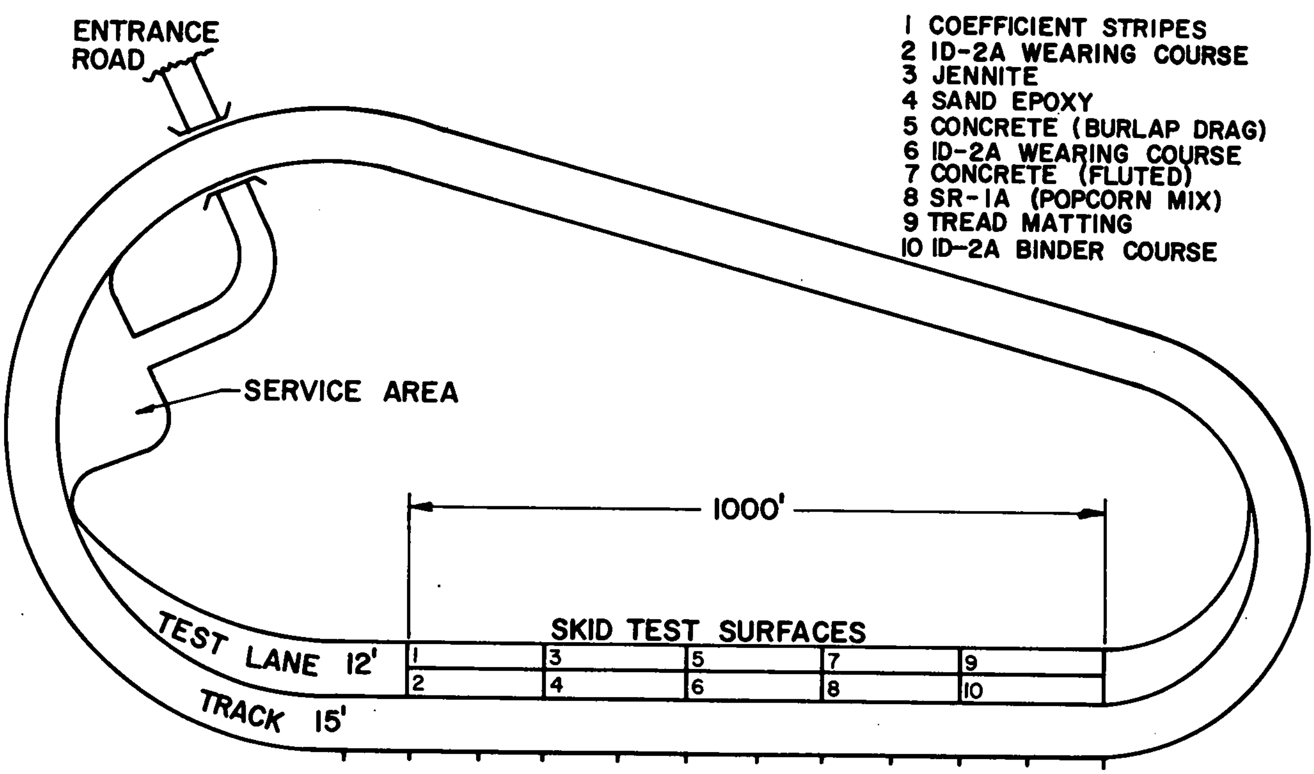


Figure C-1. Test surfaces installation at Pavement Durability Facility.

d. Medium texture bituminous concrete.
e. Bleeding asphalt.
f. Hot-mix plant seal.
g. Epoxy-type surface treatment.

Other criteria applied to the choices included having:

a. Skid number range of 20 to 50 with a selection of different textures in the 30- to 45-SN range.
b. Range of coefficient-speed gradients from approximately 0 to 1 SN per mile per hour.
c. Maximum number of different aggregates.
d. Maximum range of textures.

The final choice of surfaces was further influenced by cost, availability of materials, and the experience and capability of the construction personnel.

The test surface area was paved by the contractor responsible for all other construction of the test track using personnel experienced in highway construction. The paving and application of the test surfaces were completed in a two-week period ending the first week of September 1972, one month before the correlation program began. After a period of approximately two weeks, each of the surfaces was subjected to a high-pressure water wash, an initial skid test survey, and was given a series of "break-in" tests prior to the correlation program. Just prior to the program, the test surfaces were thoroughly cleaned by a power broom.

A description of each of the test surfaces follows:

1. Coefficient-stripes: The coefficient-stripes were installed by the project personnel on a Pennsylvania specification ID-2A bituminous concrete wearing surface. The stripes were constructed of 2-ft-wide, Presslab's self-adhesive plastic pavement marking material cut to lengths and applied at intervals on the surface to provide a periodic friction variation for excitation of the test wheel. The stripes were placed in two adjacent 2-ft lanes, yielding a total of five available frequencies (1, 2, 4, 8, and 16 Hz at 40 mph), each being of at least 1-sec test duration.

2. ID-2A wearing course: Pennsylvania specification ID-2A bituminous concrete wearing surface (*47*) installed by the contractor consisted of 42 percent Pennsylvania Type A limestone coarse aggregate 1-B (½-in. max. size) and 58 percent crushed stone fines plus 5.5 percent AC2000 asphalt cement. The surface was machine spread and compacted by steel-wheel and pneumatic-tire rollers.

3. Jennite: Pennsylvania ID-2A wearing course treated by project personnel with a commercially available coal-tar pitch seal coat applied in two layers: the first, Jennite J-16 (80 sq ft per gallon) and the second, Jennite J-16 mixed 3 to 1 with AFR Plus (100 sq ft per gallon).

4. Sand-epoxy: Pennsylvania ID-2A wearing course treated by project personnel with Colma Tar Coating (Sika Chemical Co.), a two-component coal tar modified epoxy resin compound, then covered with sand. The epoxy was spread uniformly by squeegee at an excess rate of 30 sq ft per gallon. Once the spreading was accomplished, the area was immediately saturated with 20-40 Flint Shot Ottawa sand (1.2 sq ft per pound) broadcast by hand. The treatment was allowed 24 hr for curing and then thoroughly broomed to remove excess sand.

5. Burlap drag concrete: The surface was produced on an 8-in., reinforced portland cement concrete pad constructed by the contractor. As the concrete was poured and hand-finished by smooth float, the surface was given a light application of transverse burlap drag.

6. ID-2A wearing course: Same as surface No. 2.

7. Fluted concrete: The surface was produced on 8-in., reinforced portland cement concrete constructed by the contractor like that of surface No. 5. The poured concrete was finished to a smooth surface by normal methods, after which it was immediately refloated by transverse application of a 40-in. Haivala magnesium float having corrugations on ⅜-in. centers and producing about ⅛-in. penetration.

8. SR-1A (popcorn): Pennsylvania SR-1A experimental hot-mix plant seal was installed by the contractor. The surface, consisting of 85 percent Pennsylvania 1-B graded coarse crushed river gravel aggregate and 15 percent crushed stone fines plus 6.5 percent AC2000 asphalt cement, was machine laid and compacted by steel-wheel and pneumatic-tire rollers.

9. Tread Matting: Tread Matting is the trade name for a commercially available textured steel plate material produced by the Morton Manufacturing Company. The surface is characterized by ⅜-in. diameter by 3⁄16-in.-high unperforated hemispherical dimples in a regular pattern of ⅝ in. between centers. The surface was purchased as eight sheets of 14-gauge cold-rolled steel, 2 ft by 10 ft. The sheets were bolted end-to-end, producing a 2 by 80-ft test surface secured to a paved surface by four pins per sheet. The surface was detergent cleaned but unused at the time of the correlation program. The matting was stored in a dry location to prevent rust and was installed by project personnel just before use.

10. ID-2A binder course: Pennsylvania ID-2A specification bituminous concrete binder course (*47*) was installed by the contractor. The surface material, consisting of 5 percent Pennsylvania Type A limestone coarse aggregate 1-B (½-in. maximum size), 63 percent 2-B coarse aggregate (1-in. maximum size), and 32 percent crushed stone fines plus 4.3 percent AC2000 asphalt cement, was machine laid and compacted by steel-wheel and pneumatic-tire rollers.

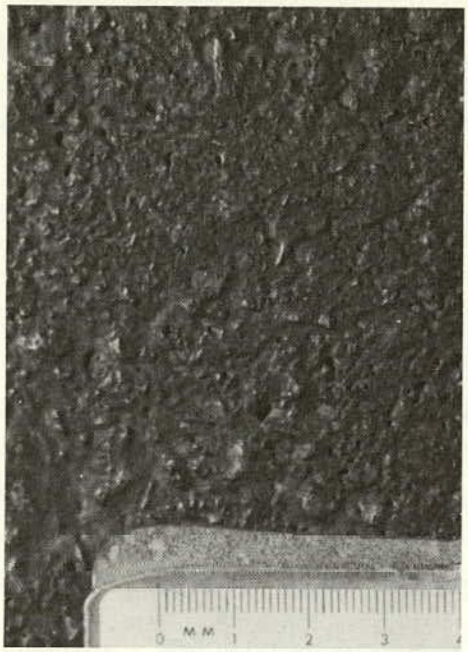
Surfaces No. 3, 4, 5, and 6 were used as the primary test surfaces in the skid tester correlation program. Close-up photographs of these surfaces are shown in Figure C-2, and samples of the surface profiles obtained with a profile tracer (*48*) are shown in Figure C-3.

Surface Characteristics

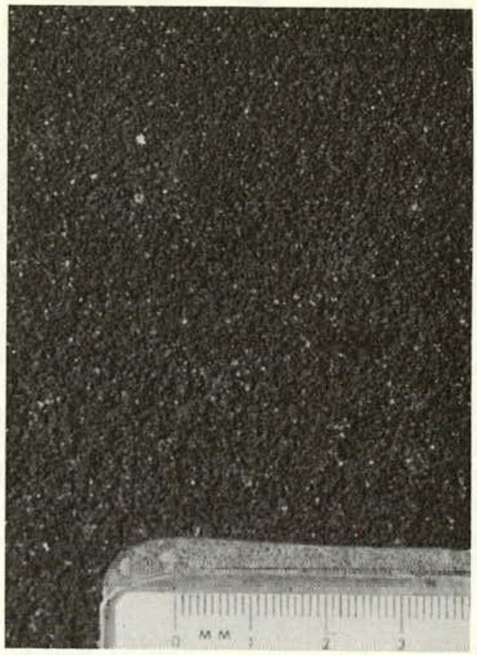
Since installation, the test surfaces were exposed to a number of different types of tests to measure and monitor their characteristics. By far the most comprehensive of these has been the skid tests conducted before, during, and after the skid tester correlation program.

For the six permanent surfaces used in the correlation program, Table C-1 gives the skid numbers and speed gradients determined with the Penn State road friction tester at various points in the testing activity.

The September 15 tests were the initial tests and first traffic on the surfaces. The October 4 and 5 dates were approximately midway through the correlation program.



Site 3, jennite



Site 4, sand-epoxy

Site 5, burlap drag concrete

Site 6, ID-2A

Figure C-2. Photographs of the four primary surfaces.

The mean skid characteristics for the four primary surfaces obtained in the correlation program are given in Table C-2. The data represent the averages from all tests in the second correlation after all corrections were applied.

Other tests which have been conducted on the surfaces include surveys with the British portable tester, the Penn State drag tester, and a pressurized outflow meter. The British portable tests were conducted in the longitudinal direction on the surfaces and in accordance with ASTM E 303. Test procedures for the Penn State drag tester (*49*) and the pressurized outflow meter (*4*) are described in the references. Table C-3 summarizes the results of these tests, which were made once before and once after the correlation program.

Permeability tests at 60-psi pressure conducted simultaneously with the outflow meter tests indicated no measurable permeability on any of the surfaces.

The Primary Surfaces

Construction of nine test surfaces allowed a choice of the best ones because of the possibility that not all would prove suitable for the intended function. The Jennite, sand-epoxy, burlap drag concrete, and the ID-2A wearing course surfaces were selected for primary use in the correlation program. This choice of surfaces offered:

1. Surface types of portland cement concrete, bituminous concrete, and surface treatment.
2. A well-distributed preprogram skid number range of 14 to 55.
3. Preprogram skid number-speed gradients of 0.3 to 1.0 SN per mile per hour.
4. Surface textures based on maximum aggregate sizes ranging from 0.033 in. (sand-epoxy) to 0.5 in. (ID-2A wearing course).

In addition the surfaces were all adjacent, which facilitated the conduct and control of test activities, and were located in the portion of the tangent where tests were most easily accomplished.

From the standpoint of correlation testing, surface stability and uniformity are important. Figure C-4 shows the skid numbers of the four primary surfaces measured by the Penn State road friction tester versus the number of tests accumulated on each surface during the test activities. The Jennite and the burlap drag concrete stabilized most rapidly and with the least change, although the concrete changed further in the tests when the surfaces lay idle for a period of time between tests. The sand-epoxy, on the other hand, was the slowest to stabilize but, from appearance of the data, offers good promise of long-term stability.

The uniformity of the surfaces may be judged in two ways—longitudinally and laterally. The longitudinal uniformity is reflected in the force fluctuations of the skid test record. The handmade Jennite and sand-epoxy surfaces on a percentage basis exhibited the lowest degrees of fluctuation. Similarly, these surfaces had negligible change in average friction level from end to end, whereas the burlap-drag concrete had approximately a 6 SN drop. The skid trace of the ID-2A wearing course indicated the friction level at the midpoint of the surface was approximately 6 SN lower than at either end.

The lateral uniformity or lateral profile requires a different method of test. The test surfaces were essentially new at the beginning of the correlation program. The individual skid test data from the first eight testers in the correlation program were plotted as a function of the lateral position at which the tests occurred. Within the normal variability of the data, a discernable profile was difficult to determine.

The same type of data was plotted for all tests in the second correlation, at which time the surfaces were being exposed to their 350th through 650th skid tests. The data plot for each tester was adjusted in mean level to make all data points fall within the smallest possible band. Figure C-5 shows resulting plots for each surface. All surfaces exhibit data trends that evidence a lateral profile. The dashed lines indicate the approximate shape. The sand-epoxy surface, site 4, has maintained the best uniformity in total magnitude and severity of lateral profile. The ID-2A wearing course, by the same measure, has the poorest.

When the data for individual testers are considered separately, a consistent lateral profile does not appear. During the correlation program's second week, tests were conducted to determine whether five testers would measure the same lateral profile when using identical test procedures. The tests were conducted on site 6 with five testers, running one behind the other. Five tests by each tester were conducted as close as possible to a selected lateral position, then the position was shifted. Figure C-6 shows the five-test

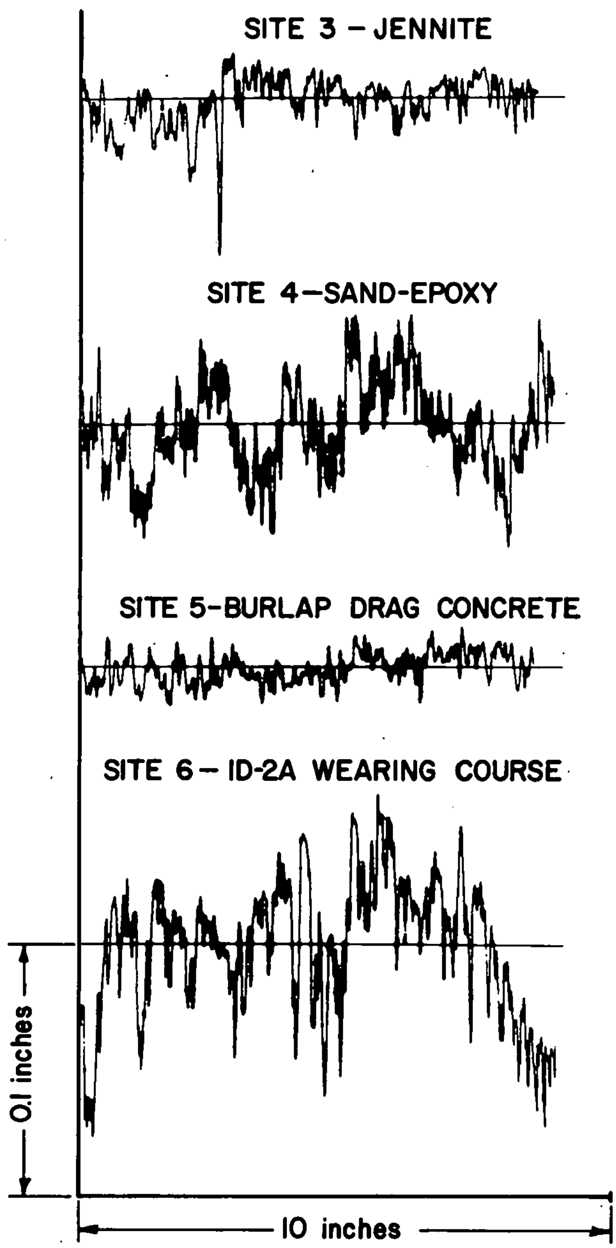


Figure C-3. Sample surface profiles of the four primary surfaces.

TABLE C-1

SKID CHARACTERISTICS OF SIX TEST SURFACES OVER ONE AND ONE-HALF MONTHS OF INTENSIVE USE

		SKID NUMBER,[a] SN						SKID NUMBER GRADIENT,[b] G					
DATE	NO. OF TESTS TO DATE	JEN-NITE	SAND-EPOXY	BURLAP DRAG CON-CRETE	ID-2A [c]	FLUTED CON-CRETE	SR-1A	JEN-NITE	SAND-EPOXY	BURLAP DRAG CON-CRETE	ID-2A [c]	FLUTED CON-CRETE	SR-1A
Sept. 15	10	16	65	36	57	54	52	0.30	0.57	0.73	1.0	0.14	0.60
Sept. 21	50	14	55	37	44	54	44	—	—	—	—	—	—
Oct. 4	350	12	48	32	40	—	—	0.15	0.52	0.50	0.50	—	—
Oct. 5	600	12	46	32	41	—	—	0.15	0.46	0.53	0.63	—	—
Oct. 12	750	12	47	34	41	—	—	—	—	—	—	—	—
Oct. 12	150	—	—	—	—	51	48	—	—	—	—	0.35	0.50
Oct. 25	800	11	47	37	43	—	—	—	—	—	—	—	—

[a] SN is the skid number at 40 mph determined by Penn State tester, average of five tests minimum.
[b] G is the 40-mph skid number gradient (expressed in skid number per miles per hour) determined from 30- and 50-mph tests.
[c] Surface 6.

TABLE C-2

MEAN SKID CHARACTERISTICS OF FOUR PRIMARY SURFACES

			SPEED GRADIENT (SN/MPH) FOR		
SITE	SURFACE	SN_{40}	30 MPH	40 MPH	50 MPH
3	Jennite	11.47	0.1946	0.1626	0.1306
4	Sand-epoxy	45.67	0.4372	0.3972	0.3572
5	Burlap drag concrete	32.77	0.6982	0.5404	0.3824
6	ID-2A	38.84	0.6545	0.3725	0.0905

TABLE C-3

SURFACE CHARACTERISTICS MEASURED BY THE BRITISH PORTABLE TESTER (BPN), PENN STATE DRAG TESTER (DTN), AND PRESSURIZED OUTFLOW METER (POM)

		SEPT. 24		OCT. 27		
SITE	SURFACE	BPN	DTN	BPN	DTN	POM (SEC)
3	Jennite	53	42	46	34	12.6
4	Sand-epoxy	78	55	86	51	4.7
5	Burlap drag concrete	66	58	75	58	5.4
6	ID-2A	73	57	75	53	2.7
7	Fluted concrete	63	—	69	—	0.6
8	SR-1A	71	57	73	57	0.9

average for each tester at each selected lateral position. Comparison of this profile with that in Figure C-5 shows good agreement.

Other Test Surfaces

The other surfaces utilized in the second week of the correlation program were the fluted concrete, SR-1A (popcorn) mix, and the Tread Matting surfaces.

The fluted concrete was originally selected for a test surface because of a reported better stability when compared against other concrete texturing methods (*50*). In constructing this surface, difficulty was experienced in trying to achieve both lateral and longitudinal uniformity of the finish. Early testing revealed that the surface produced a skid trace record with a severe decay (approximately 5 SN per second of skid) possibly due to longitudinal surface variations or other effects. The correlation tests conducted on this surface demonstrated the strong influence such an effect can have on skid-resistance measurement. Figure C-7 shows the tester correlation obtained on this surface. The skid test data of tester No. 12 were evaluated twice, once immediately after lock-up and once delayed 1 sec. after lock-up (i.e., the middle of the trace), with an obvious effect on the agreement between testers.

The lateral profiles on this surface determined from a plot of data from all testers indicated a 5 SN difference between the centerline and either edge.

Similar correlation tests were conducted on the SR-1A (popcorn) mix with the results shown in Figure C-8. This surface proved comparable to the ID-2A wearing course in longitudinal uniformity. No discernable lateral profile had developed in the relatively few tests accumulated.

A sufficient number of tests were not accumulated to adequately evaluate the stability of SR-1A or fluted concrete surfaces.

Tests were conducted on the Tread Matting surface to determine correlation and uniformity. Because of its initial polishing tendency, tests were run with each tester following another. Twenty tests at 30 mph were conducted. The mean SN_{30} for all testers was 18.88 with a 1.75 SN (9.3 percent) range. After correction of the individual test data for a slight skid number change due to polishing during the tests, the standard deviation for the data of each tester was computed and found to be close to, but not significantly better than, the values exhibited on the Jennite surface.

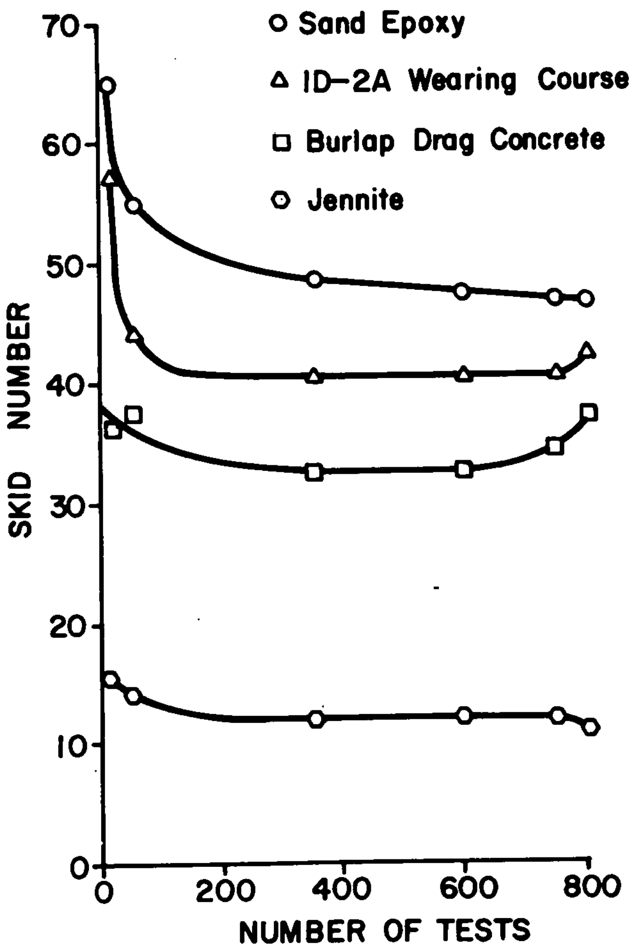


Figure C-4. Skid number changes on the primary test surfaces.

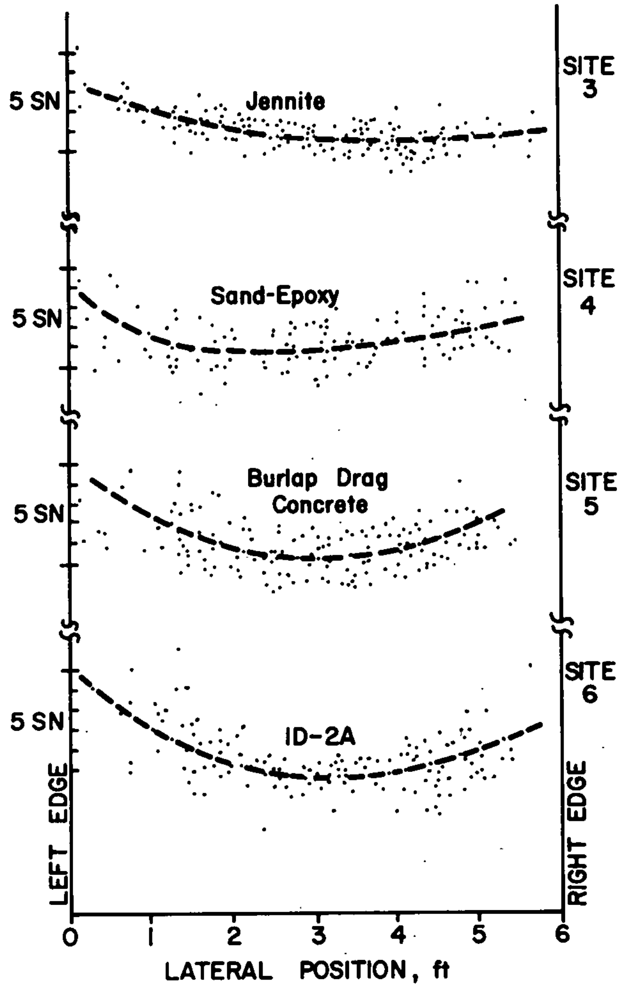


Figure C-5. Lateral profiles developed on the four primary test surfaces.

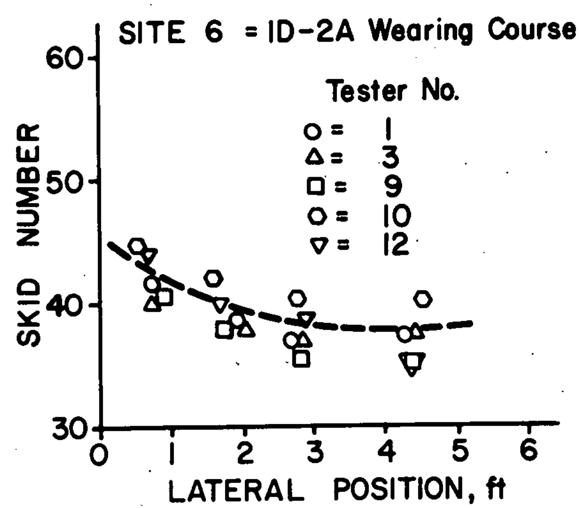


Figure C-6. Lateral profile measured by five testers.

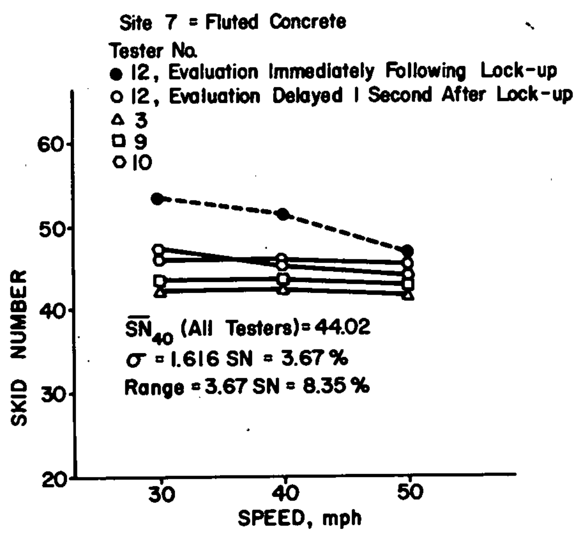


Figure C-7. Skid tester correlation on site 7.

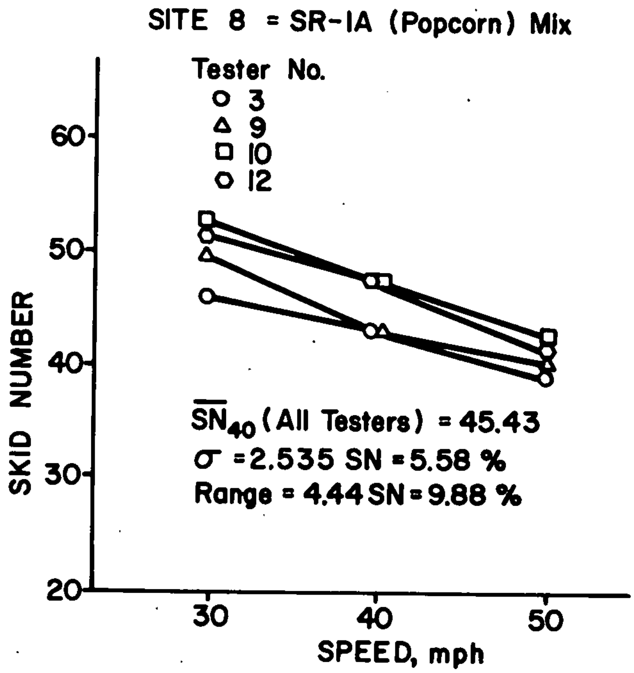


Figure C-8. Skid tester correlation on site 8.

APPENDIX D

STATISTICAL METHODS

Skid resistance and speed data were processed and analyzed. Chart units off the recorder of each tester were converted to force or torque, depending on the type of calibration of the particular tester. All data of the second correlation were converted to force, using the factors determined in the platform calibration. Skid numbers were computed from these force or torque values according to ASTM E 274. Speed was computed from the elapsed time measured by tape switches on the test sites. Thus, for each skid number, the corresponding actual speed was known. All computations were made on an IBM 360/67 or 360/50 computer at the Computation Center of The Pennsylvania State University.

The statistical analyses applied in various phases of the project can be found in most textbooks on applied statistics (*51, 52*). Efforts were made to use generally accepted terminology. Specific terms used in this project are defined in the brief descriptions of the different analyses given below.

ANALYSIS OF VARIANCE (ANOV)

The primary analysis of the test data during the first week of the correlation program was based on the "complete 3-way, fixed-effect analysis of variance" method. It was applied to skid numbers and to speed. The three factors were skid tester, test site, and nominal speed. The statistical program (STPAC-AOVUM) is provided by the Computation Center.

The Model

The analysis of variance is based on a linear model given by

$$Y_{ijkm} = u + T_i + P_j + V_k + (TP)_{ij} + (PV)_{jk} + (TV)_{ik} + (TPV)_{ijk} + e_{ijkm}$$

$$i=1, \ldots, a;\ j=1, \ldots, b;\ k=1, \ldots, c;\ m=1, \ldots, n$$

where all parameters in the model are components of fixed-effect factors (except the error term e_{ijkm}), and combined factors in parentheses are components of interaction of these factors The term "fixed-effect factor," as applied to the three variables, implies that the levels of these factors are not randomly selected. The participating skid testers were not randomly selected from all skid testers in the United States, but are representative of them. Neither was the selection of test sites and test speeds random. It was based on several considerations, one of them being the representativeness of pavements and speeds found in survey

testing. The error term e_{ijkm} represents random fluctuations caused by uncontrolled effects and is a random-effect component, as opposed to the fixed-effect factors. It is assumed that e_{ijkm} is normally and independently distributed with mean 0 and variance σ_e^2.

Statistical Layout

The statistical layout used is a complete (no missing observations) 3-factor cross (all levels of one factor meet with all levels of another factor) design with equal numbers of observations per cell. The design is given formally in Table D-1.

ANOV Table and Estimate of Variance Components

A sample printout of the analysis of variance is shown in Figure D-1. Some of the terms are given in Table D-2. The printout lists also the total sum of squares, which is the sum of squares of all individual observations; the correction factor, which is the mean of all observations squared and multiplied by the number of observations; and the corrected total sum of squares, which is the difference between the two.

The last column lists the probability corresponding to the computed F ratio. These probabilities were equal to 0.000 in all the analyses, which means that the differences within each factor (source) are statistically significant at level $\alpha = 0.000$.

The large sums-of-squares (SS) values for factors 2 and 3 were expected because test sites and speeds of widely varying skid resistance had been chosen. The magnitude of the first factor is, however, of primary interest in this project because it signifies the differences among the skid testers. It too was large, giving large F-ratios and corresponding zero probabilities. The F-ratio is obtained by dividing mean square (MS) by error mean square (EMS); it is a measure of the variation among the testers relative to the variation in the repeat tests of the single testers.

The sum of squares for each source of variation is computed by summation, and typical formulae are:

$$SS_T = \sum_i Y_i^2 \ldots / bcn - CF$$

$$SS_{TP} = \sum_i \sum_j Y_{ij}^2 \ldots / cn - CF - SS_T - SS_P$$

$$SS_{TPV} = \sum_i \sum_j \sum_k Y_{ijk}^2 / n - CF - SS_T - SS_P - SS_V - SS_{TP} - S_{PV}$$

where CF (correction factor) $= \dfrac{Y^2 \ldots}{abcn}$. The "." notation means summing over the dotted index.

An estimate of variance component of each source can be made by equating mean square to expected mean square:

$$s_E^2 = MS_E$$

and

$$s_T^2 = (MS_T - MS_E)/bcn$$

where s is the estimate of σ. In computing the tester variance, all interaction factors are eliminated so that s_T^2 may be considered a measure of pure tester variance. However, when the interaction terms are statistically significant, as is the case here (probability = 0.000), s_T^2 is too conservative an estimate of the variability among skid testers.

The relative effect of the factors in the interaction terms can not be separated, but another estimate of tester variance can be obtained that includes the interaction terms.

$$s_A^2 = \frac{SS_T + SS_{TP} + SS_{TV} + SS_{TPV}}{(a-1)bcn}$$

It is clear that s_A^2 is an overestimate of tester variation and may better be considered the over-all variance in skid testing among testers. If variances are computed separately

VARIABLE NUMBER 2, SNCT

ANALYSIS OF VARIANCE SUMMARY TABLE

THIS IS AN EXACT ANALYSIS

SOURCE		SUMS OF SQUARES	DF	MEAN SQUARES	F RATIO	PROBABILITY
1	TESTER	1241.1	14	88.651	68.099	0.000
2	PAVEMENT	186829.7	3	62276.581	47839.151	0.000
3	SPEED	7997.0	3	2665.670	2047.695	0.000
12		1045.2	42	24.886	19.117	0.000
13		143.5	42	3.417	2.624	0.000
23		1088.8	9	120.973	92.928	0.000
123		436.2	126	3.462	2.659	0.000
ERROR		1249.7	960	1.302		

TOTAL SUM OF SQUARES	1412609.
CORRECTION FACTOR	1212577.
CORRECTED TOTAL SUM OF SQUARES	200031.

Figure D-1. Typical printout of analysis of variance.

TABLE D-1

STATISTICAL LAYOUT FOR COMPLETE 3-FACTOR CROSS DESIGN (WITH EQUAL NUMBER OF OBSERVATIONS PER CELL)

PAVEMENT	TESTERS				
	T_1			T_2 . . .	T_a
	Speed				
P_1	V_1	V_2 . . .	V_c		
	Y_{1111}		Y_{11c1}		
	Y_{1112}				
	Y_{111n}	. . .	Y_{11cn}		[a]
P_2					
P_b					

[a] The indices for observations Y_{inkm} can be filled in accordingly.

for each test site and speed (based on cell means) the average of all these variances, $\bar{s}^2$, can be shown to be equal to $s_A{}^2$. It can be computed by

$$s_A{}^2 = \frac{1}{bc}\sum_{j=1}^{b}\sum_{k=1}^{c}\left[\frac{\sum_{i=1}^{a}\left(\frac{\sum_{l=1}^{n} Y_{ijkl}}{n}\right)^2 - a\left(\frac{\sum_{i=1}^{a}\sum_{l=1}^{n} Y_{ijkl}}{an}\right)^2}{a-1}\right]$$

Thus, whenever the effect of interactions is statistically significant, it is advisable to examine the "inclusive" variance ($s_A{}^2$) as well as the "pure" variance ($s_T{}^2$). The former underestimates as the latter overestimates the expected variability, but knowing both gives a better feel for the effect of the variable in question.

The computer program for ANOV routinely applies Bartlett's test for homogeneity of variances among observation cells. These tests were negative in some cases, but no corrections were considered necessary because the F tests in ANOV are robust with respect to departure from homogeneity of variances, especially in the case of equal numbers of observations per cell.

Interpretation of the results of the analysis of variance led to the conclusion that the differences between the 15 sets of test data are significant; in other words, they cannot be explained by random variations. Since these results are inclusive of all testers, the question arose whether one or several testers could be identified as being responsible for the large variations.

A multiple comparison test (CMCMP, PSU Computation Center) was applied to make a pairwise comparison between each tester and all others. This test was applied to several of the ANOV results, some averaged over all test sites and some separate for each test site. Figure D-2 shows typical results. No single tester could be identified as being alone outside the range of the critical difference, and, therefore, elimination of results for one or two testers from the analysis of variance would not make the variations insignificant.

CORRELATION AND REGRESSION ANALYSIS

Two sets of corresponding numbers can be tested for correlation to determine the degree of dependence of one on the other. The correlation coefficient ranges between 0 and ±1, the latter signifying perfect correlation. Measured speeds and skid numbers gave a low correlation factor of 0.11. Similarly, correlation between rubber hardness and skid number was low, 0.30. Instead of a formal test, correlation can be estimated by plotting the data and observing the trend.

A regression analysis can be used to determine dependence between the variables. Several regression models were considered, such as linear, polynomials, exponential, power series, and logarithmic. Five regression models were selected and tried on available skid-resistance versus speed

TABLE D-2

EXPLANATION OF TERMS IN THE ANALYSIS OF VARIANCE

SOURCE OF VARIATION	SUM OF SQUARES (SS)	DEGREE OF FREEDOM	MEAN SQUARE,[a] (MS)	F-RATIO [b]	EXPECTED MEAN SQUARE, ($\sigma_e{}^2$)
Tester	SS_T	$a-1$	MS_T	MS_T/MS_E	$\sigma_e{}^2 + bcn\,\sigma_T{}^2$
Pavement	SS_P	$b-1$	MS_P	MS_P/MS_E	$\sigma_e{}^2 + acn\,\sigma_P{}^2$
Speed	SS_V	$c-1$	MS_V	MS_V/MS_E	$\sigma_e{}^2 + abn\,\sigma_V{}^2$
TP interaction	SS_{TP}	$(a-1)(b-1)$	MS_{TP}	MS_{TP}/MS_E	$\sigma_e{}^2 + cn\,\sigma_{TP}{}^2$
TV interaction	SS_{TV}	$(a-1)(c-1)$	MS_{TV}	MS_{TV}/MS_E	$\sigma_e{}^2 + bn\,\sigma_{TV}{}^2$
PV interaction	SS_{PV}	$(b-1)(c-1)$	MS_{PV}	MS_{PV}/MS_E	$\sigma_e{}^2 + an\,\sigma_{PV}{}^2$
TPV interaction	SS_{TPV}	$(a-1)(b-1)(c-1)$	MS_{TPV}	MS_{TPV}/MS_E	$\sigma_e{}^2 + n\,\sigma_{TPV}{}^2$
Error	SS_E	$abc(n-1)$	MS_E	—	$\sigma_e{}^2$

[a] Mean square = sum of square/degrees of freedom.
[b] F-ratio = mean square/error mean square.

data at three nominal speeds. The analysis was done on MZNZTAB (Dept. of Statistics, PSU). The within-speed experimental errors and the standard deviations of experimental and computed data are given in Table D-3. The within-speed experimental error is the random variation of skid number within each of the nominal speeds. It can be considered a lower boundary for the standard deviation of the regression models. The test statistic for Friedman's test is

$$T = \frac{12}{bk(k+1)} \sum_{j=1}^{k} R_j^2 - 3b\,(k+1)$$

and the critical value for T is read from an f^2 table with $k-1$ degree of freedom. The T value calculated for the given ranking is 2.422 and the critical value at 95 percent level is 9.488. Therefore, the results fail to reject the null hypothesis at 95 percent level and conclude that the differences among models are not statistically significant. In fact, this T value is highly insignificant—not even significant at 75 percent level. Since none of the five models proved to be statistically superior, the second-order polynomial was selected, which can be related to physical phenomena.

To fit the data to the assumed model

$$Y = a + bx + cx^2$$

the least-square method is used. Assuming n sets of observations X_i, Y_i, $i = 1, \ldots n$ are given, then n simultaneous equations

$$Y_i = a + bx_i + cx_i^2 + d_i$$

can be set up, where d_i are the deviation terms. We define

$$S = \sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} (Y_i - a - b\,x^i - c\,x_i^2)^2$$

then a, b, and c are obtained by minimizing S. This is done by a computer program (*53*) that also prints a plot of residuals and computes the T ratio and the R^2 value.

The plot of residuals is examined for trends; it should have none; that is, the residuals should be random.

The T ratio is a measure of the significance of each of the independent variables in the regression.

R^2 measures the percentage of variation explained by the computer regression.

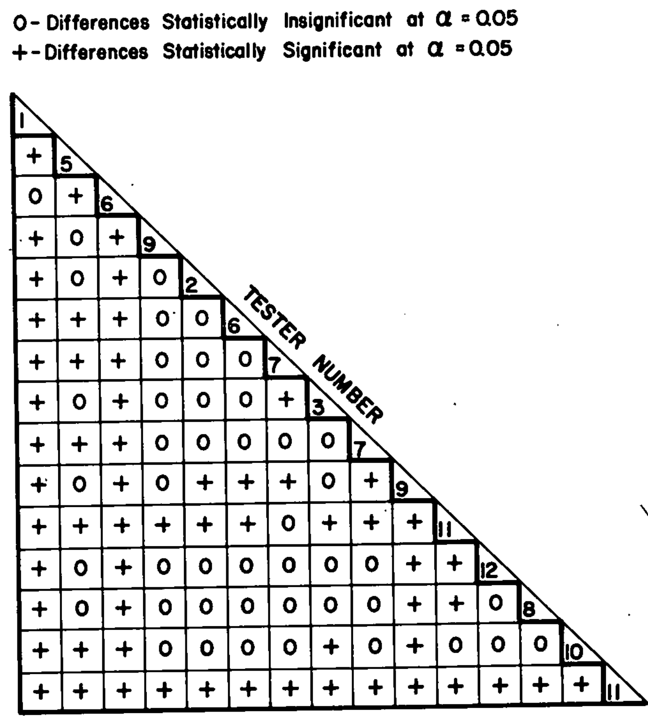


Figure D-2. Results of multiple comparison test for significance of differences in mean skid numbers, ANOV–9.

TABLE D-3

TABLE OF STANDARD DEVIATIONS FOR COMPARISONS

MODEL DATA SET	WITHIN SPEED EXPECTED ERROR	LOG SN = $a+b$ LOG V	SN = $a+bV+cV^2$	SN = $a+\frac{b}{V}+\frac{c}{V^2}$	SN = $a+b\sqrt{V}$	SN = $a+\frac{b}{\sqrt{V}}$
1	1.44	1.45	1.43	1.43	1.39	1.58
2	2.65	2.55	2.73	2.64	3.10	2.61
3	3.78	2.95	3.013	3.0050	3.0015	3.0038
4	2.45	4.33	2.61	3.00	3.37	4.56
5	3.13	3.25	3.131	3.130	3.07	3.21
6	1.78	2.08	1.94	1.95	2.43	1.98
7	3.85	3.82	3.68	3.83	3.57	4.03
8	2.73	2.64	2.76	2.76	2.78	2.69
9	3.38	2.92	2.562	2.560	2.54	2.76

APPENDIX E

DETAILED SKID DATA FROM THE CORRELATION PROGRAM

The following tables list the detailed skid test data acquired in the 1972 Skid Tester Correlation Program, and the modifications to the data as corrections were applied. All skid numbers were obtained from the program staff evaluation of the skid test records.

Each mean skid number is the average of five skid tests by a single tester distributed laterally across the test site at the indicated nominal speed. The testers were assigned into groups of four, each group taking approximately one-half day to complete all tests. Data for tester No. 4 in group No. 1 were not available because of tester malfunctions (Appendix G).

Groups No. 1 through 4 represent the data acquired in the first correlation with the testers operated in their arrival condition. Data in groups No. 5 through 8 were for the second correlation after a common water nozzle and new program test tire were installed. The force and load calibrations obtained between the first and second correlations provided corrections applicable to all data.

The uncorrected data obtained in the first correlation are given in Table E-1. The skid records were evaluated by the program staff and were converted to skid numbers by the ASTM equation using chart scale factors, hitch heights, trailer lengths, and test wheel loads provided by the tester crews. These data are used in ANOV-1.

Table E-2 contains the same data with correction for a procedural error in evaluation of the data from tester No. 1 due to a zero offset. These data are used in ANOV-2.

Table E-3 represents the data given in Table E-2 corrected for force and load calibrations. In this case the program-staff-evaluated skid records were converted to skid numbers by the ASTM equation using the chart scale factors, hitch heights, trailer lengths, and test wheel loads determined in the calibrations. These data are used in ANOV-3.

The uncorrected data obtained in the second correlation are given in Table E-4. These data, used in ANOV-4, are comparable to those given in Table E-1 with the exception that standard water nozzles and program test tires were used on all testers.

Table E-5 gives the second correlation data from Table E-4 corrected for force and load calibrations as explained previously. These data are used in ANOV-5.

Table E-6 gives corrections to the data of Table E-5 for a reduction of the skid number variation due to lateral position. The corrections were determined by subjectively

TABLE E-1

FIRST CORRELATION DATA; UNCORRECTED (ANOV-1)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
1	1	19.2	22.2	19.2	20.2	60.4	62.0	57.2	59.9	44.6	50.3	41.1	45.3	56.0	59.3	50.6	54.2
	2	13.3	15.0	12.6	13.0	54.7	56.6	48.8	53.4	40.6	44.5	33.5	38.3	52.4	59.2	43.4	47.8
	3	14.6	16.2	13.2	14.4	53.4	57.6	48.2	53.0	37.2	43.6	31.8	36.2	45.4	57.6	42.0	47.2
Group mean:		15.7	17.8	15.0	15.9	56.2	58.7	51.4	55.4	40.8	46.1	35.5	39.9	51.3	58.7	45.3	49.7
2	1	21.9	21.2	20.1	20.6	56.7	60.7	54.0	57.2	30.5	35.7	24.5	28.4	39.2	42.2	34.8	36.0
	5	12.1	12.9	9.8	10.6	43.1	45.6	40.6	42.9	29.8	32.7	24.3	28.8	32.6	41.9	30.0	32.0
	6	11.5	13.8	10.2	12.3	47.2	52.3	42.8	45.0	33.8	37.4	28.4	33.6	39.9	44.9	35.7	38.6
	7	16.2	18.8	15.0	15.5	60.5	65.1	58.3	58.2	38.7	48.2	33.4	39.4	45.0	48.6	42.3	47.6
Group mean:		15.4	16.7	13.8	14.7	51.9	55.9	48.9	50.8	33.2	38.5	27.6	32.5	39.2	44.4	35.7	38.5
3	5	10.7	12.2	10.2	10.5	44.5	48.3	40.8	44.5	29.9	32.9	26.9	29.4	34.5	39.2	33.4	35.4
	8	12.8	15.5	11.0	12.1	50.2	56.6	44.4	49.6	33.8	42.6	29.2	33.7	45.3	50.9	39.4	43.8
	9	13.6	14.6	10.8	11.9	48.8	55.8	47.4	51.2	35.8	40.3	30.2	35.3	42.1	48.4	39.9	41.6
	10	14.3	15.9	12.7	13.9	55.2	58.0	50.3	55.5	36.7	44.3	32.6	36.9	51.7	56.7	45.7	48.6
Group mean:		12.8	14.5	11.2	12.1	49.7	54.7	45.7	50.2	34.0	40.0	29.7	33.8	43.4	48.8	39.6	42.3
4	2	13.8	14.9	10.8	12.9	51.8	54.4	48.1	50.3	35.2	42.1	30.4	35.3	41.3	47.1	38.1	41.0
	8	12.8	16.1	11.8	12.8	51.9	56.2	45.1	51.6	36.3	42.2	29.9	33.8	42.9	48.6	39.3	42.1
	11	11.8	12.6	10.4	10.9	46.9	50.8	43.0	46.1	32.4	36.2	29.7	32.2	45.7	48.8	39.8	41.9
	12	11.8	13.0	10.2	10.9	47.2	53.0	42.8	47.0	31.0	36.8	27.2	30.0	38.4	43.9	34.2	38.8
Group mean:		12.5	14.1	10.8	11.9	49.4	53.6	44.7	48.7	33.7	39.3	29.3	32.8	42.1	47.1	37.8	40.9
Grand mean:		14.0	15.7	12.4	13.5	51.5	54.7	47.5	51.0	35.1	40.7	30.2	34.4	43.5	49.2	39.2	42.4

reducing high skid-resistance values measured at the extreme edges of the test surfaces. These data are used in ANOV-7.

Table E-7 gives further correction to the data of Table E-6 to compensate for zero shift errors that had occurred with testers No. 1 and 6. These data are used in ANOV-8.

Table E-8 gives temperature corrections to the data of Table E-7. All data were corrected to a common tempera-

TABLE E-2

FIRST CORRELATION DATA; CORRECTED FOR EVALUATION ERRORS (ANOV–2)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
1	1	15.0	17.3	12.5	14.4	54.5	56.9	50.2	52.9	31.6	38.7	27.6	31.8	44.0	47.5	39.6	42.7
	2	13.3	15.0	12.6	13.0	54.7	56.6	48.8	53.4	40.6	44.5	33.5	38.3	52.4	59.2	43.4	47.8
	3	14.6	16.2	13.2	14.4	53.4	57.6	48.2	53.0	37.2	43.6	31.8	36.2	45.4	57.6	42.0	47.2
Group mean:		14.3	16.2	12.8	13.9	54.2	57.0	49.1	53.1	36.5	42.3	31.0	35.4	47.3	54.8	41.7	45.9
2	1	14.4	14.4	12.5	13.6	50.5	52.8	45.8	50.1	30.5	35.7	24.5	28.4	39.2	42.2	34.8	36.0
	5	12.1	12.9	9.8	10.6	43.1	45.6	40.6	42.9	29.8	32.7	24.3	28.8	32.6	41.9	30.0	32.0
	6	11.5	13.8	10.2	12.3	47.2	52.3	42.8	45.0	33.8	37.4	28.4	33.6	39.9	44.9	35.7	38.6
	7	16.2	18.8	15.0	15.5	60.5	65.1	58.3	58.2	38.7	48.2	33.4	39.4	45.0	48.6	42.3	47.6
Group mean:		13.5	15.0	11.9	13.0	50.3	53.9	46.9	49.0	33.2	38.5	27.6	32.5	39.2	44.4	35.7	38.5
3	5	10.7	12.2	10.2	10.5	44.5	48.3	40.8	44.5	29.9	32.9	26.9	29.4	34.5	39.2	33.4	35.4
	8	12.8	15.5	11.0	12.1	50.2	56.6	44.4	49.6	33.8	42.6	29.2	33.7	45.3	50.9	39.4	43.8
	9	13.6	14.6	10.8	11.9	48.8	55.8	47.4	51.2	35.8	40.3	30.2	35.3	42.1	48.4	39.9	41.6
	10	14.3	15.9	12.7	13.9	55.2	58.0	50.3	55.5	36.7	44.3	32.6	36.9	51.7	56.7	45.7	48.6
Group mean:		12.8	14.5	11.2	12.1	49.7	54.7	45.7	50.2	34.0	40.0	29.7	33.8	43.4	48.8	39.6	42.3
4	2	13.8	14.9	10.8	12.9	51.8	54.4	48.1	50.3	35.2	42.1	30.4	35.3	41.3	47.1	38.1	41.0
	8	12.8	16.1	11.8	12.8	51.9	56.2	45.1	51.6	36.3	42.2	29.9	33.8	42.9	48.6	39.3	42.1
	11	11.8	12.6	10.4	10.9	46.9	50.8	43.0	46.1	32.4	36.2	29.7	32.2	45.7	48.8	39.8	41.9
	12	11.8	13.0	10.2	10.9	47.2	53.0	42.8	47.0	31.0	36.8	27.2	30.0	38.4	43.9	34.2	38.8
Group mean:		12.5	14.1	10.8	11.9	49.4	53.6	44.7	48.7	33.7	39.3	29.3	32.8	42.1	47.1	37.8	40.9
Grand mean:		13.2	14.9	11.6	12.7	50.7	53.9	46.4	50.1	34.2	39.9	29.3	33.6	42.7	48.4	38.5	41.7

TABLE E-3

FIRST CORRELATION DATA; CORRECTED FOR EVALUATION ERRORS, AND FORCE AND LOAD CALIBRATIONS (ANOV–3)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
1	1	14.7	16.9	12.3	14.1	53.4	55.9	49.2	51.9	31.0	38.0	27.2	31.2	43.1	46.6	38.8	41.8
	2	13.0	14.7	12.3	12.8	53.8	55.7	47.9	52.5	39.8	43.7	32.9	37.6	51.5	58.3	42.6	47.0
	3	13.2	14.7	11.9	13.0	48.3	52.1	43.6	48.0	33.7	39.4	28.8	32.8	41.1	52.1	38.0	42.7
Group mean:		13.6	15.4	12.2	13.3	51.8	54.6	46.9	50.8	34.8	40.4	29.6	33.9	45.2	52.3	39.8	43.8
2	1	14.1	14.1	12.3	13.3	49.5	51.7	44.9	49.0	29.8	35.0	24.0	27.8	38.4	42.3	34.0	35.2
	5	13.7	14.6	11.1	12.0	48.9	51.7	46.1	48.7	33.6	37.0	27.4	32.6	36.9	47.5	34.0	36.2
	6	12.1	14.5	10.8	13.0	49.7	55.1	45.0	47.4	35.6	39.3	29.8	35.3	41.9	47.3	37.5	40.6
	7	14.6	17.0	13.5	14.0	54.3	58.4	52.3	52.2	34.8	43.3	30.1	35.5	40.5	43.6	38.0	42.8
Group mean:		13.6	15.0	11.9	13.1	50.6	54.2	47.1	49.3	33.4	38.6	27.8	32.8	39.4	45.2	35.9	38.7
3	5	12.1	13.8	11.5	11.9	50.2	54.6	46.0	50.2	33.8	37.2	30.4	33.2	38.9	44.3	37.7	40.0
	8	12.9	15.7	11.1	12.2	50.7	57.2	44.9	50.1	34.1	43.0	29.5	34.0	45.7	51.4	39.8	44.3
	9	13.3	14.3	10.6	11.7	47.9	54.7	44.5	50.2	35.2	39.6	29.7	34.6	41.3	47.5	39.2	40.8
	10	13.4	14.9	12.0	13.1	51.7	54.3	47.1	51.9	34.4	41.5	30.6	34.6	48.4	53.1	42.8	45.5
Group mean:		12.9	14.7	11.3	12.2	50.1	55.2	45.6	50.6	34.4	40.3	30.0	34.1	43.6	49.1	39.9	42.6
4	2	13.5	14.6	10.6	12.7	51.2	53.8	47.6	49.8	34.7	41.6	29.9	34.8	40.8	46.6	37.5	40.5
	8	12.9	16.2	11.9	12.9	52.6	57.0	45.7	52.2	36.8	42.7	30.3	34.2	43.4	49.3	39.8	42.6
	11	12.1	12.9	10.7	11.2	48.1	52.1	44.1	47.3	33.2	37.1	30.5	33.0	46.8	50.1	40.8	42.9
	12	12.2	13.4	10.5	11.2	48.6	54.6	44.1	48.4	31.9	37.9	28.0	30.9	39.6	45.2	35.2	40.0
Group mean:		12.7	14.3	10.9	12.0	50.1	54.4	45.4	49.4	34.1	39.8	29.7	33.2	42.6	47.8	38.3	41.5
Grand mean:		13.2	14.8	11.5	12.6	50.6	53.8	46.3	50.0	34.2	39.8	29.3	33.5	42.6	48.3	38.4	41.5

ture according to the assumed factor of 4 percent per 10 deg F (i.e., skid number decreases by 4 percent with a temperature rise of 10 F). The wet-pavement temperatures measured during the program were used for the correlation.

TABLE E-4

SECOND CORRELATION DATA; WITH STANDARD NOZZLE AND PROGRAM TIRE, UNCORRECTED (ANOV–4)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
5	1	11.1	11.7	8.1	8.9	40.7	44.6	37.0	42.4	33.7	38.1	28.1	31.0	37.8	41.6	34.6	36.6
	5	10.5	12.8	10.2	11.0	40.7	43.3	36.9	41.3	33.8	37.6	31.0	32.8	28.2	35.1	24.3	27.1
	6	10.4	11.5	9.1	10.1	41.2	46.4	38.3	40.6	28.4	36.6	22.0	28.0	32.3	35.0	29.5	32.4
	9	12.6	14.3	10.4	11.4	47.0	50.6	42.7	47.0	34.8	42.6	27.8	33.7	39.6	45.0	37.7	41.0
Group mean:		11.1	12.6	9.4	10.3	42.4	46.2	38.7	42.8	32.7	38.7	27.2	31.4	34.5	39.2	31.5	34.3
6	2	12.4	15.5	10.0	11.7	47.3	53.0	43.0	48.3	33.2	38.7	28.3	34.5	40.6	45.6	38.3	40.0
	6	9.9	11.4	7.9	9.9	40.9	45.7	37.6	41.9	36.3	38.8	31.4	34.2	40.0	45.2	37.1	40.3
	7	12.8	15.8	10.0	13.5	52.9	56.7	49.5	52.8	36.7	46.6	31.5	37.3	45.9	52.3	41.0	45.6
	3	13.8	15.3	11.6	13.4	50.2	53.3	45.1	49.3	36.2	43.2	32.3	36.7	43.7	49.0	40.5	43.4
Group mean:		12.2	14.5	9.9	12.1	47.8	52.2	43.8	48.1	35.6	41.8	30.9	35.7	42.5	48.0	39.2	42.3
7	7	14.3	16.1	11.2	13.9	54.3	58.9	50.2	51.9	36.8	41.2	33.5	35.8	44.6	49.5	40.4	43.6
	9	12.8	13.7	10.9	12.5	46.5	50.9	41.2	47.4	33.2	36.6	26.8	32.2	39.1	43.9	37.5	38.3
	11	12.5	13.3	10.3	11.3	47.6	51.0	44.4	46.3	34.4	39.4	31.8	35.2	39.5	44.6	37.5	39.4
	12	11.5	12.5	9.6	11.2	45.3	49.6	40.7	44.8	32.4	38.2	27.2	32.0	41.4	48.8	36.2	39.8
Group mean:		12.8	13.9	10.5	12.2	48.4	52.6	44.1	47.6	34.2	38.8	29.8	33.8	41.1	46.7	37.9	40.3
8	8	11.8	13.7	10.6	11.1	46.5	51.4	43.5	47.7	32.5	39.7	28.0	32.1	39.8	44.3	36.5	38.3
	10	12.1	13.1	11.4	11.0	51.2	54.5	47.1	50.5	35.4	43.7	30.9	35.2	44.9	50.8	43.0	44.1
	11	13.3	14.6	11.4	12.1	46.9	53.3	45.5	48.8	35.9	42.3	30.1	35.7	40.0	45.7	39.4	40.9
Group mean:		12.4	13.8	11.1	11.4	48.2	53.1	45.4	49.0	34.6	41.9	29.7	34.3	41.6	46.9	39.6	41.1
Grand mean:		12.1	13.7	10.2	11.5	46.6	50.9	42.8	46.7	34.2	40.2	29.4	33.8	39.8	45.1	36.9	39.4

TABLE E-5

SECOND CORRELATION DATA; STANDARD NOZZLE AND PROGRAM TIRES, CORRECTED FOR FORCE AND LOAD CALIBRATIONS (ANOV–5)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
5	1	10.9	11.5	8.0	8.8	40.0	43.8	36.4	41.6	33.1	37.4	27.6	30.5	37.1	40.9	33.9	35.9
	5	11.9	14.4	11.5	12.4	46.4	49.4	42.0	47.1	32.0	39.9	27.5	30.8	38.4	42.8	35.2	37.3
	6	11.0	12.1	9.6	10.6	43.3	48.8	40.2	42.7	29.8	38.5	23.1	29.4	34.0	36.8	31.0	34.1
	9	12.4	14.1	10.3	11.2	46.2	49.7	41.9	46.2	34.2	41.9	27.3	33.1	38.8	44.2	37.1	40.3
Group mean:		11.5	13.0	9.8	10.7	44.0	47.9	40.1	44.4	32.3	39.4	26.4	30.9	37.1	41.2	34.3	36.9
6	2	12.1	15.2	9.8	11.4	46.5	52.0	42.3	47.5	32.6	38.0	27.7	33.8	39.8	44.8	37.6	39.2
	6	10.4	12.0	8.3	10.4	43.0	48.1	39.5	44.0	38.1	40.1	33.0	36.0	42.0	47.6	39.0	42.4
	7	11.5	14.2	8.9	12.2	47.5	51.0	44.5	47.4	33.1	42.0	28.4	33.6	41.3	47.1	36.9	41.0
	3	12.5	13.8	10.5	12.1	45.4	48.2	40.8	44.6	32.8	39.1	29.2	33.2	39.5	44.3	36.6	39.3
Group mean:		11.6	13.8	9.4	11.5	45.6	49.8	41.8	45.9	34.1	39.8	29.6	34.1	40.6	45.9	37.5	40.5
7	7	12.9	14.5	10.1	12.6	48.8	52.9	45.1	46.7	33.2	37.1	30.2	32.3	40.2	44.5	36.4	39.2
	9	12.6	13.5	10.7	12.3	45.7	50.0	40.5	46.5	32.6	36.0	26.3	31.6	38.4	43.1	36.8	37.6
	11	12.8	13.6	10.5	11.6	48.7	52.1	45.4	47.4	35.2	40.3	32.5	36.1	40.4	45.7	38.4	40.3
	12	11.8	12.9	9.9	11.5	46.7	51.1	41.9	46.1	33.4	39.3	28.0	33.0	42.6	50.3	37.3	41.0
Group mean:		12.5	13.6	10.3	12.0	47.5	51.5	43.2	46.7	33.6	38.2	29.2	33.2	40.4	45.9	37.2	39.5
8	8	11.9	13.8	10.7	11.3	47.0	51.9	44.0	48.2	32.8	40.1	28.2	32.4	40.2	44.8	36.9	38.7
	10	11.4	12.3	10.7	10.3	48.0	51.0	44.1	47.3	33.2	40.9	28.9	33.0	42.1	47.6	40.3	41.3
	11	13.6	15.0	11.7	12.4	48.0	54.5	46.5	50.0	36.7	43.3	30.8	36.5	41.0	46.7	40.3	41.8
Group mean:		12.3	13.7	11.0	11.3	47.7	52.5	44.9	48.5	34.2	41.4	29.3	34.0	41.1	46.4	39.2	40.6
Grand mean:		12.0	13.5	10.1	11.4	46.1	50.3	42.3	46.2	33.5	39.6	28.6	33.0	39.7	44.7	36.9	39.3

TABLE E-6

SECOND CORRELATION DATA; STANDARD NOZZLE AND PROGRAM TIRE, CORRECTED FOR FORCE AND LOAD CALIBRATIONS, AND LATERAL POSITION (ANOV-7)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
5	1	10.5	11.5	8.0	8.8	39.4	43.1	36.4	41.6	33.1	37.4	27.6	30.5	36.6	40.3	33.9	35.9
	5	11.9	14.4	11.5	12.4	46.4	49.4	42.0	47.1	32.0	39.9	27.5	30.8	38.4	42.8	35.2	37.3
	6	11.0	12.1	9.6	10.6	43.3	48.8	40.2	42.7	29.8	38.5	23.1	29.4	34.0	36.8	31.0	33.7
	9	12.4	14.1	10.3	11.2	46.2	49.7	41.9	46.2	34.2	40.1	27.3	33.1	38.8	43.5	37.1	40.3
Group mean:		11.4	13.0	9.8	10.7	43.8	47.7	40.1	44.4	32.3	39.0	26.4	30.9	36.9	40.8	34.3	36.8
6	2	12.1	15.2	9.8	11.4	46.5	52.0	42.3	47.5	32.6	38.0	27.7	33.8	39.8	44.8	37.6	39.2
	6	10.4	11.7	8.3	10.4	43.0	48.1	39.5	44.0	38.1	40.8	33.0	36.0	42.0	47.6	39.0	42.4
	7	11.5	14.2	8.9	12.2	47.5	51.0	44.5	47.4	33.1	42.0	28.4	33.6	41.3	46.7	36.9	41.0
	3	12.5	13.8	10.5	12.1	45.4	48.2	40.8	44.6	32.8	39.1	29.2	33.2	39.5	43.8	36.6	39.3
Group mean:		11.6	13.7	9.4	11.5	45.6	49.8	41.8	45.9	34.1	40.0	29.6	34.1	40.6	45.7	37.5	40.5
7	7	12.9	14.5	10.1	12.6	48.8	52.9	45.1	46.7	33.2	37.1	28.6	32.3	40.2	44.5	36.4	39.2
	9	12.6	13.5	10.7	12.3	45.7	50.0	40.5	46.2	32.6	36.0	26.3	31.6	38.4	42.8	36.8	37.7
	11	12.8	13.6	10.5	11.6	48.7	52.1	45.4	47.4	35.2	40.3	32.5	36.1	40.0	45.7	38.4	40.3
	12	11.8	12.9	9.9	11.5	46.7	51.1	41.9	45.8	33.4	39.3	28.0	33.0	41.2	49.0	37.3	39.8
Group mean:		12.5	13.6	10.3	12.0	47.5	51.5	43.2	46.5	33.6	38.2	28.8	33.2	39.9	45.5	37.2	39.2
8	8	11.9	13.8	10.7	11.2	47.0	51.9	44.0	48.2	32.8	40.1	28.2	32.4	40.2	44.8	36.9	38.7
	10	11.4	12.3	10.7	10.3	48.0	51.0	44.1	47.3	33.2	40.9	28.9	33.0	41.1	47.4	38.9	40.3
	11	13.6	15.0	11.7	12.4	48.0	54.5	46.5	50.0	36.1	43.3	30.4	36.5	41.0	46.7	39.9	41.0
Group mean:		12.3	13.7	11.0	11.3	47.7	52.5	44.9	48.5	34.0	41.4	29.2	34.0	40.8	46.3	38.6	40.0
Grand mean:		12.0	13.5	10.1	11.4	46.0	50.3	42.3	46.2	33.5	39.5	28.5	33.0	39.5	44.5	36.8	39.1

TABLE E-7

SECOND CORRELATION DATA; STANDARD NOZZLE AND PROGRAM TIRE, CORRECTED FOR FORCE AND LOAD CALIBRATIONS, LATERAL POSITION, AND ZERO SHIFT ERRORS (ANOV-8)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
5	1	12.5	13.5	10.0	10.8	41.5	45.3	38.5	43.8	33.1	37.4	27.6	30.5	36.6	40.3	33.9	35.9
	5	11.9	14.4	11.5	12.4	46.4	49.4	42.0	47.1	32.0	39.9	27.5	30.8	38.4	42.8	35.2	37.3
	6	11.0	12.1	9.6	10.6	43.3	48.8	40.2	42.7	31.9	40.6	25.1	31.5	37.1	39.9	34.1	35.7
	9	12.4	14.1	10.2	11.2	46.2	49.7	41.9	46.2	34.2	40.1	27.3	33.1	38.8	43.5	37.1	40.3
Group mean:		11.9	13.5	10.3	11.2	44.3	48.3	40.6	44.9	32.8	39.5	26.9	31.5	37.7	41.6	35.1	37.3
6	2	12.1	15.2	9.8	11.4	46.5	52.0	42.3	47.5	32.6	38.0	27.7	33.8	39.8	44.8	37.6	39.2
	6	12.4	13.6	10.3	12.4	43.0	48.1	39.5	44.0	34.0	36.6	28.9	31.8	37.8	43.3	34.8	38.1
	7	11.5	14.2	8.9	12.2	47.5	51.0	44.5	47.4	33.1	42.0	28.4	33.6	41.3	46.7	36.9	41.0
	3	12.5	13.8	10.5	12.1	45.4	48.2	40.8	44.6	32.7	39.1	29.2	33.2	39.5	43.8	36.6	39.3
Group mean:		12.1	14.2	9.9	12.0	45.6	49.8	41.8	45.9	33.1	38.9	28.5	33.1	39.6	44.6	36.5	39.4
7	7	12.9	14.5	10.1	12.6	48.8	52.9	45.1	46.7	33.2	37.1	28.6	33.3	40.2	44.5	36.4	39.2
	9	12.6	13.5	10.7	12.3	45.7	50.0	40.5	46.2	32.6	36.0	26.3	31.6	38.4	42.8	36.8	37.7
	11	12.8	13.6	10.5	11.6	48.7	52.1	45.4	47.4	35.2	40.3	32.5	36.1	40.0	45.7	38.4	40.3
	12	11.8	12.9	9.9	11.5	46.7	51.1	41.9	45.8	33.4	39.3	28.0	33.0	41.2	49.0	37.3	39.8
Group mean:		12.5	13.6	10.3	12.0	47.5	51.5	43.2	46.5	33.6	38.2	28.8	33.5	39.9	45.5	37.2	39.2
8	8	11.9	13.8	10.7	11.2	47.0	51.9	44.0	48.2	32.8	40.1	28.2	32.4	40.2	44.8	36.9	38.7
	10	11.4	12.3	10.7	10.3	48.0	51.0	44.1	47.3	33.2	40.9	28.9	33.0	41.1	47.4	38.9	40.3
	11	13.6	15.0	11.7	12.4	48.0	54.5	46.5	50.0	36.1	43.3	30.4	36.5	41.0	46.7	39.9	41.2
Group mean:		12.3	13.7	11.0	11.3	47.7	52.5	44.9	48.5	34.0	41.4	29.2	34.0	40.8	46.3	38.6	40.1
Grand mean:		12.2	13.8	10.3	11.7	46.2	50.4	42.5	46.3	33.3	39.4	28.3	32.9	39.4	44.4	36.7	38.9

TABLE E-8

SECOND CORRELATION DATA; STANDARD NOZZLE AND PROGRAM TIRE, CORRECTED FOR FORCE AND LOAD CALIBRATIONS, LATERAL POSITION, ZERO SHIFT ERRORS AND TEMPERATURE (ANOV–9)

TEST SITE:		3				4				5				6			
SPEED, MPH:		40	30	50	40	40	30	50	40	40	30	50	40	40	30	50	40
GROUP	TESTER	MEAN SKID NUMBER															
5	1	12.5	13.5	9.9	10.6	41.0	44.7	37.9	42.9	34.1	38.5	28.3	31.1	38.3	42.2	35.3	37.4
	5	12.4	15.0	11.9	12.9	48.4	51.5	43.6	48.7	31.3	38.9	26.7	29.8	38.6	42.8	35.0	36.9
	6	11.4	12.5	10.0	11.0	45.3	51.1	42.1	44.6	31.9	40.6	25.0	31.4	38.2	40.9	34.8	36.3
	9	12.8	14.4	10.5	11.4	46.8	50.3	42.3	46.4	32.5	37.9	25.7	31.0	38.0	42.4	35.8	38.6
Group mean:		12.3	13.8	10.6	11.5	45.4	49.4	41.5	45.6	32.4	39.0	26.4	30.8	38.3	42.1	35.2	37.3
6	2	11.3	14.1	9.1	10.7	43.1	48.3	39.2	44.1	30.5	35.6	26.0	31.7	37.3	42.0	35.3	36.8
	6	11.6	12.8	9.6	11.6	41.1	45.9	37.9	42.4	31.6	34.0	26.9	29.6	35.2	40.2	32.4	35.5
	7	10.7	13.3	8.3	11.4	44.1	47.2	41.3	44.0	30.9	39.1	26.5	31.3	38.5	43.5	34.5	38.2
	3	11.7	13.0	9.8	11.3	42.5	45.1	38.2	41.7	30.5	36.4	27.2	30.9	36.8	40.8	34.1	36.6
Group mean:		11.3	13.3	9.2	11.2	42.7	46.6	39.1	43.0	30.9	36.3	26.6	30.9	36.9	41.6	34.1	36.8
7	7	12.3	13.9	9.7	12.1	46.5	50.4	43.2	44.7	32.4	36.2	27.7	31.2	39.5	43.8	35.6	38.2
	9	12.4	13.3	10.5	12.0	44.5	48.8	39.3	44.6	31.2	34.5	25.3	30.5	36.7	40.1	35.3	36.1
	11	12.6	13.4	10.5	11.5	46.4	49.7	43.5	45.6	34.1	39.0	31.4	34.9	39.2	44.7	37.8	39.6
	12	11.6	12.6	9.7	11.3	45.9	50.5	41.2	45.1	31.9	37.6	26.9	31.6	40.7	48.4	37.0	39.6
Group mean:		12.2	13.3	10.1	11.7	45.8	49.8	41.8	45.0	32.4	36.8	27.8	32.0	39.0	44.2	36.4	38.4
8	8	11.4	13.2	10.3	10.8	45.3	50.0	42.5	46.6	30.8	37.6	26.6	30.5	37.7	42.0	34.8	36.4
	10	10.8	11.7	10.2	9.8	45.5	48.4	42.1	45.1	31.0	38.2	27.0	30.8	38.3	44.1	36.3	37.6
	11	12.7	14.1	11.0	11.7	45.0	51.1	43.8	47.0	34.4	41.3	29.2	35.1	39.1	44.6	38.2	39.5
Group mean:		11.6	13.0	10.5	10.8	45.3	49.8	42.8	46.2	32.1	39.0	27.6	32.1	38.4	43.6	36.4	37.8
Grand mean:		11.9	13.4	10.1	11.3	44.8	48.9	41.2	44.9	31.9	37.7	27.1	31.4	38.1	42.9	35.5	37.5

APPENDIX F

FORCE TABLE AND LOAD CALIBRATIONS

A most critical element in correlating skid testers is the force and load calibration of the test wheel. The National Bureau of Standards, under contract with the Federal Highway Administration, has studied the equipment and procedures required for valid and accurate calibrations. Arrangements were made to obtain the cooperation of the National Bureau of Standards in conducting the force plate and test wheel load calibrations for the Skid Tester Correlation Program. The NBS personnel performed the program calibrations with NBS equipment according to their latest prescribed procedures (*54*).

CALIBRATION PROCEDURES

The calibration station was set up in a garage parking area. An air-bearing-type, horizontal force and vertical load calibration platform was used. The force output was applied to one axis of an 11 by 17-in. X-Y plotter. The friction transducer output from the tester, provided through a standard connector installed previously, was applied to the other axis of the plotter. The zeros were set on the X-Y plotter and gain calibration signals from the platform and tester set and recorded the scale on each axis. The value of the tester gain calibration signal in torque or force was recorded directly on the graph.

The tow vehicle and trailer were precisely aligned on a level surface. Both vehicles were jacked up and blocked under their wheels to the same height as the calibration platform. The trailer's longitudinal axis was established from the hitch point and the center point between the wheels. The longitudinal axis of the test wheel was determined from the trailer axis and was marked on the floor. The calibration platform was aligned and centered under the test wheel. After lowering the test wheel onto the platform with its brake released, the instrumentation zeros were reset. After engaging the brake, the force was increased slowly and continuously to 750 lb, then released in the same manner.

The force application was then repeated a second time to provide a second plot. The level and alignment of the

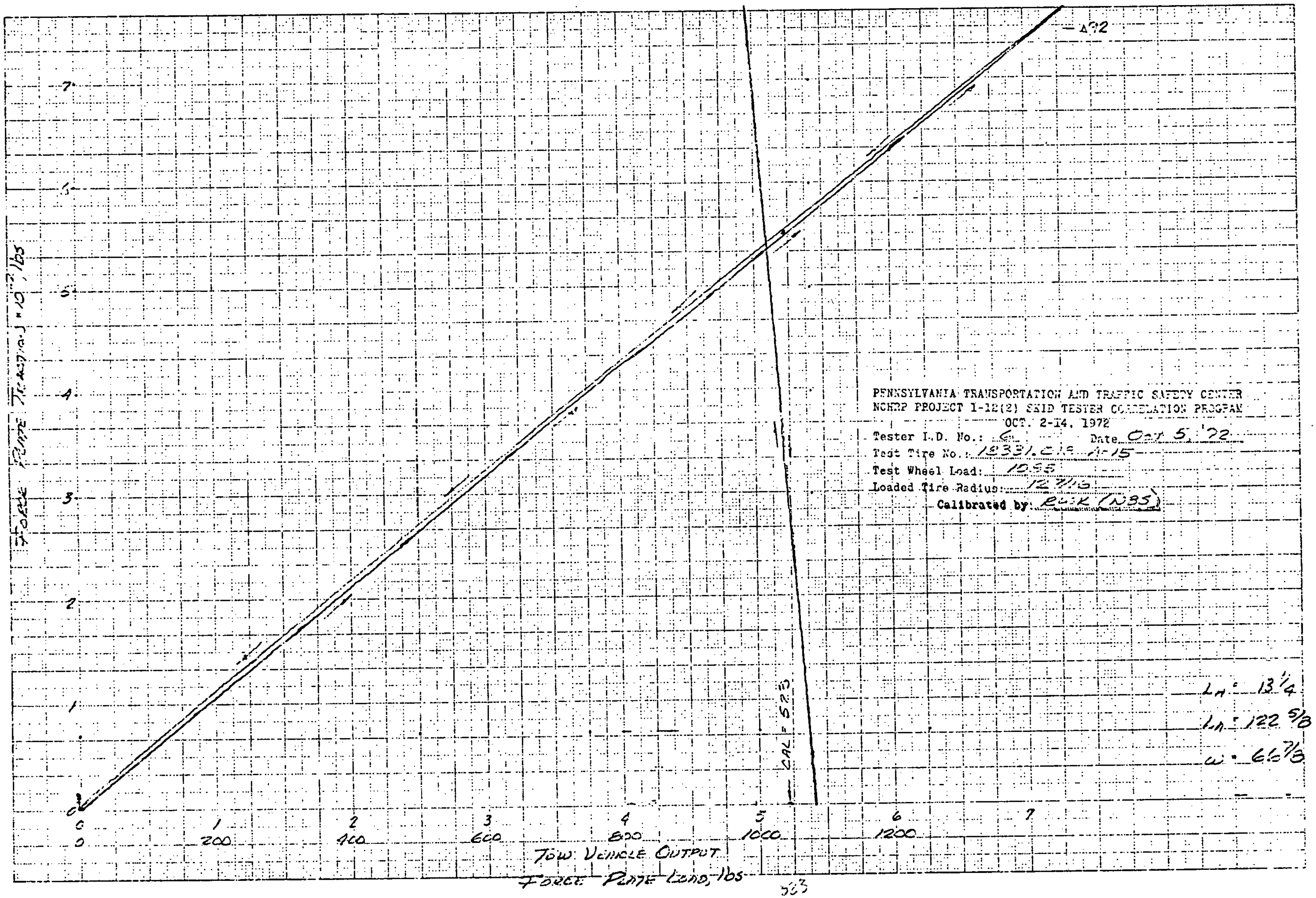


Figure F-1. Typical X-Y plot of force and load calibration.

platform were continuously checked during force application.

After two satisfactory force calibrations, the calibration platform load output was substituted for the tester output on the X-Y plotter. The load zero and scale were set with the test wheel raised. The test wheel was lowered to determine the static wheel load. With the brake engaged, the force was again applied to determine the unloading effect on the test wheel.

The date of test and tire serial number, static tire radius, hitch height, and trailer length were recorded on the X-Y plots.

Figure F-1 shows a typical plot obtained in this fashion. Any hysteresis in the tire, transducer, or instrumentation system is readily apparent although the source is not revealed.

To determine the force calibration or correction factor for each tester, the equivalent value of the tester gain calibration signal was compared against the corresponding platform value. For testers that had a force equivalent to the gain calibration signal, a force-to-force comparison was obtained. With testers for which the gain calibration signal was equivalent to a torque, the effective tire radius was used for conversion to a force.

The test wheel static load measured on the calibration platform was compared with that expected by the crew and used in all previous skid number determinations.

The results of the calibrations are summarized in Table F-1. Six of the testers had negligible hysteresis (less than 10 lb). Four had modest values between 10 and 20 lb, and one had 35 lb, which is clearly excessive.

The force errors were relatively high, amounting to more than 8 percent in several cases. The average over all testers was 4.65 percent. The testers with force-measuring systems were not significantly closer in calibration than those with torque-measuring systems. On testers No. 9, 10, and 12, all of which had been calibrated in torque, the average error was close to 6 percent.

The load calibrations of the testers yielded an average error of 1.9 percent. Only 7 of the 12 testers were within 1 percent. It is notable that 6 of the 12 testers had load values out of the 885- to 1,085-lb range permitted by ASTM E 274.

The combination of the force and load errors, which would be directly reflected in the determination of skid numbers by each tester, had an average value over all testers of 4.73 percent. Combined errors as large as 10 percent were observed.

TABLE F-1

SUMMARY OF FORCE AND LOAD CALIBRATION RESULTS

TESTER NUMBER	HYSTERESIS	FORCE GAIN CAL.[a]	FORCE ERROR (%)	LOAD CALIBRATION[b]	LOAD ERROR (%)	COMBINED ERROR (%)
1	Negligible	575/558	+3.05	1005/1000	+0.5	2.54
2	Negligible	720/717 TF[c]	+0.42	1085/1110[d]	−2.25	2.73
3	10 lb	382/362 TF	+5.52	1000/1050	−4.76	10.79
4	—[e]	—[e]	—[e]	1185/1090[d]	−0.46	—
5	17 lb	580/635 TF	−8.66	1110/1130[d]	−1.77	7.01
6	Negligible	523/550	−4.91	1085/1085	0.0	4.91
7	35 lb	780/725 TF	+7.59	1070/1100[d]	−2.73	10.61
8	Negligible	580/572 TF	+1.40	1085/1075	+0.93	0.47
9	12 lb	840/790 TT[f]	+6.33	1084/1087[d]	−0.28	6.63
10	Negligible	730/794 TT	−8.06	1055/1155[d]	−8.66	0.66
11	12 lb	380/387 TF	−1.81	1040/1035	+0.48	2.28
12	Negligible	315/326 TT	−3.37	1000/1000	0.0	3.37
Average error:			4.65		1.90	4.73

[a] Tester calibration value in force or torque units/corresponding value determined from actual force plate calibrations.
[b] Test wheel static load value used by tester crew/static load measured in calibration.
[c] TF, Torque Transducer-gain calibration value determined from previous force calibration.
[d] Does not conform to ASTM E 274.
[e] Data not available due to transducer failure.
[f] TT, Torque Transducer-gain calibration value determined from previous torque calibration, static wheel radius used to convert force calibration value to torque.

APPENDIX G

SKID TESTER MALFUNCTIONS

The 12 testers participating in the skid tester correlation program each performed between 160 and 400 individual skid tests, the number depending on the particular portion of the program in which they participated.

Anticipating that some equipment breakdowns would occur, diagnostic equipment and personnel from electronic and mechanical services shops were available to aid in the repairs. Despite the malfunctions that occurred, repairs or corrections were accomplished that allowed 11 of 12 testers to complete their entire program of tests.

The malfunctions were of many types. Some were detected by the tester crews, others showed up only in calibrations, and some affected data validity while others did not. The specific malfunctions outlined represented improper functioning of a tester to the degree that correction was either required at the time or, if that was not possible, correction was called for before returning the tester to routine use after the program.

Instrumentation

a. The force signal zero on tester No. 1 tended to offset periodically and eventually became erratic in the last tests. All test data had to be corrected for zero shift. After its return home, the tester was found to have a defective force transducer.

b. During force calibration of tester No. 4, the torque transducer was found to be defective, a condition which had been suspected by the tester crew. The transducer was replaced.

c. The peripheral electronics in tester No. 5 developed intermittent noise that showed up on the force signal. The condition complicated the force plate calibration, but could not be corrected.

d. The strip chart recorder on tester No. 5 was found to be nonlinear during torque calibration. An appropriate correction was applied to the data.

e. Tester No. 7 exhibited 35 lb of transducer hysteresis in force calibration. The condition was reported to be indicative of strain gage bonding defects common to that make of tester.

f. The strip chart recorder on tester No. 8 intermittently failed to scale properly on the different attenuation settings required for operation. The problem disappeared during diagnosis.

g. A zero drift problem occurred on tester No. 10 that was eventually traced to moisture in a signal-wire junction box. The problem was corrected.

h. The strip chart recorder ink pen on tester No. 10 intermittently failed to write. An on-board force signal integrator was used during these periods to acquire the skid data.

i. The a-c rectifier bridge in the instrumentation system of tester No. 11 failed. The problem was diagnosed and the rectifier diodes were replaced.

Water Systems

a. The water system on tester No. 2 experienced a temporary restriction of flow during tests. The problem was detected and corrected by the tester crew. Data correction was not required.

b. On tester No. 4, the water pump drive sprocket failed. A replacement sprocket was obtained and installed by the crew.

c. During water calibrations, the pumping systems on testers No. 4, 5, and 7 were found to have inadequate capacity to provide speed-proportional flow much above 40 mph.

APPENDIX H

TECHNICAL INFORMATION ON SKID TESTERS

A study was conducted by obtaining detailed technical data on representative skid trailers from several state highway departments and other agencies. Schematic drawings, shown in Figures H-1 to H-5, were prepared and used in collecting this information. Table H-1 gives the testers' dimensions, and Table H-2 gives details on their watering systems and nozzles.

Wheel and hitch loads were determined in level position. Where possible, hitch load was also determined in raised position and the corresponding angle was measured. From

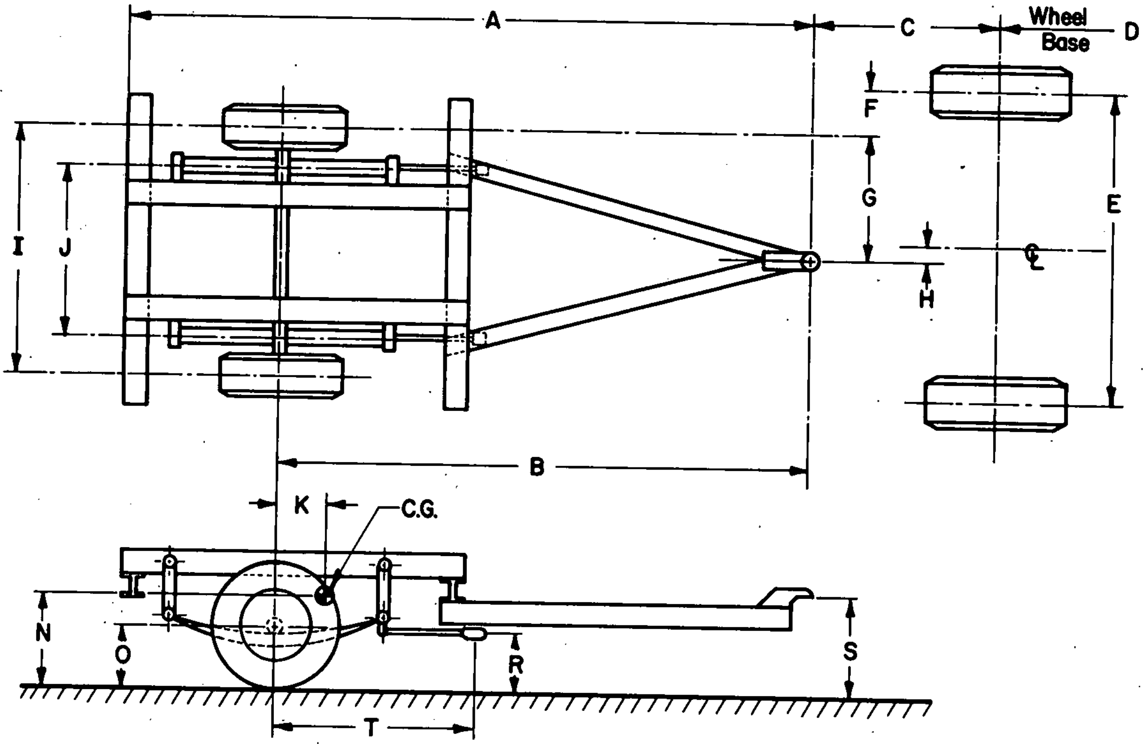
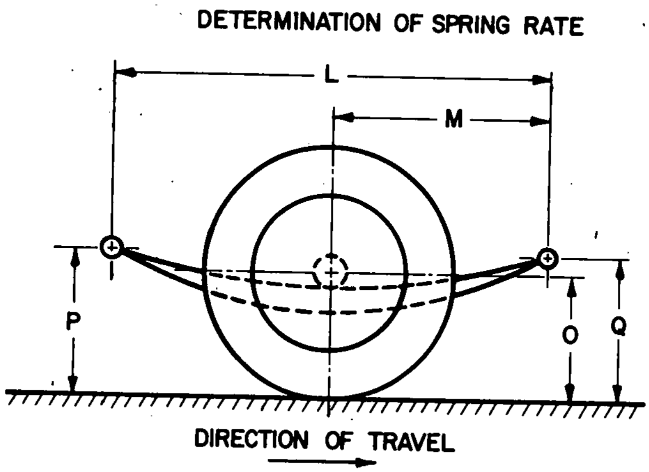
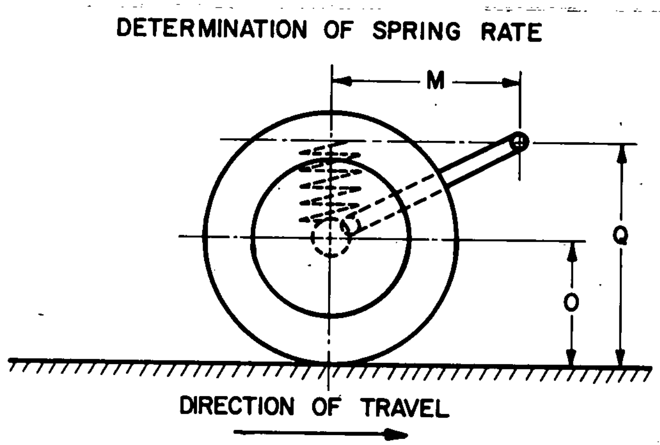


Figure H-1. Skid trailer dimensions.



	O	P	Q	L	M
STANDARD TEST LOAD LBS.					
LOAD ADDED LBS.					
LOAD ADDED LBS.					
LOAD ADDED LBS.					
LOAD ADDED LBS.					
LOAD ADDED LBS.					

Figure H-2. Spring rate data form for leaf spring suspension.



	O	Q	M
STANDARD TEST LOAD LBS.			
LOAD ADDED LBS.			
LOAD ADDED LBS.			
LOAD ADDED LBS.			
LOAD ADDED LBS.			
LOAD ADDED LBS.			

Figure H-3. Spring rate data form for coil spring suspension.

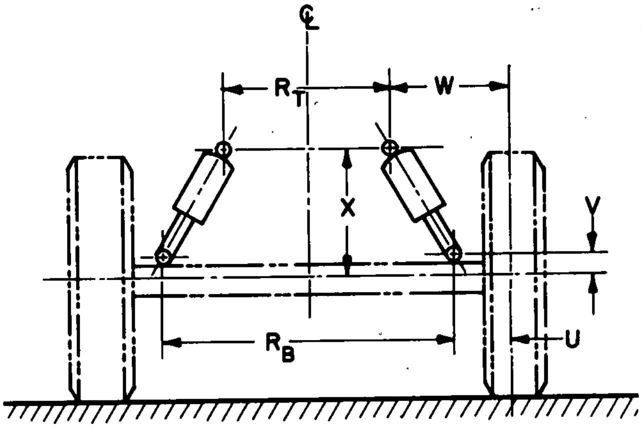


Figure H-4. Mounting of shock absorbers.

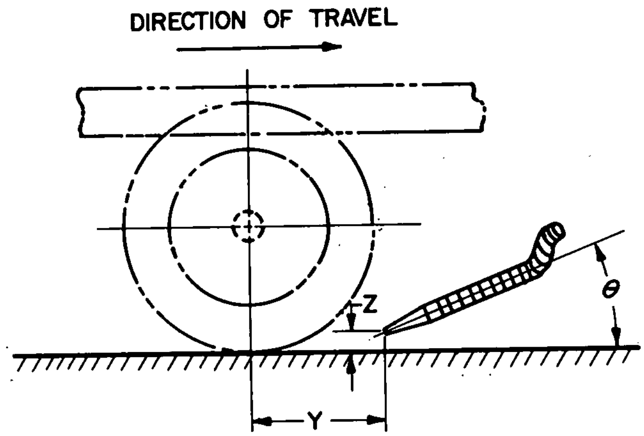


Figure H-5. Position of water nozzle.

this information the position of the center of gravity was found from

$$K = \frac{W_0}{W} B \quad \text{and} \quad W_1 = \frac{W_0 B \cos \alpha - W(N-O) \sin \alpha}{B \cos \alpha - (S-O) \sin \alpha}$$

where W is the total trailer weight, W_0 and W_1 are the respective hitch loads in level and raised position, and α is the corresponding angle. K and N determine the position of the center of gravity.

The static spring rate was determined by measuring spring deflection at different loads. To determine damping of the suspension system, a drop test was performed. With the trailer axle blocked, the trailer body was raised a few inches and dropped. A linear potentiometer mounted to the body recorded the drop and subsequent oscillations. All suspension systems were found to be slightly underdamped and the damping coefficient in this case is given by

$$C = \frac{2m}{T} \log \frac{X(t)}{X(t+T)}$$

where m is the tester mass, T is the period of oscillation,

TABLE H-1

SKID TESTER DIMENSIONS [a]

PARTICIPATING TESTER	PARAMETER [b] OVER-ALL LENGTH (A)	HITCH TO WHEEL CENTER (B)	HITCH TO TRUCK REAR WHEEL CENTER (C)	TRUCK WHEEL BASE (D)	TRUCK WHEEL CENTER TO CENTER (TRACKING WIDTH) (E)	TESTER WHEEL CENTER TO CENTER (TRACKING WIDTH) (I)	TESTER SUSPENSION SPACING (J)	SHOCK ABSORBER SPACING, TOP (R_T)	SHOCK ABSORBER SPACING, BOTTOM (R_B)	HITCH HEIGHT (S)	MEASURING ELEMENT TO WHEEL (T)	LOWER SHOCK MOUNT TO WHEEL CENTER, VERTICAL (V)	UPPER SHOCK MOUNT TO WHEEL CENTER, VERTICAL (X)
Conn.	172.5	111.0	45.0	131.0	70.0	59.5	34.5	29.0	45.8	12.0	—	0.0	—
Del.	155.0	119.0	54.0	166.0	63.5	60.8	36.0	11.5	28.0	17.5	—	4.5	10.5
Ind.	170.0	110.9	50.5	131.5	62.0	57.0	31.5	25.2	43.0	12.5	—	−1.5	8.5
Ky.	183.0	122.0	54.0	127.5	63.0	65.0	43.0	31.5	51.5	15.0	—	−6.5	12.0
Md.	150.0	106.0	55.0	174.0	70.0	61.2	40.6	14.0	34.0	12.0	—	−5.0	—
N. C.	151.0	111.0	55.0	168.0	62.0	64.0	36.0	16.8	36.0	13.2	—	1.5	10.2
Ohio	183.0	122.0	54.0	127.5	63.0	65.0	43.0	31.5	51.5	—	—	−1.5	8.5
Va.	169.0	119.8	63.0	132.0	69.5	64.8	36.0	41.0	41.0	12.5	—	−0.8	12.0
W. Va.	153.0	117.5	40.5	166.0	64.0	62.0	36.0	15.0	30.0	16.0	—	−4.5	8.5
FHWA	156.0	122.0	42.0	131.0	63.0	65.0	42.0	36.0	38.0	14.8	43.0	1.5	9.5
NBS-1	153.0	118.0	46.0	132.0	67.0	60.0	35.5	9.5	28.5	13.8	—	−4.8	9.5
NBS-2	134.0	103.0	46.0	132.0	67.0	68.8	45.0	19.5	38.8	13.8	—	−5.5	10.8
SIT	138.0	102.0	55.0	126.5	63.0	60.8	33.2	43.8	43.8	9.5	11.5	0.0	18.0

[a] All dimensions are in inches.
[b] Letters in parentheses are keyed to parameters illustrated in Figures H-1 and H-4.

$X(t)$ and $X(t+T)$ are the amplitudes of two successive oscillations. The period and amplitudes are taken from the recording. The accuracy of this method is not high, although the values obtained seem to be of the right order of magnitude. Table H-3 gives wheel and normal hitch loads, location of center of gravity, mean static spring rate, damping coefficients, natural frequencies, and the time required for a 90-percent amplitude decay in the drop tests.

TABLE H-2

DETAILS ON WATERING SYSTEMS

PARTICIPATING TESTER	FLOW RATE	NOZZLE TYPE	NOZZLE WIDTH (IN.)	NOZZLE POSITION: TO WHEEL CENTER (IN.)	NOZZLE POSITION: TO GROUND (IN.)	NOZZLE POSITION: INCLINATION (DEG)
Conn.	Prop. speed	Brush	8.0	60.0 [a]	0.0	—
Del.	Prop. speed	Flat	4.0	14.3	2.8	20
Ind.	Prop. speed	Brush	10.5	57.0 [a]	0.0	75 [a]
Ky.	Prop. speed	Flat	5.4	20.0	3.0	22
Md.	Constant [a]	Brush and round nozzle		19.0	7.0 [a]	—
N. C.	Pressurized tank	Nozzle and shield	5.2	18.0	5.8 [a]	9 [a]
Ohio	Prop. speed			20.0	3.0	22
Va.	Prop. speed	20-tube package		18.0	2.0	10 [a]
W. Va.	Prop. speed	Flat	4.0	12.0	2.0	15 [a]
FHWA	Variable	Brush		24.5 [a]	0.0	90 [a]
NBS-1	Prop. speed	Flat	4.0	15.0	1.5	49 [a]
NBS-2	Prop. speed	Flat		15.0	2.2	27
SIT	Prop. speed	Flat	6.0	18.5	1.5	45 [a]

[a] Does not conform to ASTM E 274.

TABLE H-3

SKID TRAILER DATA

TRAILER	WHEEL LOAD (LB) LEFT	WHEEL LOAD (LB) RIGHT	HITCH LOAD (LB)	CENTER OF GRAVITY (IN.) TO GROUND	CENTER OF GRAVITY (IN.) TO CENTER OF WHEEL	MEAN SPRING RATE (LB/IN.)	DAMPING COEFFICIENT (LB-SEC/FT)	NATURAL FREQUENCY (CPS)	DROP TEST 90% DECAY TIME (SEC)
Conn.	1100 [a]	1070	186	15.8	8.8	212	288	2.2	0.75
Del.	1085	1100 [a]	100	—	—	355	62	1.1	1.0
Ind.	1085	1085	150	—	—	336	134	1.2	2.0
Ky.	1000	1010	130	15.6	7.4	520	156	1.8	0.9
Md.	1040	1055	168	14.9	7.8	438	93	1.7	0.5
N. C.	1062	1070	197	19.6	9.0	586	217	2.3	0.8
Ohio	1080	1100 [a]	90 [a]	—	—	560	137	1.8	1.0
Va.	1060	1020	192	17.2	10	302	200	2.6	0.75
W. Va.	—	—	—	—	—	550	267	2.5	0.6
FHWA	1023	1029	101	18.7	5.7	425	126	2.2	0.5
NBS-1	1095 [a]	1080	120	21.5	7.4	300	55	1.6	0.5
NBS-2	1011	1035	152	18.9	7.2	274	134	1.5	0.7
SIT	1075	1050	145	—	—	510	270	2.5	0.5

[a] Does not conform to ASTM E 274.

APPENDIX I

ESTIMATE OF ERROR IN SKID TESTING

Error sources and the estimated errors in skid testing are given in Table I-1. All estimates have been made for a pavement of average skid resistance (between 40 and 50 SN) and a test speed of 40 mph. Two estimates of error are given; the first, "as is," is based on review of skid resistance data for several representative skid testers; the second, "reduced," is an estimate of reduced errors resulting from improved procedures, correction of data, and, in some cases, improved equipment.

Normally all or some of the errors act simultaneously and an estimate of the combined effects has been made for three modes of testing, which are given in Table I-2. Modes 1 and 2 are for a single tester in repeat and survey testing, respectively. It is assumed that a few tests have been run for preconditioning and are not included in the data. It is also assumed that all tests are made within a short period of time. The computation includes only those errors that may vary from test to test. Thus, the computed error band is about the mean skid resistance measured by the same tester, which may be far from the mean measured by any other tester. The error band is a measure of precision only.

In testing modes 3(a) and 3(b), the combined error

TABLE I-1

ERROR SOURCES IN SKID TESTING AND THE ESTIMATED ERROR BANDS AT 40 MPH, AS IS AND REDUCED BY CORRECTIVE ACTION

SYMBOL	ERROR SOURCE	ERROR ESTIMATED (SN) AS IS	REDUCED
X_1	Speed holding	±1.5	±0.8
X_2	Speed measurement	±1.5	±0.8
X_3	Temperature	±4	±2
X_4	Water film	±2.5	±1
X_5	Lateral position	+4	+2
X_6	Longitudinal position	±2	±2
X_7	Pavement conditioning and deterioration	−2	−1
X_8	Variability among tires	±1	±0.5
X_9	Tire construction	±1	±0.5
X_{10}	Tire condition	±1	±1
X_{11}	Inflation pressure	±1	±1
X_{12}	Wheel load error	±1	±0.2
X_{13}	Wheel load range	±2	±1
X_{14}	Dynamic wheel load	±1	±0.5
X_{15}	Calibration error	±3	±0.5
X_{16}	Operator data evaluation	±3	±1
X_{17}	Procedure of data evaluation	±2	±1

TABLE I-2

PREDICTED TOTAL ERROR BANDS FOR THREE MODES OF TESTING CONDUCTED IN BOTH AS-IS AND REDUCED CONDITIONS

$$\text{TOTAL ERROR BAND} = \left[\sum_i x_i^2\right]^{1/2}, \quad x_i\text{—INDIVIDUAL ERROR BANDS.}$$

MODE	FACTORS	ERROR BAND (SN) AS IS	ERROR BAND (SN) REDUCED	ERROR BAND (SN) FOR MEANS OF FIVE REPEAT TESTS AS IS	ERROR BAND (SN) FOR MEANS OF FIVE REPEAT TESTS REDUCED	ESTIMATE, s_A MEANS AS IS	ESTIMATE, s_A MEANS REDUCED	ESTIMATE, s_A SINGLE TESTS AS IS	ESTIMATE, s_A SINGLE TESTS REDUCED
1. Repeat testing by single tester	$X_1, X_4, X_5, X_{14}, X_{16}$	9.5	4.0	4.2	1.8	1.8	0.8	4.1	1.7
2. Inventory testing by single tester	$X_1, X_4, X_5, X_6, X_{14}, X_{16}$	10.5	5.6	4.0	2.5	2.0	1.1	4.5	2.4
3. (a) Tester comparison	$X_1, X_2, X_3, X_4, X_5, X_7, X_8, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}$	15.8	7.3	7.0	3.3	3.0	1.0	—	—
(b) Correlation program	$X_1, X_3, X_4, X_5, X_7, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}$	15.3	6.8	6.8	3.0	2.9	1.3	—	—

bands for a group of testers are considered—mode 3(a) for simple comparison testing without special preparation, mode 3(b) for a well-organized correlation program. In both cases systematic error sources are included on the assumption that those are normally distributed among several testers. For example, there is an even chance for testers to be calibrated too low or too high.

In all modes the combined error is computed as given in Table I-2. When n repeat tests are made, the error band containing the means of these repeat tests in reduced by a factor $1/\sqrt{n}$. These have been computed for $n = 5$, the minimum number of repeat tests recommended by ASTM E 274. The last row of the table gives the corresponding standard deviations, which were computed from the error band (range) by the relationship

$$d_n \cdot \text{range} = \text{standard deviation}$$

The factor d_n is a function of the sample size and is listed in *NBS Handbook 91* (*10*, p. 2-6) for sample sizes between 2 and 16.

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