NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 61

EVALUATION OF STUDDED TIRES

PERFORMANCE DATA AND PAVEMENT WEAR MEASUREMENT

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY OFFICIALS IN COOPERATION WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATION:
PAVEMENT DESIGN
PAVEMENT PERFORMANCE
MAINTENANCE, GENERAL
HIGHWAY SAFETY

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1969

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.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-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 departments and by committees of AASHO. 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 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 Highway 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.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

NCHRP Project 1-9 FY '67

NAS-NRC Publication 1715

Library of Congress Catalog Card Number: 70-600462

FOREWORD

By Staff

Highway Research Board

Highway engineers in recent years have become concerned about the increasing use of studded tires and the resultant effects on pavements. This report contains a current state-of-the-knowledge with regard to both studded tire performance and methods of assessing pavement wear. It consists of an annotated bibliography covering all known research on the subject from U.S. and European sources, a review and evaluation of the data and results of completed studies, and recommendations for future research aimed at improving the effectiveness of studded tires and resolving the questions concerning their effect on pavements from the standpoint of wear. Highway safety, research, maintenance, and pavement design engineers will find the information in the report useful.

Studded automobile tires first came into extensive use in the Scandinavian countries in about 1961 and within a few years were being marketed in this country. Their acceptance and use in the snowbelt states has been rapid—estimates of sales exceed 6 million studded tires annually. Although several individual states and other agencies have conducted studies on the performance of studded tires and their effect on pavement wear, there was a need for a nationwide approach to the problem resulting in the initiation of the investigation reported herein. Due to the limitation of available time and funds, the objectives were confined to (1) the correlation and evaluation of available data on performance of studded tires, and (2) the development of a comprehensive method for future measurement of pavement wear caused by studded tires. No actual testing, other than that required for validation of the proposed measurement method, was scheduled.

The researchers of Cornell Aeronautical Laboratory have prepared correlations of published and unpublished information on both effectiveness of studded tires and pavement wear resulting from their use. It was determined that under certain conditions they do improve highway safety in northern climates. The several factors such as ice temperature, number and placement of studs, stud protrusion, and stud wear, that influence their relative effectiveness are reviewed in the report. Recommendations are included for a systematic approach to the development of the optimum studded tire, in the sense of achieving the most benefit at the least cost, both from the standpoint of cost of installation and cost of pavement maintenance.

Although a lack of uniformity in variables made it difficult to correlate previously conducted pavement-wear tests, there was ample evidence that the problem is severe enough to warrant a comprehensive investigation. The variety of evidence and opinion on the question of whether studs have a polishing or roughening effect on the pavement was particularly striking. Equipment suitable for quantitative measurement of the effects of studded tires on pavements was found to be lacking; therefore, a major effort in the Cornell study was devoted to the design of an instrument specifically for determining both pavement wear and roughness to the nearest 0.001 inch and to construction of a breadboard model.

The report contains recommendations for controlled, systematic means of thoroughly investigating pavement wear on a nationwide basis. A field test road containing a number of pavement cores and using the wear and roughness meter developed during this project, a laboratory accelerated test, and studies of secondary damage possibilities are the basic measures suggested in the pavement wear program. Such a program would permit assessment of the pavement wear effects of studded versus unstudded tires on either a national basis or for any particular set of local conditions. It would also provide valuable information for materials engineers and designers who must utilize available materials while at the same time producing highway surfaces offering maximum safety to the motoring public and requiring minimum maintenance by the highway department.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 1-9 by the Cornell Aeronautical Laboratory with F. R. Haselton, Staff Engineer, Vehicle Research Department, as principal investigator, under the general guidance of F. Dell 'Amico, Assistant Head, Vehicle Research Department. The other authors are, respectively: P. Rosenthal, Head, Material Sciences Section, Applied Physics Department; K. D. Bird, Head, Vehicle Research Department; and P. J. Joseph, Associate Physicist, Applied Physics Department. Arthur L. Pulley and James E. Greene, both of the Laboratory, also contributed to the project, the former in making his practical experience available and the latter by assisting in the analysis of stud-ice mechanics.

The authors are especially indebted to E. A. Whitehurst, Director, Tennessee Highway Research Program, who provided assistance in matters regarding the analysis of the National Safety Council Winter Driving Hazards Program; and to Flt. Lt. McKee of the RCAF for his excellent cooperation in seeking information on the RCAF program, beyond that appearing in their report.

The cooperation of the following individuals and organizations is also gratefully acknowledged:

Malcolm D. Graham, Director, Bureau of Physical Research, Department of Public Works, State of New York, who provided the pavement core specimens and information on their history.

Ragner Carlstadt, Manager, Engineering Development, Kennametal Corp., who provided studs and information on their properties, manufacture, installation, and testing.

Peter Miller II, Director of Engineering, Studegrip Division, Studebaker Corp., who provided studs and information on stud specifications, installation, and testing.

Harry Nichols, Shaler Division, National Rivet Corp., who provided studs and information on their installation.

Warren M. Shwayder, Shwayder Chemical Metallurgy Corporation, who provided a sample stud and information on its composition.

The greater portion of the limited resources allocated to this program by the HRB were applied to methods of assessing pavement wear. As a public service, however, a portion of the work on studded tire *effectiveness* was carried out with internal CAL resources. The extensive treatment given the effectiveness problem in this report reflects this fact.

EVALUATION OF STUDDED TIRES

PERFORMANCE DATA AND PAVEMENT WEAR MEASUREMENT

SUMMARY

Studded tire performance is a function of many variables having to do with the tires, the studs and the surfaces upon which they operate. Failure to recognize, measure, and control these variables is the largest single reason for the apparently conflicting and contradictory claims on studded tire performance.

Braking, tractive, and cornering performance is affected by (in addition to surface conditions) the unstudded tire characteristics, stud configuration, stud protrusion, stud arrangement in the tire, vehicle speed, etc. In this report, a stud resistance coefficient for operation on ice is derived and all U.S. data are correlated with this parameter and ice temperature. The correlation function may be considered a statistical representation of the typical American studded tire from which various performance calculations showed the following: (1) maximum braking effectiveness is obtained at 32°F. Studded tires on the rear of the vehicle will reduce stopping distance by 12 to 30 percent while studded tires on front and rear reduce stopping distance by 32 to 46 percent, (2) considerable improvement in cornering capability is indicated. With all four wheels studded at 32°F, it is calculated that a vehicle might be able to negotiate a curve at 40 mph on which it will breakaway in a skid at 30 mph without studded tires. The same variables affect traction as braking. The limited evidence available indicates that braking and traction effectiveness of studded tires is generally comparable.

No significant loss of braking performance on bare pavements is indicated with less than 100 studs per tire. Stopping distance might be increased by 10 percent with 200 studs.

Studded tires definitely offer an increase in safety to the users. There is evidence that considerably better studded tires could be offered to the American public than are now on the market.

The magnitude of pavement wear reported in nine documents, eight pilot studies and one more elaborate study, and tests at CAL confirm the need for an investigation that takes into account all variables affecting pavement wear by studded tires and by other traction aids. The major task of the wear study reported herein—development of methods for determining pavement wear due to studded tires and other causes—has been accomplished.

The available literature on road wear was found to be limited in quantity of tests and in consideration of the pertinent variables. At the request of the sponsor, heavy emphasis was placed on the development of methods for measuring wear and roughness, and on their validation. By analysis of available test data, the results of single stud tests at CAL, and drawing from experience in related disciplines, the variables entering the wear process were enumerated, their relative importance was judged, and methods for their investigation were outlined. Finally, mathematical relations between the variables were developed which can serve in arriving at predictions of wear under local traffic conditions.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

The modern studded tire received its first extensive use on automobiles in the Scandinavian countries in the 1961-1962 season. Subsequently, its use has spread to other European countries where there are significant winter driving problems. In the 1963-1964 winter season, studded tires began to be used in both the United States and Canada. Miller (*8*) presents information showing the rapid acceptance of studded tires in the U.S. with an order of magnitude increase in the number of tire studs sold in each of the next two years following their introduction in this country. There can no longer be any doubt as to the acceptance of studded tires as a winter driving aid by a significant proportion of the vehicle owners in the northern climates of this country where their use is legal.

This increased use has come in spite of a number of legitimate questions that have been publicly raised about performance of studded tires and their effect on the public roads. It will be shown in this report that, without question, tires can be designed and studded which, when used on all four wheels, will offer very significant improvement in braking, traction and cornering performance on icy highways within certain temperature limits. It can also be shown from existing literature that studded tires do cause accelerated wear and damage to highways. Thus, the questions that confront the vehicle owner, the studded tire manufacturer, the safety engineer, and the highway engineer are not whether studded tires offer increased safety and convenience or whether studded tires damage highways, but questions of degree, optimization, economics, and priority.

As prerequisites to optimization and cost effectiveness studies, it is essential that additional information be obtained on both studded tire performance and pavement wear. Information is also needed on winter driving conditions as accident causation or contributive factors. It is clearly in the public interest to know the trade-offs so that studs can be used in a manner to maximize performance and minimize highway damage. With the passage of the National Traffic and Highway Safety Acts of 1966, the American people were committed to providing increased automotive safety. The use of studded tires, in furtherance of the purposes of this legislation, must be examined and the various economic factors considered.

The scope of the present program precluded both the conduct of additional performance experiments and any but very limited laboratory experiments on the highway wear problem. It was not possible to visit organizations that have conducted test programs on either performance or wear and discuss the programs first hand with the people who had conducted them. It was necessary to rely completely on published material. There has been much confusion and (seemingly) many conflicting claims with regard to studded tire performance. It is the present authors' conclusion that these conflicting claims and confusion stem largely from an empirical and incomplete approach to performance determination. There appear to be a number of cases where the basic precepts of scientifically conducted experiments were not observed. There was often failure to recognize, and therefore to control or measure, important variables; there was inadequate parameter control and variation; repeatability and confidence levels were not established; base runs were not made; etc. Coming out of such experiments have been many unsubstantiated and unqualified conclusions.

The research approach followed in the performance investigation was to examine test methods and data rather than conclusions or claims. Fortunately, well-conceived, properly-conducted experimental programs have been reported. From the analysis which is discussed herein, certain very definite trends and patterns have emerged from the studded tire performance mystique. The important variables have been identified and in many cases quantitative conclusions are possible. The authors have attempted to include sufficient detail in the report so as to permit the reader to determine rather precisely how the data were handled, what assumptions were made, and what processes were used in arriving at the conclusions.

The tire performance investigation reported here differs from the damage investigation in scope and objective. The former concentrated on critical analysis and evaluation of existing performance data. The latter emphasized the development of methods for assessing pavement damage, and included investigation of the nature of wear, its measurement in test situations, and prediction of actual road wear.

Because of the great interest shown by the general public, the tire and stud manufacturers, and the highway engineering community in the pavement wear and the stud effectiveness problems, it is essential to indicate clearly, at the outset, the limited scope of the present investigation. The objectives of the study were confined to the following two tasks: (1) Correlation of data on the frictional characteristics of studded tires on ice, packed snow, and on bare pavements (wet and dry); and (2) development of a method, or methods, of quantitative assessment of the difference in wearing and abrasive effects of studded versus unstudded tires on different types of surfaces.

CHAPTER TWO

FINDINGS

The findings of any project of the type of this one, primarily of the "literature search" category, are necessarily circumscribed by the publications reviewed, both as to the methods described and the resulting data presented and analyzed. Such results as were obtainable in the current instance are summarized in the following. Detailed discussions of the several points are presented in appendices, as follows:

STUDDED TIRE PERFORMANCE

Braking

1. A significant body of data has been produced on braking performance from both U.S. and foreign sources. Vehicle stopping distance and friction trailer measurements have both been employed. Repeatability tests of a standard tire (the ASTM E-17 rubber highway tread) have established a reasonable confidence level in the accuracy of the friction trailers both between and within the several test programs.

2. Data on highway tread and snow tires show good agreement between friction trailer and vehicle stopping distance tests on ice. The two methods of testing do not give equivalent results for studded tires. The differences are such that higher effective coefficients of friction are indicated in the constant-speed (20 mph) friction trailer tests than in the variable-speed stopping distance tests.

3. Friction coefficients of both highway tread and snow tread tires are a function of ice temperature. Friction coefficients for the highway tread tires nearly double from a minimum value at 32°F to a maximum at about 0°F. Below zero little further increase is noted and there is some evidence of a decrease.

4. Snow tire friction coefficients show a variation similar to the highway tread except that they are less nonlinear. There is a dearth of low-temperature data, but the evidence is that the friction is still continuing to increase at − 5°F, the coefficient being twice its value at 32°F.

5. Studs in number and configuration typical of American tires give an increment of effective friction coefficient at 32°F which is almost as great as that of the basic tire. However, the studs lose effectiveness as the ice temperature is reduced. Extrapolation of existing data (which go to only −5°F) indicates that all effectiveness of the studs will be lost at −10°F.

6. There tends to be some scatter in all the ice data which cannot be accounted for by measurement imprecision. The factors responsible for the scatter must be, in part, with the ice and in part with the tire. There is consistently more scatter in studded tire results than unstudded. Lack of control or knowledge of stud protrusion and shape may account for much of this scatter. The primary conclusion is, however, that after all steps are taken with regard to parameter control and measurement, numerous repeat runs are essential. To make one or two runs to evaluate a device, configuration or parameter is a waste of time and is bound to lead to erroneous conclusions.

7. Because of insufficient data and lack of control of stud protrusion, no quantitative conclusions can be made regarding the effects of protrusion, although it appears that within the limits of these tests, effectiveness increases with increased length.

8. In assessing effects of stud wear, account must also be taken of tire wear. No definitive evaluation of the effect of wear is possible because of lack of protrusion control and the qualitative nature of the term wear. It does appear, however, that for the type of use the subject worn tires had received, the effectiveness of the studs as compared with new studs in new tires was reduced. Somewhat systematic wear measurements by the RCAF showed nearly equal wear of rubber and studs (resulting in constant protrusion) on front tires and greater wear of the rubber (resulting in increased protrusion) on rear tires.

9. A parameter which infers a variation of stud effectiveness proportional to the number of studs correlates the American data no better than one which is independent of the number of studs. The scatter of the data is such that reliable conclusions on the effect of the number of studs are not possible.

10. Swedish data in which considerably more studs were used show that if additional lines of studs are provided, increased effectiveness can be achieved up to at least 260 studs.

11. There is no evidence that the aluminum oxide studs were any more or less effective than the tungsten carbide studs in spite of average stud protrusions which were somewhat greater than those on the other tires.

12. There is little difference in stopping distance between a car equipped only with highway tread tires and one equipped entirely with studded tires at temperatures of 0°F and below. As the ice temperature increases, considerably shorter stopping distances are indicated for the studded tire car. At 30°F a reduction of nearly 50 percent is indicated using the friction trailer data. Calculations based on stud

effectiveness determined from stopping distance data indicate that the shortening of stopping distances may be more nearly 30 percent, however.

13. Experimental problems in testing in packed snow precluded quantification of stud effectiveness. Qualitatively, however, the evidence is that studs provide some additional braking performance.

14. Bare pavement stopping distance tests show that stopping performance with tires equipped with up to 100 studs is not significantly degraded (and sometimes improved—particularly on wet pavements). With more studs, performance seems to become progressively degraded, but with as many as 216 studs, the friction coefficients are decreased by less than 10 percent.

Traction

1. Studded tires on the drive wheels offer potentially large improvements in accelerating from rest and from rolling conditions.

2. The conclusions listed under braking on the influence of ice temperature, such as stud number, pattern, protrusion, wear, are generally applicable to the traction condition.

3. Studs appear to be about as effective in traction braking.

Cornering

1. The greatest deficiency in stud effectiveness data is in cornering performance.

2. All four tires must be studded if significant cornering performance is to be achieved.

3. A very simple analytic model in which braking effectiveness data are used in the calculation of cornering effectiveness indicates large potential cornering gains if all four tires are studded.

Safety

1. As with many vehicle factors, the data on accident causation and contributing factors needed to make hard quantitative assessments of the significance of studded tires on safety simply do not exist.

2. The much higher accident rates during the winter months, after making allowance for the fewer daylight hours, indicate that the decreased tire friction coefficients on icy or snow-covered pavements are significant causative factors. It follows that any means of increasing the effective friction coefficients will increase driving safety.

3. The National Safety Council's admonitions that even with the higher friction coefficients offered by studded tires, stopping distances will still be considerably longer than those on dry pavement, while true, should not be interpreted as suggesting that the potential improvements are not worthwhile.

General

1. Comparison of U.S. with foreign practice in studded tires suggests that a systems approach in the design of studded tires could considerably improve the effectiveness of such tires over what is presently achieved, whatever number of studs is employed.

2. While the empirical approach to studded tire development which has been used in this country has resulted in a product which offers a significant measure of performance improvement, research on basic stud-ice mechanics has not been accomplished.

3. Because of implications with regard to safety and to highway damage, the development of optimum studded tires cannot be left exclusively to the private sector. Government sponsored research in all aspects—stud-ice mechanics; stud design and retention; tire design; stud-highway interaction—is essential and in the public interest.

PAVEMENT WEAR

1. Analysis of the literature on pavement wear due to studded tires and exploratory single stud tests have demonstrated that such pavement wear is severe enough to warrant a comprehensive investigation of the conditions which control its severity.

2. On the basis of analysis of road wear problems, it is concluded that *both* wear and roughness must be measured. An instrument for such measurement was designed and the validity of the measurement method was demonstrated with a breadboard model of the instrument.

3. The variables affecting the magnitude of pavement wear were studied and two test methods were developed. They are an accelerated indoor test and a closed loop field test.

4. Four specific aspects of road maintenance associated with the type of wear caused by studded tires and the tie-in of wear with maintenance decisions at the local agency level were pointed out.

CHAPTER THREE

INTERPRETATION

STUDDED TIRE EFFECTIVENESS

Differences Between American and Foreign Practice

From the material presented in Chapter Two and Appendix A it is quite clear that there are noteworthy differences between American studded tires and those used in foreign countries (including those used by the RCAF). The data correlated in Figure A-9 included tires from most of the major tire manufacturers in the U.S. and are considered to be a representative cross section. The number of studs per tire varies from 64 to 108 with an average of about 80. The minimum number of studs in the RCAF program was 72, going up to 366 studs per tire. The number of studs in the Swedish study varied from 52 to 260. The Swedish report recommends about 150 studs per tire for European cars and conditions. The authors did not elaborate on the specific characteristics of the cars and the conditions. The recommendation appears to be based on a compromise between the increased performance gains on ice and snow and performance losses on bare pavement. Road damage problems are not mentioned.

The foreign work also gives attention to the stud arrangement. Footprints are presented in both the RCAF and Swedish reports while none are in the U.S. literature. That the number of lines could be significant is recognized in both foreign reports but not the U.S. reports, suggesting that there has not been concern by the manufacturer and that an important variable has not been taken into account in U.S. practice. The procedure seems to have been to modify existing tread molds to provide holes for studs rather than to design new treads to permit effective stud installation. Potential gains in studded tire performance are both achievable and practical.

Practice in the U.S. has generally been to use studded tires on the rear wheels only. Such a procedure is, of course, justified in consideration only of traction. If only two wheels are to be studded, better braking would probably be achieved if they were on the front. Little cornering improvement can be expected unless all tires are studded. This practice is reported to be rather common in Europe.

While it was beyond the scope of this study to examine stud and tire design as such, it seems likely that stud wear properties and protrusion length have received reasonable attention by U.S. stud manufacturers; that the pragmatic approach has led to the use of materials with about the right wear characteristics; that the protrusions used represent reasonable compromises between stud effectiveness and stud retention in the tire.

Stopping Distance

Using the correlated stud resistance coefficients shown in Figures A-9 and A-10 as being statistically representative of current American studded tires, stopping distances on ice were calculated for a passenger car with several combinations of tires. The cases considered were for highway tires on the front with (1) highway tires on the rear, (2) snow tires on the rear, and (3) studded snow tires on the rear. A fourth case with studded highway tires on the front and studded snow tires on the rear was also calculated. The highway tire characteristics used were those shown for the 1966 standard in Figure A-6; the snow tire characteristics were Brand A in Figure A-7; the incremental stud resistance was calculated from Figure A-10. Seventy-two studs were considered in both front and rear tires when applicable. The calculations are then based on friction trailer data. It will be recalled that agreement between friction trailer and vehicle data was good for both highway and snow tires, but for studded tires, stopping distances calculated from friction trailer results were less than those measured on the vehicle. Thus, the advantages calculated for the studded tire configurations and shown in Figure 1 are believed to be greater than would be expected in reality.

At the lower temperatures (−5°F to 0°), the differences between the four configurations are not great; the longest stopping distance of 108 ft for four highway tires is reduced 18 percent to 88 ft with four studded tires. As the temperature increases, the stopping distance for the unstudded tires increases markedly and is about 173 ft at 30°F. The solid curve for all four tires studded shows a reduction of nearly 50 percent.

The measured stopping distance data shown in Figure A-5 were used in the calculation of a stud effectiveness reduction factor which could be applied to the friction trailer correlations used in preparing Figure 1. To give an indication of how optimistic the data in Figure 1 may be, these factors were applied to the stud effectiveness with the results shown as the dashed lines. The stud effectiveness factor varies from 1.0 at 0°F to 0.5 at 30°F. Making the corrections significantly reduces the apparent advantages of the studded tires. At 30°F the stopping distances over the highway tread tire value have been reduced by only 12 percent for the studded snow tires on the rear and by 32 percent for studded tires front and rear.

Concurrent with the 1966 NSC tests at Stevens Point, CAL conducted a series of vehicle tests (*7*). These included locked wheel stopping distances with both front and rear tires studded. The data points, corrected to an initial speed of 20 mph, are shown in Figure 1. It will be noted that the experimental stopping distances with unstudded tires while slightly less are in fair agreement with the calculations. The stopping distances with the studded tires are slightly greater than those calculated. Because of the general scatter in studded tire data which has been previously discussed, only limited conclusions can be drawn

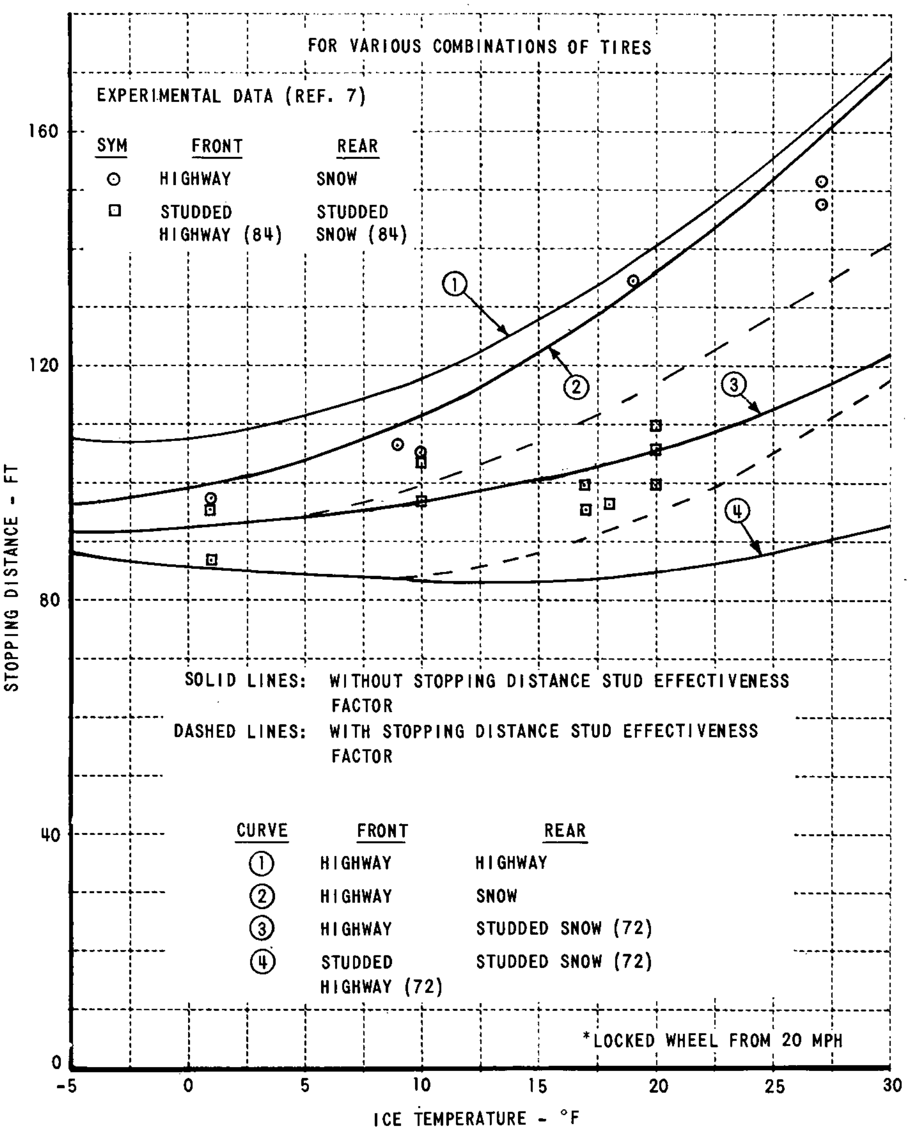


*Figure 1. Vehicle stopping distance * calculated from correlated data.*

from these few points. It does seem quite clear, however, that better agreement is obtained with the calculations using the stud effectiveness factor. Further correlations between friction trailer and stopping distances need to be made for the studded tire cases before these data can be used with confidence. The evidence is, however, that the dashed lines in Figure 1 are more realistic.

Traction

Improved traction performance with studded tires accompanies improved braking performance. While the traction gains are primarily convenience factors, the safety implications should not be overlooked. The ability to negotiate a hill where a car might otherwise be required to back down, the ability to make evasive accelerations, etc., clearly have safety implications.

Cornering

The dearth of data on cornering performance makes it impossible to provide hard data to support arguments that studded tires offer significant safety advantages in cornering although strong subjective opinions that they do have been transmitted to the authors from the top safety engineers of two of the largest automobile companies in the U.S. The very crude calculations presented earlier indicate that such may be the case. The completion of the processing, analysis, and the release of the NSC 1967 data are expected to shed considerable light on this matter.

Accident Causation

Even after establishing that studded tires shorten braking distances, improve traction, and enhance cornering capability on ice and snow, the knowledge of causation factors in the United States is inadequate to permit quantitative judgments on their effect on safety. The data base and necessary studies simply do not exist.

While there is a paucity of data on skidding on ice or snow covered highways, studies have shown that the surface of a road or street may be far more important in the occurrence of accidents than are most design and traffic control elements (*24*). Skidding may be involved in accidents in two ways: (1) the skid may occur before braking, causing the vehicle to take a different course from that intended by the driver, or (2) the skid may occur after braking, making it impossible for the driver to stop or decelerate in the anticipated distance.

(*24*) states, "Although there is overwhelming evidence that skidding is involved in a high proportion of accidents, national statistics on accidents do not specify the number in which skidding occurred."

A study of accidents on the Pennsylvania Turnpike (*24*) definitely showed that wet pavement is more hazardous than dry. The number of accidents per million miles of travel on the Turnpike for each surface condition was as follows: dry, 1.1; wet, 1.9; snow or slush, 4.8; icy, 8.2.

A summary of data on skidding in personal injury accidents in England in 1957 (*19*) indicates that there can be little question that icy pavements are important factors in accident causation. While these data are 10 years old and represent English experience, it just doesn't appear to be reasonable that the times or conditions could be so much different in the U.S. today that icy roads are not similarly important in accident causation. It seems self-evident then, that studded tires have great safety significance.

In a general discussion (*24*) of skidding accidents, it is said: "Of course, it would not be correct to attribute all skidding accidents to the pavement surface. In many instances, the vehicle is riding on ice or snow and the friction coefficient of the pavement is not involved. In other cases, the forces between the tires and roads are so great as to exceed any realistic friction values. Nevertheless, research has clearly shown that accidents do occur when friction coefficients are low and that considerable reduction in accidents can be achieved by improving pavement surface." It follows that if the effective friction coefficients can be increased (by studding tires, for example), considerable reduction of accidents can be achieved.

The NSC has emphasized that even though the percentage reductions are substantial, the stopping distances on ice are still large compared with bare pavement (and those attainable with tire chains). The Swedish report contains the admonition that "tire studding is valuable but its worth should not be overrated." These warnings are, of course, most proper if used in the context that they are made. They do not justify conclusions that studded tires should not be used because they are ineffective. Arguments that studded tires are hazardous because they give drivers a false sense of security must be put in the same category as saying the introduction of four-wheel brakes was hazardous for the same reason.

PAVEMENT WEAR AND ROAD MAINTENANCE

Appendices A, C, D, and E present a design for a wear and roughness meter and detailed recommendations for measuring pavement wear due to studded tires and other traction aids. Test methods outlined are graduated from accelerated tests in a wheel test rig, to field tests in a loop closed to other traffic, and finally to application tests on roads subject to mixed traffic. The precautions necessary to obtain valid data have been pointed out. If all these recommendations are followed, the various interested agencies will have the means to determine actual or predicted road wear due to studded tires and other traction aids on roads in their locality. The magnitude of wear, measured or predicted, will, of course, vary regionally according to the values of the various variables that influence wear rate and the number of vehicle passes.

Measured wear depths in the pilot studies were as high as 0.25 in. at a crossover point in a parking lot after 21,000 passes with a ¾-ton truck (*27*). This example is cited here in so much detail only for illustration. The point is that, under conditions that were more or less representative of actual road conditions, wear depth of tenths of an inch were obtained with numbers of passes that could occur in days at busy highways. However, the observation of the vital variables that are needed to properly weigh the measurements was incomplete. Also, comparative measurements of other highway damage were not made. Therefore, what can be said at this time is only that there is good reason for putting such measurements on a rational basis. This view is what gave rise to the current project and a rational approach to the wear determination is presented in this report.

The question that remains is, "What road maintenance problems are associated with this measured or predicted road wear?" A number of considerations enter:

1. Every reported wear test and all test interpretations indicate that maximum damage per pass occurs during panic stops. Therefore, highway locations at which panic stops are frequent should be kept under surveillance. Since traffic situations requiring frequent panic stops are undesirable, correction may best be made by road relocation or widening. However, the immediate corrective action and the one of concern here would be resurfacing of such spots. A first step would seem to be a count of the frequency of panic stops at such locations (as was actually done in one of the pilot studies); such counts should be followed by wear measurement or surveillance of road condition. Information on the dependence of such damage on axle load and other variables that is expected from the tests recommended in this study, will greatly improve the predictability of damage from panic stops.

2. The layer of pavement removed may be thick enough locally so that steps are created that require patching. Here, the roughness portion of the wear and roughness meter will be helpful by providing quantitative information. Criteria for pavement roughness or profile variation (steps) that require correction would have to be established.

3. A tendency for removal of small mortar particles and exposure of coarse aggregate has been noted and recorded

by a number of observers. The susceptibility of such exposed pavement to other damage has not been established.

Potential maintenance problems in the State of New York were explored through discussions with various highway officials. The following officials were contacted: General Supervisor, Division of Operation and Maintenance, Department of Public Works, Albany; Assistant Superintendent of Maintenance, New York State Thruway Authority, Elsemere; Maintenance Supervisor, District 5, New York State Department of Public Works, Buffalo; Supervisor of Highway Maintenance, County of Erie; and various Town of Amherst highway officials.

No information or statistics were available on the relationship between highway maintenance practice and use of driving aids, including studs. Apparently, no organized investigations have been made that relate to this problem. The unanimous opinion, however, of all of these officials, was that no additional maintenance costs have been incurred that can in any way be correlated with stud use. A few instances were reported, at a toll station stop on the NYS Thruway, for example, in which a noticeable increase in surface damage has been observed and attributed to stud use. Also, several officials were quick to point out that specific evidence of damage having been caused by tire chains, especially on trucks climbing hills, is a part of their experience. In addition, it was pointed out that while it is known that studded tires do produce damage, it is possible that the relatively low level of damage that has been casually observed in New York State thus far may be simply due to an insufficiently high use rate.

If this situation is typical of most of the states, it is obvious that there is not enough evidence available upon which to base any rational judgment of the beneficial (safety) aspects of studded tires in relationship to their deleterious aspects (increased maintenance costs). The information that is needed in order to make this judgment falls in these categories: (1) studded tire use rates; it is especially important that the data be on a comparative basis with the use of other driving aids that are not now illegal in any states (e.g., chains), (2) measures of damage and wear caused by studded tires and other driving aids, (3) the relationship between these damage measures and the resulting (increased) maintenance required, and (4) the relationship between studded tire use and safety. Information of the type needed in the last of these categories is undoubtedly the most difficult to obtain. For, not only is it necessary to first evaluate studded tire effectiveness more thoroughly, but also to relate effectiveness to (increased) safety. Finally, all four factors must be properly weighted in a cost-effectiveness sense.

In view of the obvious needs for more data on both wear and damage and on effectiveness, and in consideration of the other difficulties touched on in the preceding discussion, it does not seem likely that the studded tire safety versus damage question can be answered on a strictly rational basis within the next few years. Indeed, the problem of putting a dollar value on safety may preclude making such a strict determination at any time.

It seems likely, therefore, that a start on obtaining an answer to the question can only be taken after sufficient evidence has been collected that shows a significant economic disadvantage on the road maintenance aspect to the use of studded tires. Fortunately, the acquisition of such evidence falls on the side of the equation that is most amenable to numerical evaluation—the measurement of wear and damage and the assessment of these in economic terms.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDED RESEARCH

CONCLUSIONS

The conclusions of a project such as this, because of its predominantly "library search" character, are actually the "findings" of the project. Therefore, such conclusions as there are, have already been given as the findings in Chapter Two.

RECOMMENDED ADDITIONAL RESEARCH

Studded Tire Effectiveness

While the pragmatic approach to studded tire design and practice has resulted in products which offer winter driving safety advantages, it seems quite clear that these products are far from optimum in the sense of achieving the most benefit at the least cost direct (cost of the studded tires) and indirect (added costs of highway maintenance). Additional research in the direction of such optimization is in the interests of both the private and public sectors.

A combined theoretical and experimental research program is recommended. Such a program would start with a consideration of structural and mechanical properties of ice. (Mechanisms of rubber friction (*20* to *23*) on ice are fairly well understood.) From these the probable stud penetration and ice cutting and failure mechanisms would be formulated. Laboratory tests of single studs passing through ice at various speeds would be made to validate and refine the theoretical model which has been formulated. The interactions due to multiple studs would then be added to the theoretical model and the laboratory tests. The effects of stud configuration, protrusion length, ice temperature, sliding velocities and other variables would be determined. The laboratory experiments would then be extended to a single wheel to establish correlation with the idealized experiments and to introduce variable slip effects. The laboratory experiments would be followed by full-scale friction trailer and vehicle tests using tires in which a systematic variation (particularly stud number and arrangement) could be readily varied. Data would be correlated on the basis of the theoretical models which had been previously validated. The primary initial emphasis would be performance on ice, with braking (varying degrees of slip), traction and cornering investigations made.

Techniques would be developed for repeatable compacting of snow and for determining the properties of the compacted snow. Off-road locomotion and trafficability disciplines would be used to develop methods for predicting performance on packed snow. Full-scale friction trailer tests, similar to those made on ice would be conducted.

Assessment of Pavement Wear

Methods for measuring pavement wear and roughness developed as a primary task under this project have been presented in the body of this report. We make the following suggestions for their implementation.

ACCELERATED WHEEL TEST RIG

It is recommended that a permanent indoor test facility be operated centrally for all interested agencies. As discussed in the report, this rig serves several purposes: By incorporation of control pavement segments of uniform texture, it will serve as a reference standard by which the consistency of other tests and new materials can be evaluated; many of the test variables can be evaluated rapidly and inexpensively to the extent that functional relations are established, thereby reducing the number of road tests required to establish numerical relations.

FIELD TEST LOOP

The dimensions for the field test loop, as given earlier for illustrative purposes, are minimum and a larger loop would be acceptable. We recommend that the loop be located in a region of the country where temperatures below freezing are regularly obtainable. Any existing test loop meeting these specifications and available for one entire winter season would be acceptable, if the recommended modifications (roofed sections, installation of core sections and heating) can be installed.

It is recommended that the number of pavement cores tested be sufficient to include the major varieties of interest. However, in order to keep the total down to a manageable minimum (in view of all the other variables that must be tested) we recommend that some screening tests be made in which the range of expected differences is explored.

At the conclusion of the accelerated and the field tests, a comprehensive report should be issued which should enable each local agency to calculate expected wear (by methods outlined in Appendix E) after they have established the pertinent local variables.

ROAD TESTS

Since even the field test loop provides only a simulation of traffic conditions and not all pavement conditions can be tested, it is recommended that validation of the test results be by local agencies at local roads. Again it must be emphasized that interpretation of such tests must take into account the pertinent local pavement variables, (e.g., pavement composition and age) and traffic count for the range of other variables such as axle load, deceleration, and temperature.

SECONDARY DAMAGE

A separate investigation of secondary damage should be conducted. By secondary damage is meant road wear or other damage that is caused or aggravated by the initial action of studded tires. During the single stud tests of the current project, some pertinent observations were made in this regard, but limitations on the scope of the program did not permit extended investigation. The observation was the occurrence of what appeared visually to be hairline transverse cracks at the bottom of grooves produced under conditions of maximum friction drag. Further, single stud cutting tests and detailed surface studies are recommended to explore this phenomenon. If they do indeed occur, such cracks could play a role by weakening of pavement in subsequent freezing, salting and thawing cycles. There should be separation of such tests from tire and vehicle tests because here detailed microscopic observation of test of pavement properties is required; single stud tests of the type initiated under this program appear very suitable for such work.

TIRE-STUD RELATIONS

Both the performance of studded tires and their damage to pavements are a result of the dynamics of stud-pavement contacts. These events, in turn, are influenced by the dynamics of the tire-stud contact areas. Investigation of these tire-stud relations will lead to (1) improved understanding of performance and road damage, (2) more rational studded tire specification, and (3) better and faster methods of evaluating new stud and tire designs. Factors that should be investigated are outlined as follows:

1. Geometry. The shape of the stud and the shape and relative size of the receiving hole in the tire will determine where in the stud the forces act that resist pull-out from the tire and lateral and rotational motion. The protrusion length of the studs affects the magnitude of these forces.

2. Forces. In first approximation, the normal load as determined by stud pressure and the "cutting force" determined by the sliding velocity, control wear depth. Of

course, the orientation of the stud with respect to the tire will also affect the forces developed at tire-stud and stud-pavement contact areas.

3. Thermal effects. Heat is generated due to stud-pavement contact and due to stud-tire motion. The former is important because it raises the stud tip temperature, thus influencing its wear, and because it transmits heat to the stud-tire contact areas. Temperature increase at the latter surfaces may affect rubber strength and tightness of stud seating.

4. Stud failure. Studs can fail by pull-out and fracture. Their effectiveness is diminished by looseness and excessive wear. The effect of contact forces and heat on stud failure should be known.

APPENDIX A

STUDDED TIRE PERFORMANCE

The terms "performance" or "effectiveness" are used interchangeably in this report as generics which include braking, traction, and cornering properties. These latter terms are defined in a subsequent section of this appendix. Included here are the details of the literature review on studded tire performance together with the technical discussion of the methods described therein and the resulting data.

LITERATURE REVIEW

A literature search was conducted during the course of this program to obtain published material pertinent to studded tire performance. The documents were divided into categories of technical reports and papers, semi-technical literature appearing in trade journals or general news media and commercially- or trade association-oriented publications. It was established that the latter two categories did not contain any original information of scientific standing which had not been taken from the technical reports and papers; thus this literature was discarded. In the category of technical reports and papers, it was found that in many instances the same studies had received multiple publication. The redundancies were then eliminated in most instances.

In addition to the published reports and papers, certain preliminary reports and various privileged information was acquired. Although the restrictions placed on the use of this material have been observed, it has been determined that no substantiated information was contained in them which was in significant disagreement with the conclusions which are presented in this report. At the time of this writing, the results of the 1967 National Safety Council Winter Driving Hazard Program have not been released. The 1967 program included vehicle braking, traction and cornering tests on ice with studs mounted on all four wheels. These data will be of considerable interest in confirming some of the estimated performance and tentative conclusions included in this report.

The literature judged to be significant included one Canadian (RCAF) report and one Swedish report. Although the authors are reasonably confident that no important data from this country were overlooked, there may be foreign studies that have been reported that did not come to their attention.

Appendix H is an Annotated Bibliography and List of References. The reports and papers which were finally retained, accompanied by brief descriptions of their contents, appear first. Other references follow which do not contain information specifically on studded tires.

TECHNICAL DISCUSSION

In this report, the term "tire performance" refers to the basic functions that tires serve in transmitting longitudinal and lateral forces between the highway and the vehicle. The longitudinal forces are necessary to provide acceleration (traction) and deceleration (braking) of the vehicle while the lateral forces are required for vehicle turning or cornering. Specific performance measures are defined in the discussions of braking, traction, and cornering.

In the normal operation of tires on bare pavement (dry or slightly wet), the primary friction mechanisms are related to tire-highway adhesion (an interface phenomenon) and to hysteresis (a deformation phenomenon). Kummer (*12*) also includes cohesion, grooving, and viscous losses under the general category of friction. Friction coefficients are defined as ratios of sliding resistance to the slider load (normal to the surface). Those resistance forces which are unrelated to the normal force are not properly expressed as friction coefficients. The presence of ice, snow or slush on a highway may change the entire character of the tire performance problem into one more nearly analogous to the off-road-locomotion problem in which the physical and mechanical properties of the surface become important parameters. In general, the resistive and tractive forces will involve the surface-surface adhesive forces, surface-surface frictional forces, the internal cohesive and frictional forces, and sinkage, in addition to tire properties and loadings (*13*).

For conventional tires running or sliding on hard ice, the usual tire friction concepts will normally be valid, the use of the nondimensional tire friction coefficient being a convenient means of generalization and correlation. With studded tires, caution must be exercised on two counts: (1) in classical friction theory, the friction coefficient is assumed to be independent of normal load, and (2) stud resistance may, in part, be due to momentum exchange from the sliding tire to the fractured ice which, strictly speaking, is not considered as friction. None of the literature reviewed considered these aspects of the resistive and tractive phenomena.

The manner in which frictional considerations come into play in braking, driving, and cornering on highways is discussed by Kummer and Meyer (*14*). Although their paper was written in the context of normal highway operation, it is generally applicable to operation on ice except that the attainable friction coefficients are much lower; with the starting and braking power characteristics of passenger cars, it is frequently difficult to operate at tire slip below the limiting friction coefficients.

The importance of tire slip with studded tires is not fully understood. Some of the experimental results which are discussed indicate that there may be a critical friction coefficient at less than 100 percent slip while other data show contrary results (*6*). It is argued in Appendix F that in locked wheel braking a stud sliding in the same track as one ahead of it will not offer as great a resistance as its predecessor. Thus, it might be expected when the slip is such that a new stud comes into contact with the surface just as the track in the ice from the preceding stud ends that near-maximum effectiveness would have been reached.

In starting from rest, near-maximum tractive force would be expected at degrees of spin (negative slip) such that tracks in the ice just overlap. Once the tracks do overlap, if forward motion does not result, a decreased tractive effort, or drawbar pull, would be expected causing a loss of equilibrium with the torque input to the wheels and consequent wheel spinning. Most of the test reports reviewed report only the locked wheel (100 percent slip) braking results and the traction at the onset of wheel spinning (a low value of negative slip). If the preceding hypotheses are correct, the critical values for braking would be expected to be nearly equivalent to the tractive values.

Testing Techniques, Unstudded Tires

Kummer and Meyer (*14*) have discussed testing techniques in relation to determining highway skid resistance. Much of this discussion is appropriate to studies concerned with winter driving skid resistance. Measuring equipment that has been used for full-scale testing of studded tires falls in two categories: (1) Skid testers or friction trailers, and (2) vehicles. The friction trailers have generally been used in the steady-state locked-wheel sliding mode at a fixed speed although a Swedish machine has been used in a steady-state slip mode. Vehicles have been operated in the nonsteady-state sliding mode to measure stopping distances from some initial speed. They have also been used to pull dynamometers for traction measurement and for nonsteady-state cornering measurements.

Goodwin and Whitehurst (*15*) have presented a comprehensive paper on the skid trailer technique for measuring the surface-tire forces during skidding of a test wheel which includes detailed information on one of the skid trailers employed (UT), the metric system calibration, data recording and interpretation, etc.

The vehicle test procedures are discussed in the appropriate program references. In general, standard stopping distances were measured. However, on-board instrumentation consisting of accelerometers (*5*) or accelerometers, gyros, etc. (*7*) was also used. In the RCAF tests, a traction dynamometer was used.

In attempting to correlate studded tire braking performance taken by these two techniques (friction trailer and vehicle stopping distance), it is necessary to evaluate and compare data taken with similar tires and under similar ice conditions. The National Safety Council Winter Driving Hazards Programs conducted over the years 1963-1966 have used both test methods so that extensive data on comparative configurations are available for this purpose.

The test equipment and procedures employed are described (*1-4*). The tests were run on specially flooded and frozen areas; in 1963 and 1964 at Gaylord, Michigan and in 1964 and 1965 at Stevens Point, Wisconsin. Data were obtained in two ways: automobiles were driven in a straight course and accelerated to a speed slightly greater than 20 mph. The driver then allowed the vehicle to decelerate. At 20 mph, the brakes were locked and the distance measured for the vehicle to come to a complete stop. Other measurements were made using friction trailers supplied by General Motors, Portland Cement Association, and the Tennessee Highway Research group. The friction trailers were towed at a constant speed of 20 mph with one or both wheels (depending on the trailer) locked. Oscillograms were taken of the braking force at this speed. With a knowledge of the tire load, an effective friction coefficient between the tire and ice was then calculated. More detail on those procedures may be found in (*15*).

The tires used on all programs were 7.50×14 with a rated load of 1,085 pounds. The friction trailers were ballasted to the same weight. The test cars weighed 4,325 pounds with nearly equal static weight distribution. Statically, all wheels were within 10 pounds of the standard test weight (*1*).

Precautions were taken to assure consistency of friction trailer data by making many repeat runs in both directions with individual trailers and by comparing results between trailers. No statistical analyses have been presented, but it is clear that the authors (*2-4*) have high confidence that all three trailers gave consistent results.

During each test period, a series of tests was conducted using standard highway tread tires made from ASTM E-17 rubber and provided by the General Tire Company. These tires serve as a base configuration which establishes the repeatability of the experiments from year to year.

The standard E-17 data may be used to establish a comparison of friction trailer measurements and vehicle stopping distance measurements.

In the classical theory of sliding friction (for example, *12*), the frictional force restraining sliding motion between any two particular materials depends only upon the normal load and is independent of the area of contact and the sliding speed. Thus, if the theory is valid for tires sliding on ice, the stopping distance calculated from a measured friction coefficient should agree with the measured stopping distance and vice versa.

Figure A-1 shows the friction coefficients measured with the E-17 tires during the four test periods (*1-4*) plotted vs. ice temperature. The faired line is the least squares curve fit of all the data. It has the form first used in (*1*).

$$\mu = a + bT + cT^2 \qquad \text{(A-1)}$$

After 1963, the NSC has used linear curve fits for the E-17 highway tread data. There is strong evidence that the non-linear behavior of the E-17 and other highway tread tire data recognized by the NSC in 1963 is real. Consequently, a second-degree curve has been fitted to these data with the following results:

$$\mu = 0.0910 - 0.000304\ T - 0.000020\ T^2 \qquad \text{(A-2)}$$

The standard error of estimate is 0.0096.

Similarly, the stopping distance data measured over the four-year period are shown in Figure A-2. A least squares curve has been fit to them as follows:

$$s = 135.6 + 1.22T + 0.072T^2 \qquad \text{(A-3)}$$

As has been discussed, the friction coefficient can be converted to stopping distance and vice versa within the assumptions of the classical theory of sliding friction by letting:

$$s = \alpha + \beta T + \gamma T^2 \qquad \text{(A-4)}$$

The results are given in Table A-1.

A comparison of the measured stopping distances with those calculated from the friction coefficients is shown in Figure A-3. It may be seen that the calculated values vary from about 11 percent greater at — 10°F to about 13 percent less at 32°F than the measured values. The reasons for these discrepancies are not known*; however, since the same tires and the same ice were used for both tests, differences here tend to be ruled out. No corrections are made for the aerodynamic drag which is present on the vehicles and not the friction trailers. On a 20-mph stop the aerodynamic drag is equivalent to a friction coefficient of about 0.0015 (2½ percent of the lowest friction coefficients measured; the correction is such, however, that if it were made it would increase the differences noted in Figure A-3 at the higher ice temperatures). Since the friction trailer coefficients used in the calculations were determined at a speed of 20 mph, while the stopping distances are effectively integrations over a speed varying from 20 mph to 0 mph, a failure of the assumption that the friction coefficient is independent of speed could cause discrepancies between the two measurements.

* According to (*16*) many additional friction trailer measurements at the higher temperatures were made in the 1967 program which were lower than those presented in Figure A-1. The additional measurements will tend to reduce these discrepancies.

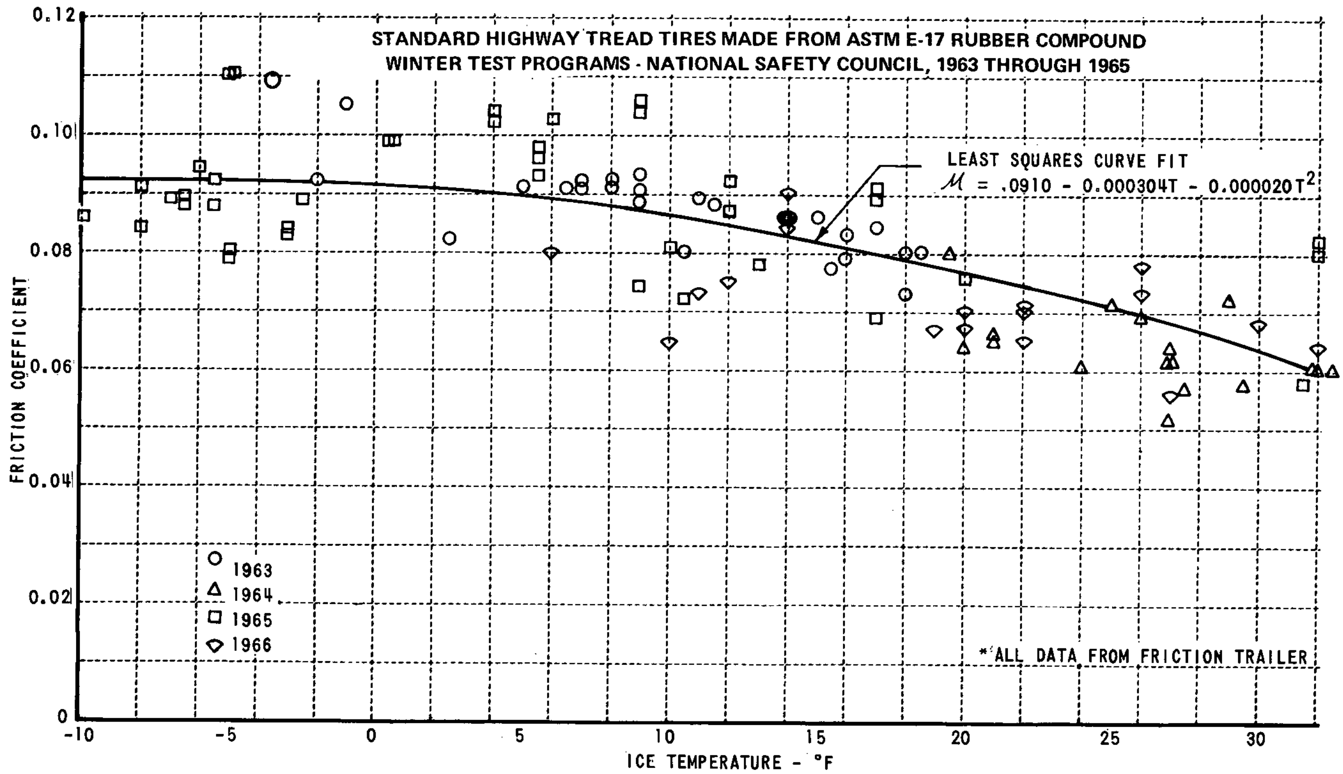


*Figure A-1. Friction coefficient * vs ice temperature.*

TABLE A-1

VALUES OF COEFFICIENTS IN FRICTION COEFFICIENT AND STOPPING DISTANCE EQUATIONS

QUANTITY FROM	FRICTION COEFFICIENT A	B	C	STOPPING DISTANCE α	β	γ
Friction Trailer	0.0910	—.000304	—.000020	143.9	0.508	0.0534
Vehicles	0.0961	—.000805	—.000017	135.6	1.22	0.072

In spite of these differences, the separate consistency of both the friction trailer and the stopping distance data is judged to be generally good. The standard errors of estimate of 0.0096 in friction coefficient and 12 feet in stopping distance over this period on experiments where there are inevitably many uncontrolled variables indicate good precision of measurement. There is considerably more scatter in the studded tire data. This scatter must be due to causes other than measurement precision.

The good consistency noted also gives reasonable confidence that, if sufficient repeat runs are made, comparisons of different configurations (using the same technique) will be valid and that incremental effects may be determined.

Experimental Data on Studded Tires

Studded tire effectiveness will be discussed under separate categories of braking, traction and cornering. Within each category, to the extent that data are available, performance on ice, compacted snow and bare pavement are discussed. The role of the various surface-tire characteristics is considered within each of these subgroups, as follows:

1. BRAKING PERFORMANCE

(a) *Braking on ice; friction trailer and vehicle measurements.* In the previous section, the agreement between vehicle data and friction trailer data for the E-17 highway tread tires was examined. It is necessary to consider this matter further since both friction trailer and vehicle data

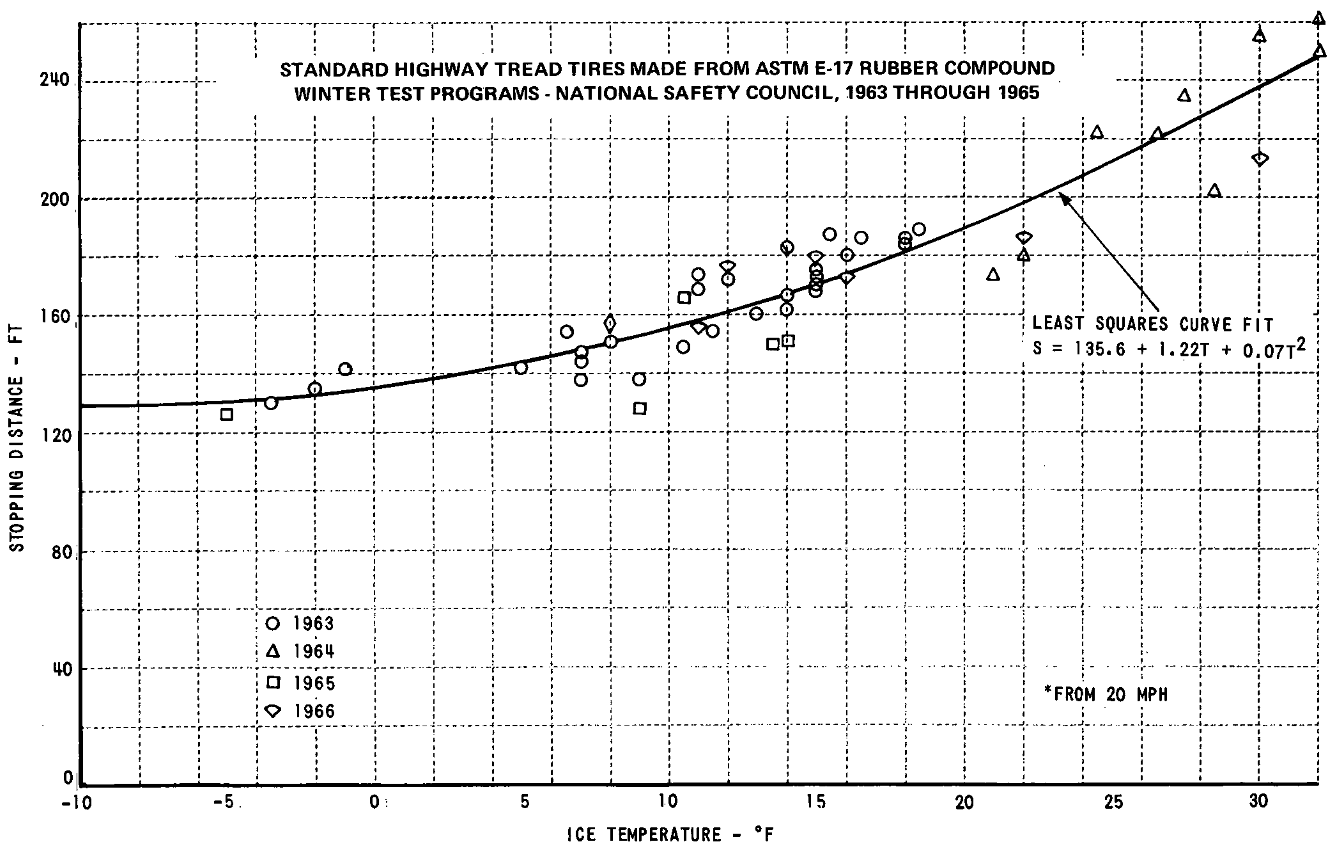


*Figure A-2. Locked-wheel stopping distance * vs ice temperature.*

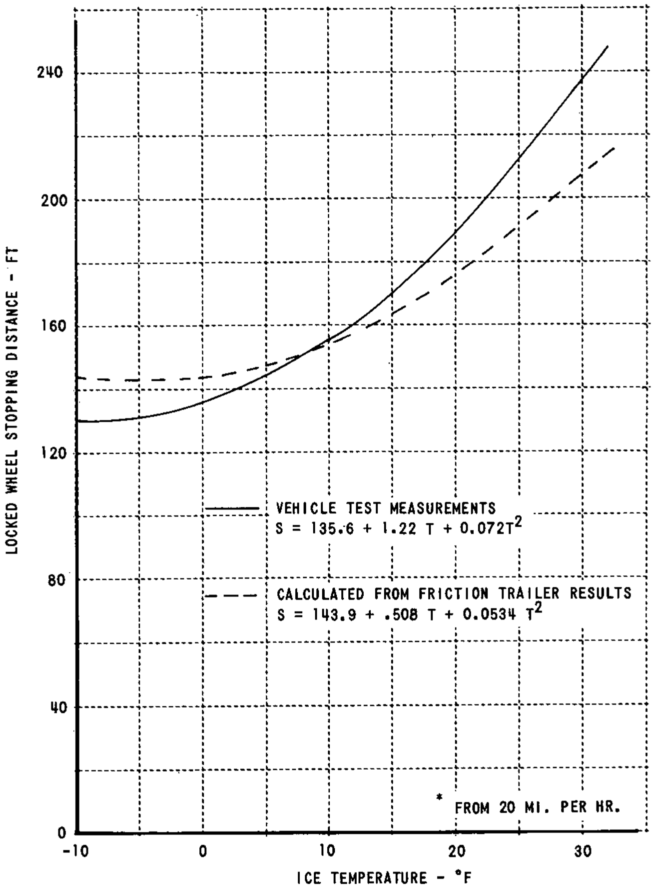


*Figure A-3. Comparison of measured vehicle stopping distance * with that calculated from friction trailer results—Standard highway tread tires made from ASTM E-17 rubber compound.*

were obtained in the NSC programs and when snow or studded tires were being tested, all four vehicle tires were not the same; the tires differed from front to rear.

Figure A-4 compares measured vehicle stopping distance and stopping distance computed from friction trailer data for the E-17 highway tread and commercial highway tread tires used during the 1966 test program. There is good agreement between vehicle stopping distance and friction trailer data for both of these tires, although there is an appreciable difference between the two tires. The agreement of the 1966 E-17 tire data at the higher ice temperatures is better than that taken over the four-year period and presented in Figure A-3. Figure A-5 is a similar plot for ordinary snow tires and studded snow tires. Here there is good agreement between data taken with the two experimental techniques for the unstudded snow tires but poor agreement between the two methods for the studded snow tires with the friction trailer data consistently indicating shorter stopping distances or greater friction coefficients.

The test vehicles used commercial highway tires on the front and snow or studded snow tires on the rear only. Vehicle deceleraton changes the static load distribution between the front and rear wheels. Both of these effects are taken into account here in calculating stopping distances. The effective friction coefficient may easily be derived to be

$$\mu_e = \frac{(a/l)\mu_r + (b/l)\mu_f}{1 + (h/l)(\mu_r - \mu_f)} \qquad \text{(A-5)}$$

in which μ_f and μ_r are front and rear friction coefficients; a and b are distances from the cg to the front and rear axles; h is the vertical distance from the ice to the cg; and l is the wheel base. μ_e was then used to calculate stopping distance. Values of μ_f and μ_r are the faired friction trailer results.

Because of the poor agreement of friction-trailer and stopping-distance data in Figure A-5, any comparisons that are made must all be based on the same test technique. There is the further implication that actual studded tire performance will not be as good as that which would be calculated from friction-trailer data—at least in the speed range of 0 to 20 mph.

Aluminum oxide as well as tungsten carbide studs were tested during the 1966 program. Comparative performance data from unstudded and porcelain studded tires showed the same results as with the tungsten carbide studs: that is, good agreement between trailer and vehicle for the base snow tires but poor agreement for the studded tires.

(b) *Stud effectiveness correlations.* Continuing with the NSC test results, Figures A-6 and A-7 show faired curves for the friction coefficients of highway and snow tires as a function of ice temperature. From inspection of these curves, it is clear that the ice temperature is an important variable which must be taken into account in studies of tire characteristics on ice. Both the level of friction coefficient and the temperature dependence are different for the several highway tread tires. There are also different levels of friction coefficient on the snow tires, although the variations with temperature are about the same. In either case, however, the attainable friction coefficient at any particular temperature will differ from tire to tire. Any meaningful measure of stud effectiveness must then be in terms of the incremental performance over the unstudded tire on which it is used. Although this may seem to be so obvious as to be trivial, it has been frequently overlooked—particularly in discussions on the effect of wear on stud effectiveness.

Friction trailer data for the new 1966 commercial Brand D snow tires with and without studs are shown in Figure A-8. The curve faired through the unstudded data is that which was used to represent the basic performance of the tire. Each studded tire data point then has the friction coefficient of the basic tire subtracted from it to give the increment in performance due to the studs. These performance increments, which will be referred to as the stud resistance coefficients ($\triangle R_s$) are plotted at the bottom of the figure as a function of ice temperature. The term "incremental friction coefficient" is avoided because the action of a stud on a locked wheel being dragged through ice is certainly not equivalent to the mechanism of sliding friction as discussed previously. $\triangle R_s$ is the incremental resistance force due to the studs divided by the weight (W) on the tire. Although $\triangle R_s$ is dimensionless, there is no evidence that it is independent of W. This fact should be kept in mind in dealing with all studded tire data.

The same procedures used in obtaining the stud resistance

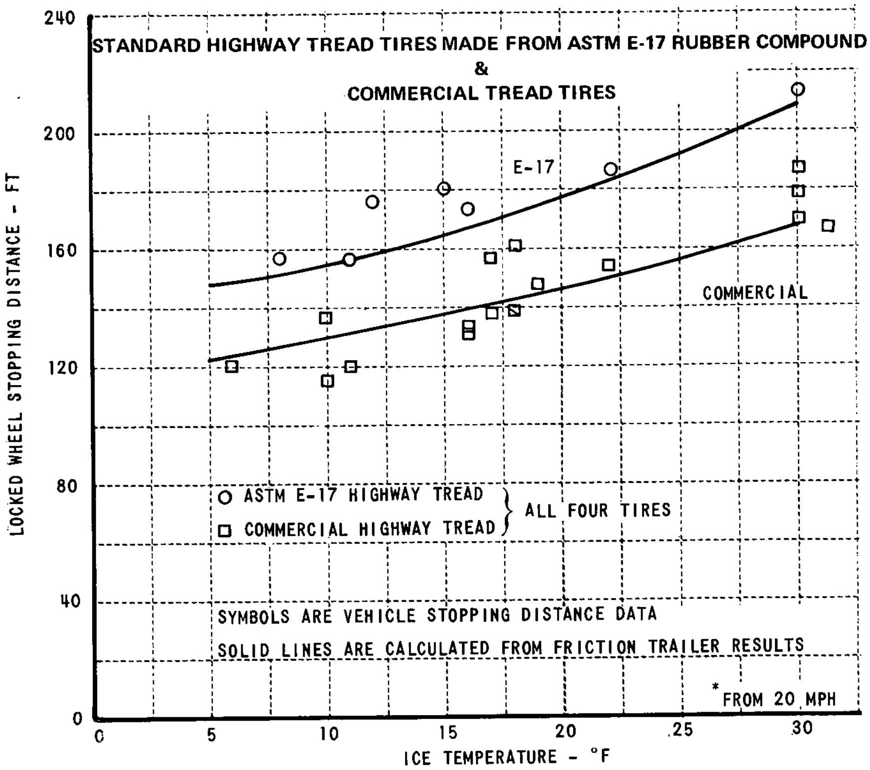


*Figure A-4. Comparison of measured vehicle stopping distance * with that calculated from friction trailer results.*

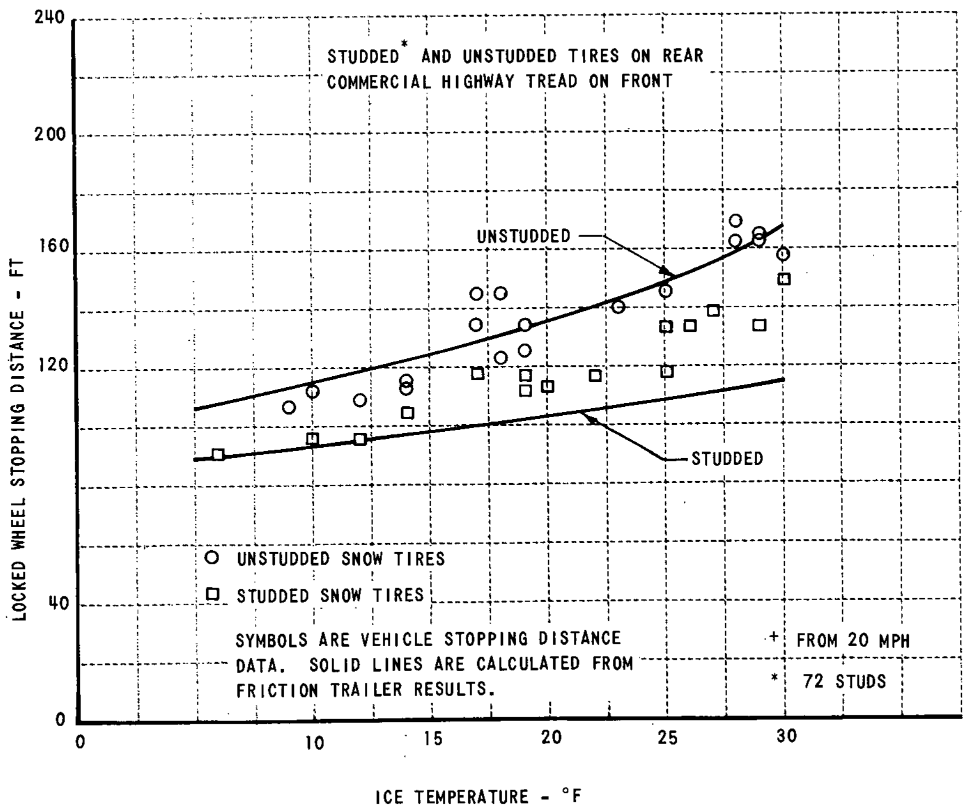


*Figure A-5. Comparison of measured vehicle stopping distance * with that calculated from friction trailer results.*

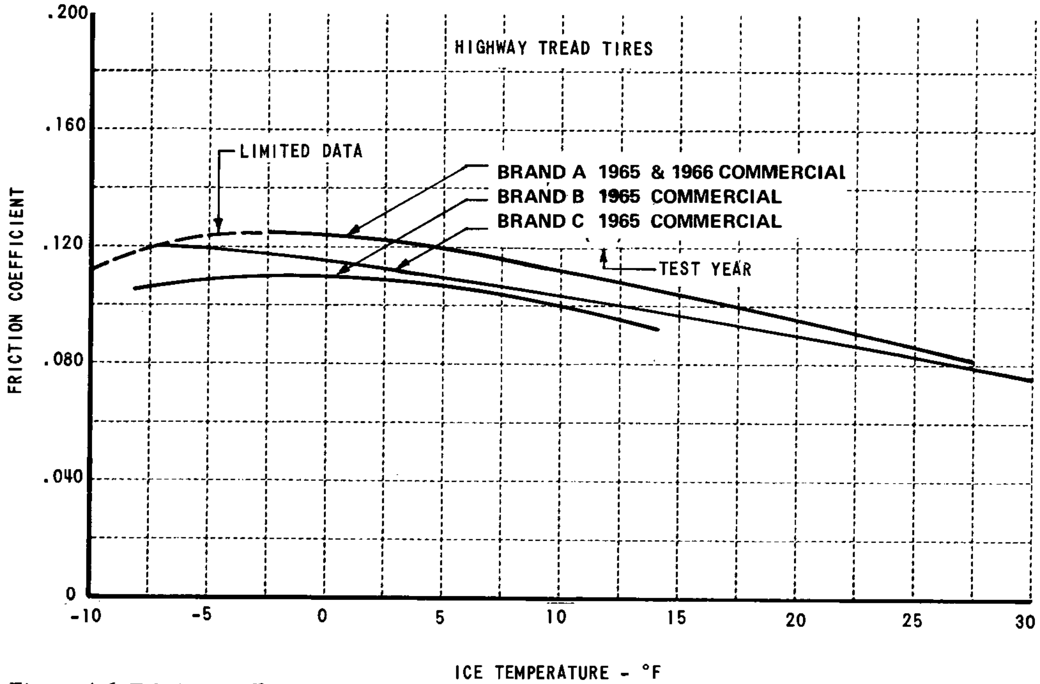


Figure A-6. Friction coefficient vs ice temperature.

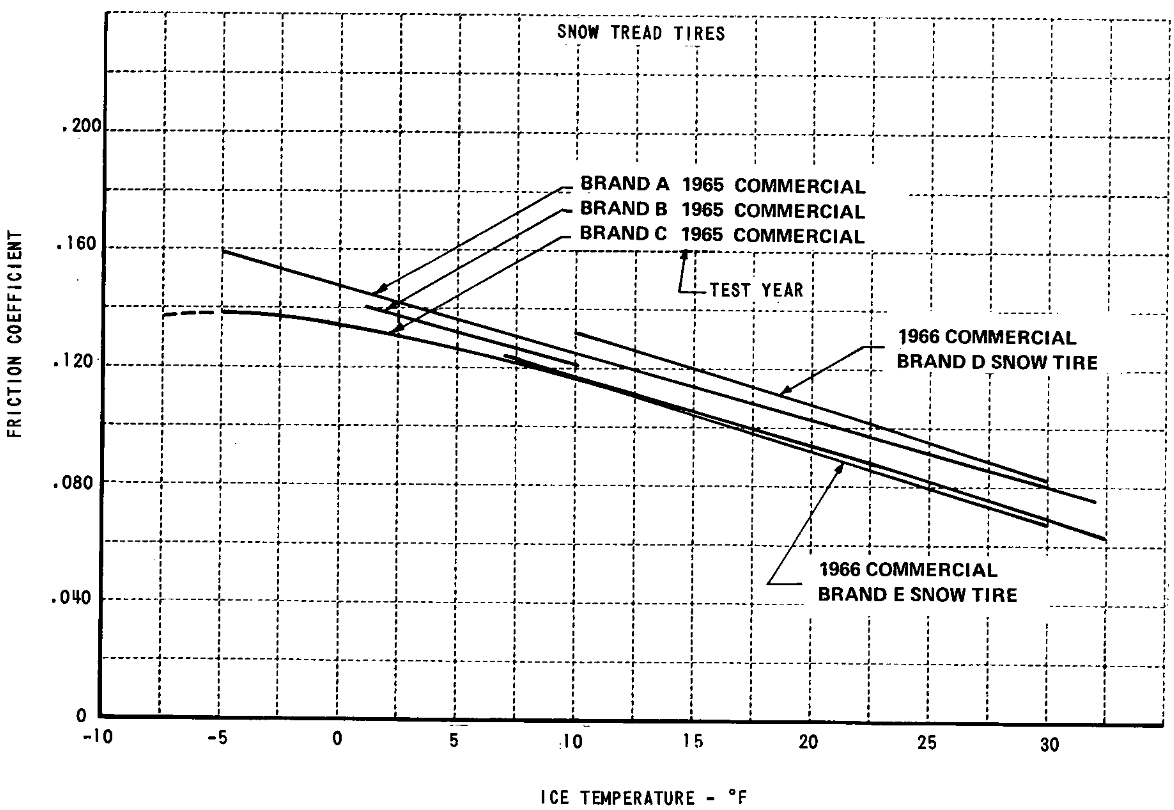


Figure A-7. Friction coefficient vs ice temperature.

coefficients on the 1966 standard snow tires were used for those tires tested in the 1964, 1965, and 1966 programs where the necessary base runs had been made. The resulting stud resistance coefficients are plotted together in Figure A-9. The straight line drawn through the data is the best least squares fit. While there is appreciable scatter (the standard error of estimate is 0.020), it is clear that stud effectiveness varies significantly with ice temperature. The correlation coefficient is calculated to be 0.566.

It will be noted that the data in Figure A-9 include tires with numbers of studs varying between 64 and 108. It was suggested previously that in locked wheel braking the effectiveness of a stud would be diminished if it were sliding in the track of one ahead of it; thus, the stud effectiveness would be expected to depend upon both the number of studs in the contact patch and their placement. Lacking information on the stud pattern (and therefore the number of separate lines of studs), a correlating parameter was tried which took into account only the total number of studs. Each stud resistance coefficient was divided by the number of studs in that tire to give a parameter $\triangle R_s/N$ which is plotted vs ice temperature in Figure A-10. Use of this parameter gives a correlation coefficient of 0.573, practically the same as was obtained for $\triangle R_s$. The standard errors of estimate are 36 percent and 38 percent of the mean values for $\triangle R_s$ and $\triangle R_s/N$, respectively. This result is discussed further in connection with some of the traction data presented.

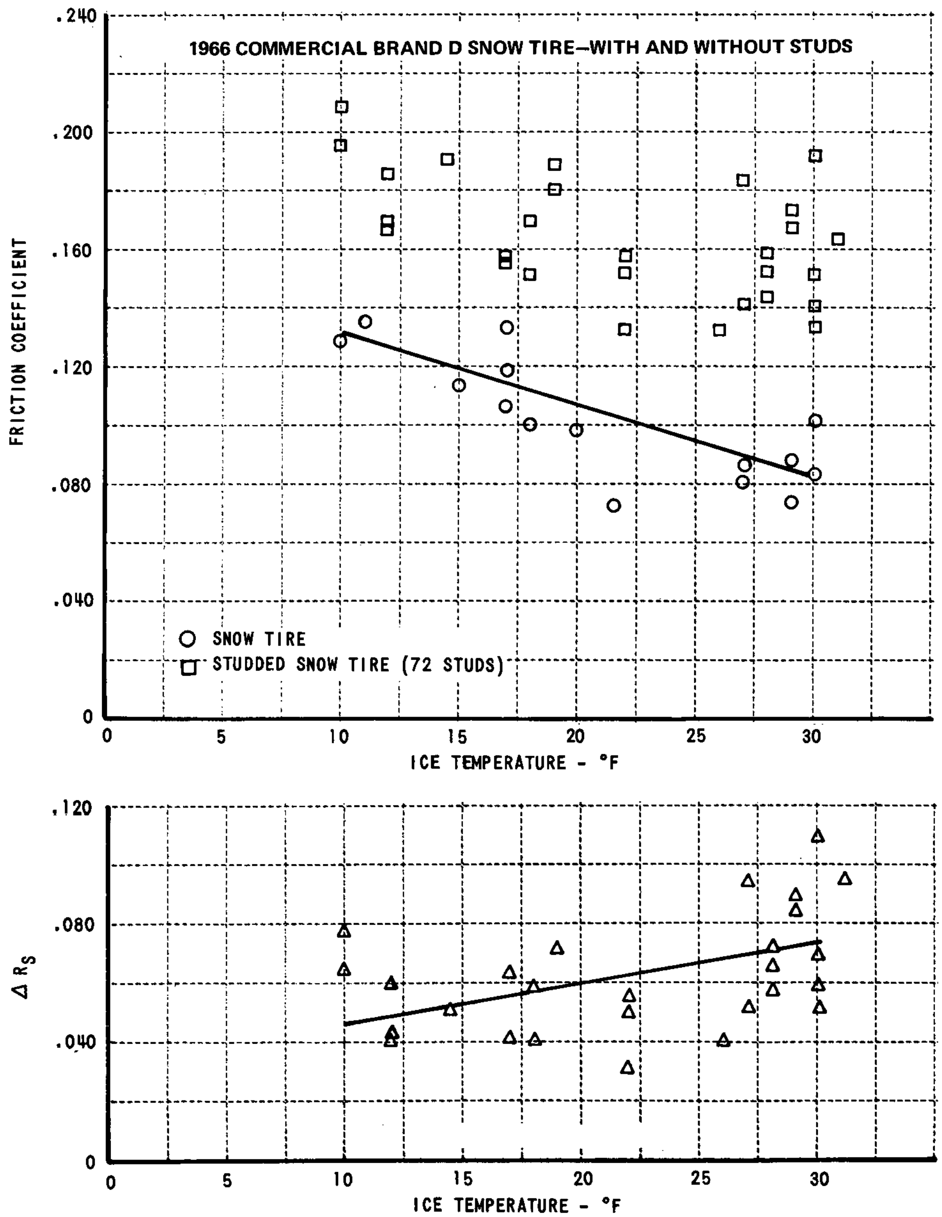


Figure A-8. Friction coefficient vs ice temperature.

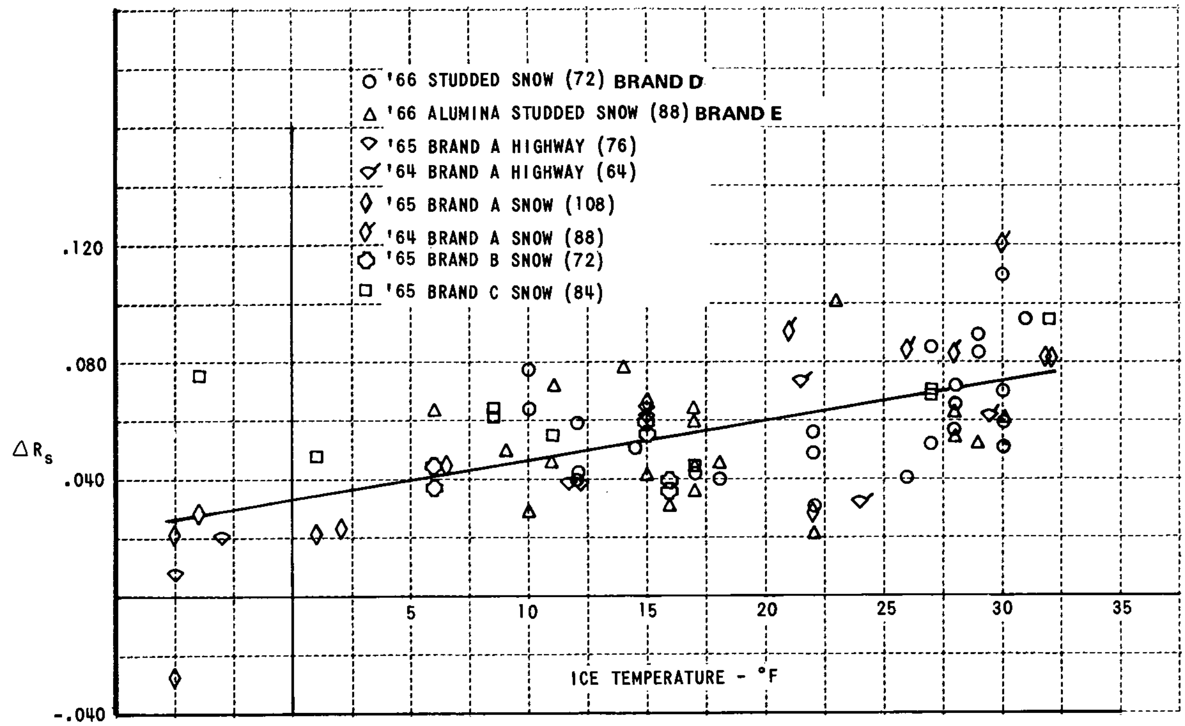


Figure A-9. Stud resistance coefficient (ΔR_s) vs ice temperature.

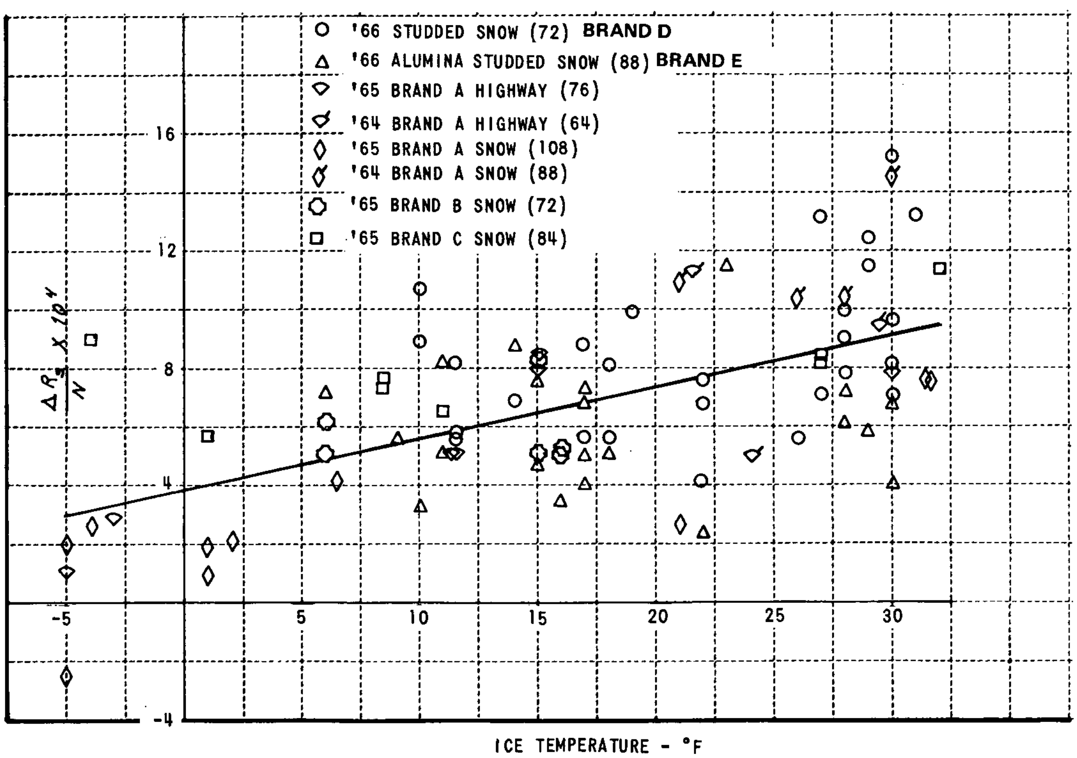


Figure A-10. Stud resistance parameter ($\Delta R_s/N$) vs ice temperature.

One of the objectives of the 1966 NSC program was to determine the influence of the number of studs. The basic tire contained 72 studs; the same tire was also tested with 48 and 144 studs. The data points for runs made with 72 studs are presented in the 1966 report; no data points, but only straight lines as shown in Figure A-11 were presented to show the effect of the number of studs for the tests with 48 and 144 studs. Tabulated data (*16*) are shown on the figure. It will be noted that there is a considerable amount of scatter in the data and that the curves which were faired by the NSC extend to temperatures somewhat below the lowest temperature actually tested. In view of these factors, there appears to be no basis for attaching credibility to the differences that are shown in the 1966 report. The fact that the data do not show a distinct increase in effectiveness with more studs is certainly of interest, however, and may be associated with the number of separate lines of studs.

The RCAF Central Experimental and Proving Establishment conducted an evaluation of studded tires that is reported (*5*). Care was taken in the installation of tungsten carbide studs in 7.75 × 15 tires. In locked wheel braking tests, 216 Seco studs were located in 8 different lines of each tire, 4 lines containing 18 studs and 4 others containing 36 studs. Stud protrusion from the jackets was 0.031 inch. However, some of the jackets protruded as much as ⅛ in. The unstudded snow tires gave a friction coefficient on ice at a temperature of 30° of 0.09, about 10 percent higher than the best snow tire tested by the NSC but not an unreasonable value. Addition of the 216 studs raised the effective coefficient to 0.250, indicating a stud resistance coefficient, ΔR_s, of 0.160 as compared with an average value of 0.073 from the NSC data. The coefficient $\Delta R_s/N$ was 7.4 10^{-4} compared with 9.1×10^{-4} for the NSC data. These two comparisons show that the addition of studs did continue to increase the effectiveness, but at less than a proportional rate.

The National Swedish Road Research Institute (*6*) has published braking data from friction trailer measurements. In the Swedish tests the number of Seco studs was varied between 52 and 260 and in the lines from 2 to 8. Runs were made at sliding speeds of 12.4 mph and 37.3 mph. The results are shown in Figure A-12 in the form of effective friction coefficient vs. the number of studs. The number of lines of studs is also shown.

The unstudded tire gave a friction coefficient at 22-23°F of 0.12, about 20 percent greater than the best NSC tire. The tires used were 5.90 × 15 India rubber tires with 104 bars which were rather more transverse than the NSC tires. Wheel load was 430 pounds and tire pressure was 20.6 psi. Stud arrangement was as follows:

Number of Studs	Number of Studs in Each Line							
52	26							26
104	52							52
156	52	26					26	52
260	52	26	26	26	26	26	26	52

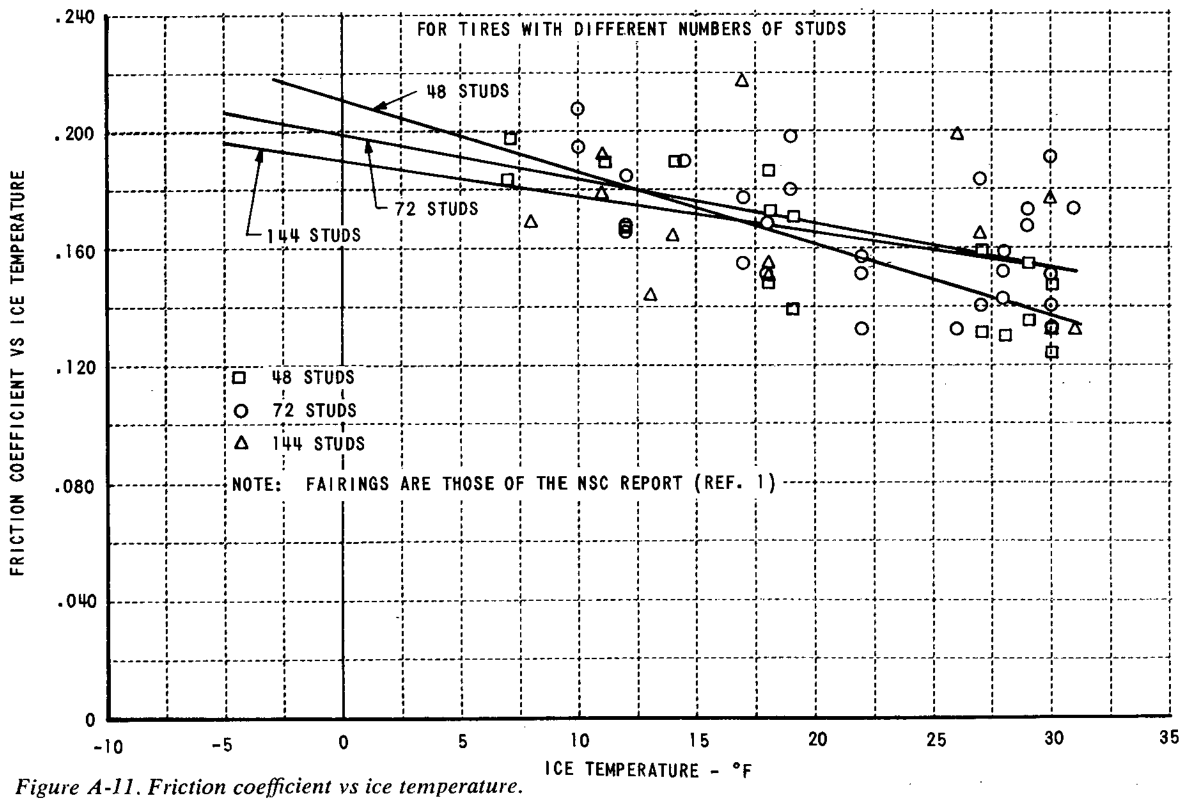


Figure A-11. Friction coefficient vs ice temperature.

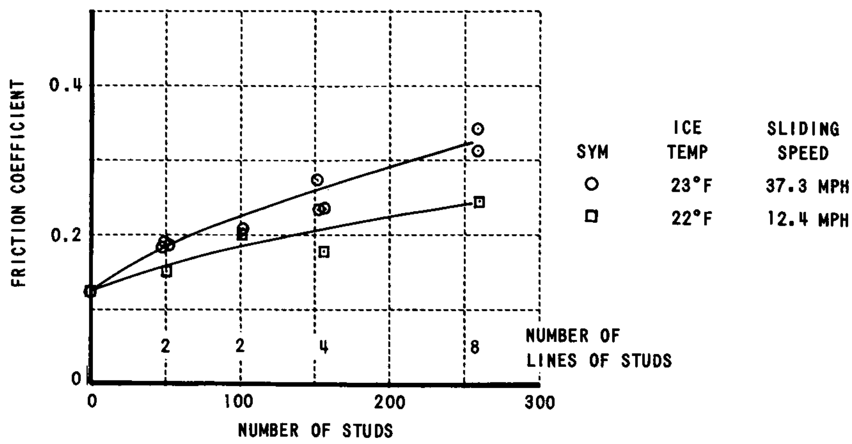


Figure A-12. Effect of number of studs and sliding speed on effective friction coefficient on ice.

There is some scatter in the data but the following trends are clear:

1. Stud resistance coefficient is a function of sliding speed, being greater at higher speeds.
2. Installation of 52 studs gives increments of resistance coefficient of about 0.032 and 0.062 at 12.4 mph and 37.3 mph, respectively. These compare with about 0.060 for the NSC data at 20 mph.
3. Doubling the number of studs in a line does not give a commensurate increase in resistance coefficient.
4. Increasing stud numbers by adding lines appears to be effective in increasing resistance coefficient.
5. At a steady sliding speed of 12.4 mph (probably most comparable with a locked wheel stop from 20 mph) and a temperature of 22°F, an incremental stud resistance coefficient of about 0.108 is indicated for 216 studs as compared with 0.160 reported by the RCAF at 30°F.

(c) *Effect of stud protrusion length.* Information in the 1966 NSC report provides a clue to the high scatter for the studded tire data. It would seem reasonable that protrusion length might be an important performance variable. It is pointed out (*4*) that the range of actual stud protrusion was rather broad. The following data are taken directly from (*4*). Two series of runs were made with 72-stud tires; in one series the average protrusion was 0.029 in. and in the other 0.045 in. The results are shown in Figure A-13. With the dearth of data points, fairing is recognized as being a hazardous procedure, but what are believed to be reasonable lines have been drawn. The incremental stud resistance coefficients have been plotted for two ice temperatures (20° and 30°) as a function of average protrusion length at the bottom of this figure. The differences between minimum and maximum average protrusions in the table could account for significant differences in stud resistance coefficient. In addition, the general belief is that a "running-in" process of perhaps 50 miles is needed to securely seat the studs. Participants in the 1966 tests report (*17*) that, in general, the studded tires were not run-in. Hence, there are further questions on the stability of the measured protrusions. The suggestion in (*4*) that much of the scatter in the data may be accounted for by uncontrolled stud protrusion is certainly plausible on the basis of the previous discussion and Figure A-13.

TABLE A-2

RANGE OF STUD PROTRUSION (AVERAGE PER TIRE)

	STUD PROTRUSION (IN.)	
TIRE TYPE	MAX.	MIN.
48 Studs, new	0.049	0.037
48 Studs, used	0.033	0.019
72 Studs, new	0.046	0.024
72 Studs, used	0.041	0.022
144 Studs, new	0.050	0.024
144 Studs, used	0.040	0.028
88 Porcelain studs, new	0.071	0.058

(d) *Effect of wear.* In considering stud wear, it is important to take into account the effect of wear of the tires themselves. While the 1966 NSC tests included used studded tires, the report does not include all of the data necessary for a valid analysis of the effects of wear. Friction trailer data are presented for the used studded tire, but data for a used tire without studs are not. Hence, the only conclusion that can be made is that the used combination is not as effective as the new combination; tire and stud effects cannot be separated. The 1965 program included used tires (less studs) from which it is possible to derive quantitative information, although the 1965 program suffered from the too limited data on too many configurations (brands) of tires. Available data are shown in Figure A-14. The data have been manipulated to obtain stud increments as described before. While it does indeed appear that stud effectiveness is diminished with wear, the assignment of quantified values is difficult. It should be noted that the

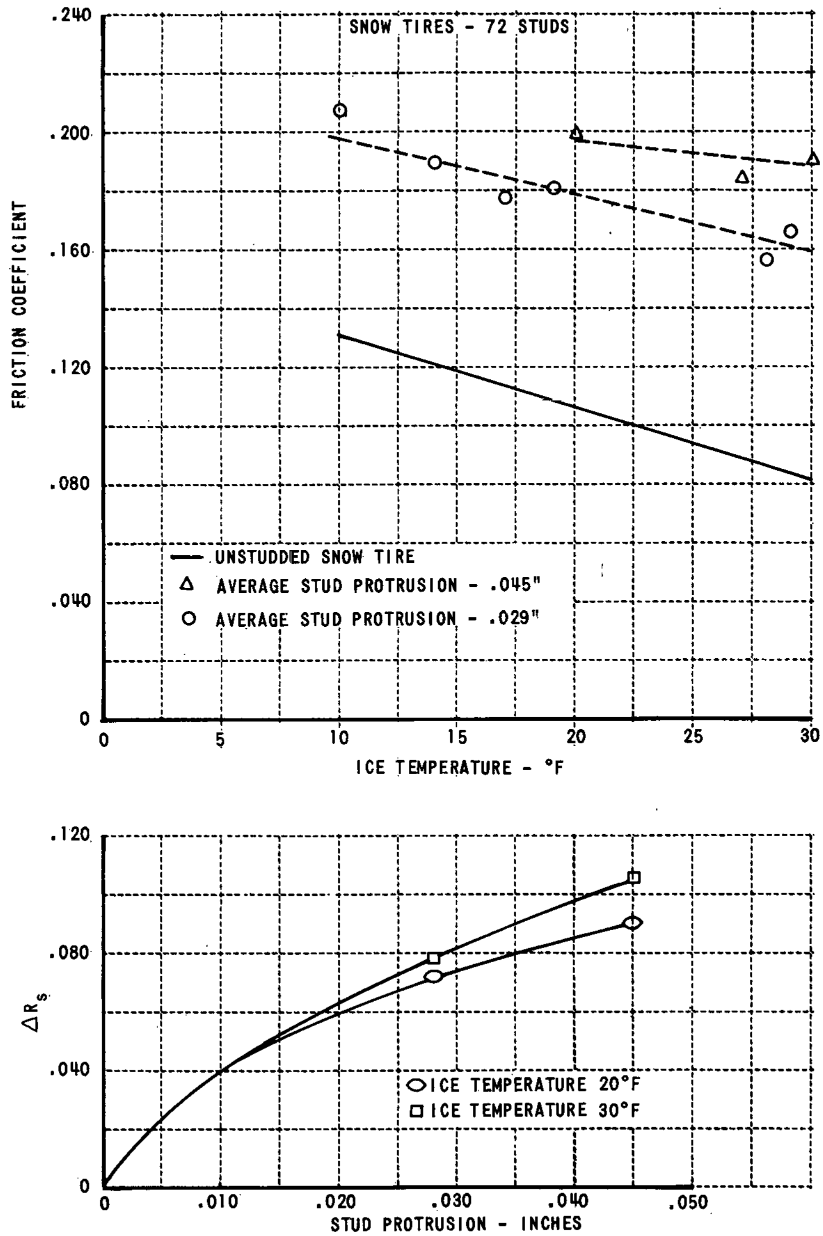


Figure A-13. Effect of stud protrusion length.

effectiveness of the snow tires themselves is reduced with wear so that all of the losses cannot be charged to the studs. The procedure discussed (*5*) where the same tires are used to investigate the effect of the number of studs (as well as no studs) by removing studs and retesting the same tires is attractive. This procedure would be especially desirable in evaluating worn tires (studded and unstudded).

In addition to the problems of protrusion control previously discussed, stud wear considerations are obscured by the qualitativeness of the term wear. A worn or used tire has been described as one which has been 5,000 miles. In order to rigorously pin down the effects of wear, either wear must be defined in terms of the physical configuration of the tire and studs or significant samples of "worn tires" and test data must be taken to define wear on a statistical basis.

While no performance data were taken, data on stud and tire wear were taken on the RCAF program. A vehicle was equipped with four studded tires and driven almost 5,300 miles, mainly on dry highways. Studs were removed from each stud line of six stud lines around the tire at intervals of 500 to 1,000 miles. Stud lengths and tread depth were measured with the results as shown in Figure A-15. It will be noted that on the front wheels the tire and stud wear were about the same so that there would be little protrusion change. On the rear wheels the tire wear was greater so that it would be expected that the stud protrusion would actually increase during this period. (*5*) and further communication with the RCAF indicate that this is not the case, as the stud protrusion was observed to remain essentially constant. This could only occur if the studs worked themselves further into the tire. Clearly additional study of the effects of wear are needed, however the RCAF data would not suggest a reduction in effectiveness of the studs unless there was a significant change in the shape of the tips of the studs.

(e) *New York State skid test results.* Locked wheel skid trailer tests were performed by the New York State Department of Public Works (*9*) at a speed of 30 mph. 7.75 × 14 snow tires loaded to 1,000 pounds were used without studs and with 67 tungsten carbide studs. The results obtained were simply tabulated in the reference with relatively little information given on such details as data repeatability, data reduction procedures, ice condition, etc. The following data were presented:

	Coefficient of Friction	
Ice	Snow Tire	Studded Snow Tire
Below 20°F	0.21	0.29
Above 30°F	0.10	0.14

The snow tires used were of conventional tread design. Examining the friction coefficients of the basic snow tires, the coefficient of 0.10 at temperatures above 30°F is more than 20 percent greater than the highest of the tires reported by the NSC and shown in Figure A-7. The test description "below 20°F" is too general to permit a good comparison with the NSC data; even at 0°F, however, the value of 0.21 is at least 25 percent greater than that of the best tire shown in Figure A-7. The increments of resistance coefficient due to the studs of 0.08 at below 20° and 0.04 at above 30° are a minimum of 35 percent greater and 45 percent less than the correlated NSC data of Figure A-9. For these reasons a low confidence level must be attached to the results of the New York State braking performance on ice evaluations.

(f) *Braking on packed snow.* For purposes of studded tire performance studies, it appears that the important characteristics of clear smooth glare ice are reasonably well defined by these adjectives plus a knowledge of its temperature (perhaps "unfrosted" should be added). As suggested in an earlier section, operation in snow is more analogous to off-road locomotion and an adequate definition of packed or compacted snow requires consideration of its structural and mechanical properties. The possibility does exist of using qualitative descriptions of the packed snow and obtaining only comparative data between tires (studded and unstudded). Since the passage of a wheel over packed snow will result in further packing, with a consequent change in its properties, such comparative tests must be done on different surfaces. This latter requirement implies that the different surfaces must be identical; since the tamping or packing is done by some mechanical means, it would be expected that it might be difficult to insure homogeneity over the areas needed for this type of study. These considerations would lead one to suspect problems in repeatability in data taken on packed snow. Indeed, this has been the case.

The NSC Winter Program of 1965 (*3*) included limited tests on packed snow. General problems with the consistency of the packed snow led to such nonrepeatabilities

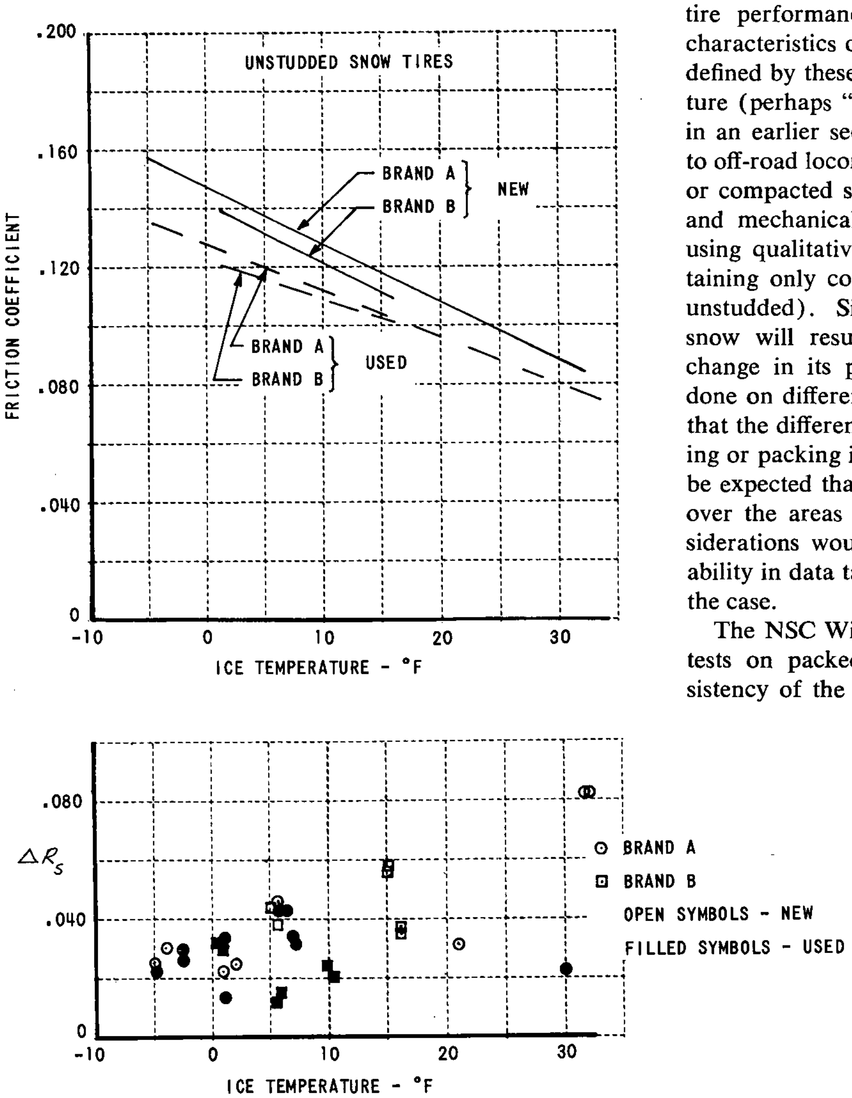


Figure A-14. Friction coefficient vs ice temperature—new and used tires.

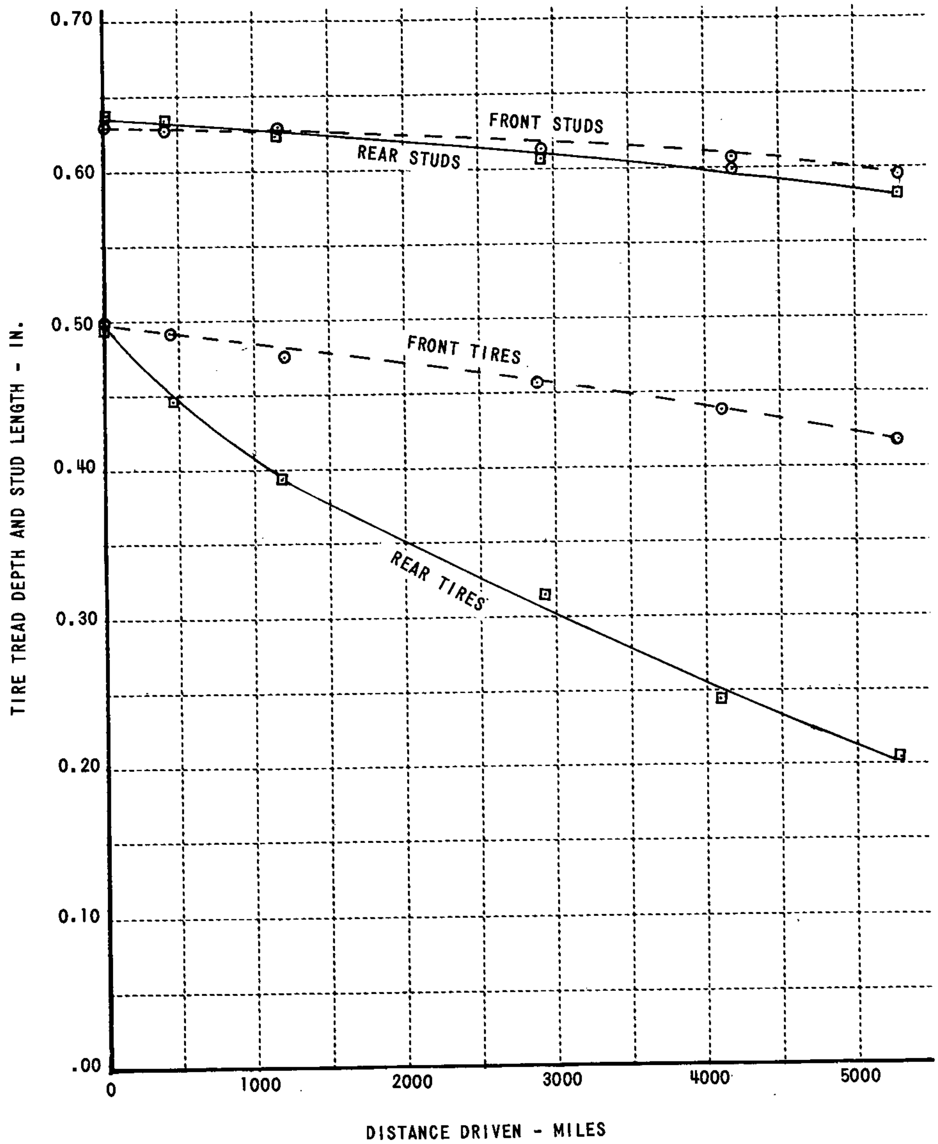


Figure A-15. Tire and stud wear vs distance driven.

that no conclusions could be drawn. Thus, there are no useful data from this source.

The National Swedish Road Research Institute, as a part of the program previously discussed, reports measurements on compacted snow. The tires and studs as used on a skid trailer were as previously discussed. Results are shown in Figure A-16 at sliding speeds of 12.4 and 37.3 mph. These and other data not shown here tend to show less consistency and more scatter than the ice data. At the higher sliding speeds, a steady increase of effective friction coefficient up to the maximum number of studs (260) is shown. At the lower sliding speed, a decrease is indicated above 156 studs. It is the present authors' belief that not too much confidence should be placed in either the very high values at 37.3 mph or the very low value at 12.4 mph in view of the experimental problems this type of investigation presents.

New York State made measurements of the braking performance of tires on packed snow using the tires and procedures previously discussed. Little information is given on the packed snow—how it was packed, its physical properties, etc., except to state that it was packed. It was further noted that the 1,000-pound wheel load on the skid trailer was sufficient to cause the rubber blocks of the snow tire treads to dig in. Notwithstanding the uncertainties as to the conditions of the tests and the questionable results of the ice tests previously discussed, there is such a dearth of data on stud performance on packed snow that the New York State results are of interest. The "average coefficients of friction" on packed snow for the snow tires and the studded snow tires were reported as 0.35 and 0.38, respectively, or an increase of 9 percent with the studded tires.

The only other performance data taken on packed snow were presented by the RCAF. As these are traction data, they will be discussed in connection with the other traction results.

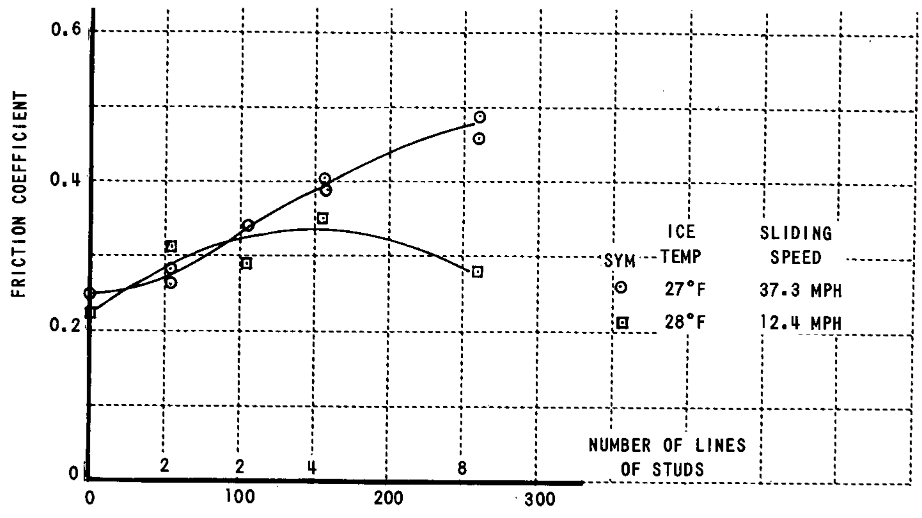


Figure A-16. Effects of number of studs and sliding speed on effective friction coefficient on compacted snow.

(g) *Braking on bare pavement.* In most parts of even the northern part of the United States, studded tires will be operating on bare pavement a large part of the time. Thus, an evaluation of tire studs as enhancements to safe vehicle operation must take into account their performance on bare roads.

Studded tire braking tests on bare roads were conducted by the Tennessee Highway Research Group with the results presented in (*4*). Snow tires without studs and with 72 or 144 tungsten carbide studs were mounted in turn on the rear wheels of a stationwagon for stopping distance tests and on the test wheel of the Group's skid trailer, described in (*15*), for measurement of locked wheel friction coefficients.

Both stopping distance and skid trailer tests were performed on two bituminous pavements, the first of which had relatively high skid resistance and the other somewhat less. Skid trailer tests were performed at 20, 30, 40 and 50 mph in most cases. The results in (*4*) have been summarized and are given in Table A-3. As no consistency with speed was indicated, the values given are averages over the speed range.

These results generally indicate that on dry pavement the presence of studs does increase stopping distance slightly. Since only the rear tires are studded and since more braking is accomplished by the front wheels, it would be expected that with studs the friction coefficients would show a greater difference than the stopping distances; the actual results are inconsistent in this respect but the numbers are quite small in all cases (less than 5 percent). On wet pavements, the vehicle and skid trailer results are in disagreement; that is, greater vehicle stopping distances were measured while the measured friction coefficients were greater. Once again the effects are quite small with actual changes indicated to be no more than 3.5 percent.

While details of the test procedures employed are not

TABLE A-3

INCREASE IN STOPPING DISTANCE OR DECREASE IN FRICTION COEFFICIENT OVER UNSTUDDED TIRE VALUES

	STOPPING DISTANCE		FRICTION COEFFICIENT	
PAVEMENT	72 STUDS (%)	144 STUDS (%)	72 STUDS (%)	144 STUDS (%)
Bituminous #1, Dry	+0.5	+5.1	+2.5	+0.9
Bituminous #1, Wet	+1.0	+1.2	+1.6	−2.8
Bituminous #2, Dry	−0.4	+3.3	+2.4	+4.0
Bituminous #2, Wet	+0.3	+1.5	+0.1	−5.8
Portland Cement, Wet	—	—	−2.6	−1.8
Average, Dry	+0.1	+4.2	+2.4	+2.4
Average, Wet	+0.6	+2.4	−1.7	−3.5

included in (*4*), the Tennessee highway research group has previously reported braking test procedures in (*15*). It is clear from this report that the group is highly competent and employs excellent research procedures. For this reason, a high degree of confidence must be placed in these data.

The New York State program previously discussed included locked wheel braking tests on new and old bituminous and concrete pavements in both wet and dry conditions. The results are summarized in Table A-4.

Noting that an increase in friction coefficient implies a shorter stopping distance, in no case did the studs reduce stopping distance; indeed, on wet surfaces a consistent improvement of friction coefficient or a reduction of stopping distance of 3 to 4 percent was found.

The RCAF studies included stopping distance measurements on bare pavement. Instrumentation, tires and techniques employed were as described previously. Locked-wheel stopping distances from 20 mph with all four wheels studded were as given in Table A-5.

Burke and McKenzie (*10*) of the Illinois Highway group have made vehicle stopping distance measurements with vehicles equipped with studded tires. While data were taken with studded tires on the rear only and with studded tires on both the front and rear, runs were not made (or reported) with the comparable unstudded tires. Hence, the Illinois data are not useful for the present purposes.

Considering all of the useful bare pavement data, braking performance will be affected by the kind of pavement (whether it is wet or dry) and the number of studs. The results are summarized in Table A-6.

2. TRACTIVE PERFORMANCE

The RCAF studded tire evaluation discussed under braking performance included traction investigations. An instrumented drawbar was used to measure the tractive force of a rear wheel drive vehicle equipped with studded and unstudded tires. At the outset of the tests the tires were fitted with 366 studs. Forty runs were made with each stud configuration. Power was slowly applied to the vehicle and readings were taken the instant the tires started spinning. Following completion of each block of runs, studs were systematically removed and another set of runs made. The results (*5*) are given in Table A-7.

The number of studs in the various lines are as indicated below for one-half of the tire, line 1 being farthest from the centerline. Studs were located symmetrically on the other half of the tire.

Line / Test	1	2	3	4	5	6
1	36	36	36	36	18	18
2	36	36	18	36	18	18
3	36	36	18	36	18	—
4	36	36	18	18	18	—
5	36	36	18	18	—	—
6	36	18	18	18	—	—
7	18	18	18	18	—	—
8	18	18	18	—	—	—
9	18	18	—	—	—	—
10	—	—	—	—	—	—

The rear axle weight for these tests was 2,165 pounds. This weight was used to calculate incremental effective resistance coefficients, ΔR_s. In going from one test to the next, 36 studs (18 per side) were removed. In some instances, the number of studs in a row is reduced from 36 to 18 and in others from 18 to 0. The decrements of ΔR_s were calculated for each reduction and separate average

TABLE A-4

STUDDED SNOW TIRE INCREASE IN FRICTION COEFFICIENTS OVER UNSTUDDED SNOW TIRES

AVERAGE FRICTION COEFFICIENT			
TYPE	SNOW TIRE	STUDDED SNOW TIRE *	INCREASE IN COEFFICIENT DUE TO STUDS (%)
Old Concrete, Dry	.70	.71	1.4
Old Concrete, Wet	.29	.30	3.3
New Concrete, Dry	.71	.71	0
New Concrete, Wet	.52	.54	3.8
Old Bituminous, Dry	.67	.68	1.5
Old Bituminous, Wet	.29	.30	3.3
New Bituminous, Dry	.69	.70	1.4
New Bituminous, Wet	.56	.58	3.6

* 67 Tungsten carbide studs.

TABLE A-5

EFFECTIVE FRICTION COEFFICIENT IN BRAKING ON DRY PAVEMENT—RCAF TESTS

PAVEMENT	UNSTUDDED SNOW TIRES	STUDDED * SNOW TIRES	% DECREASE
Dry Asphalt	0.69	0.63	8.7
Dry Concrete	0.68	0.64	5.9

* 216 studs per tire.

TABLE A-6

SUMMARY OF BARE PAVEMENT BRAKING DATA

NUMBER OF STUDS	MINIMUM AND MAXIMUM INCREASES IN STOPPED DISTANCE (%)
67	−3.8 to 0
72	−0.4 to +1.0
144	+1.2 to +5.1
216	+5.9 to +8.7

values obtained in going from 36 to 18, and from 18 to 0 studs per line. These averages were used to determine the curve at the top of Figure A-17 which is a plot of ΔR_s against the number of studs in a single line. From this variation, the separate effects of the number of studs and the number of lines can be determined with the results plotted at the bottom of Figure A-17. It was assumed that a minimum of 12 studs would be used in each line to ensure that at least one stud was in the contact patch at all times; additional studs were then added in such a way as to maintain equal numbers of studs in each line. It may be seen that best effectiveness is obtained by maximizing the number of lines within the constraint that some minimum number, believed to be about 12, should be maintained in each line.

Another form of traction test made by the RCAF involved accelerations from rolling starts (10 mph). Tests were made with the same tires previously discussed (216 studs) at a temperature of 30°F. The vehicle speed was stabilized at 10 mph and then the throttle opened wide with the acceleration measured. The vehicle had an automatic transmission and was in the "drive" range. Dry pavement tests showed that the vehicle was capable of accelerating at 6.0 ft/sec² or about 0.19 g.

Tests on ice gave accelerations of 0.056 g with the snow tires and 0.118 g with the studded tires. The vehicle was ballasted to give an equal weight distribution on all four wheels. Since the vehicle was a rear wheel drive but was required to accelerate the entire vehicle mass, these values must be doubled to obtain the effective friction coefficients. The coefficients are, therefore, 0.112 and 0.236.

It is of interest to compare the effective friction coefficients of these tires in the three different operating modes, all with 216 studs.

Operating Mode	Effective Friction Coeff. Snow Tires	Effective Friction Coeff. Studded Snow Tires	Stud Resistance Coefficients ΔR_s	Stud Resistance Coefficients $\Delta R_s/N$
Locked Wheel Braking	0.090	0.250	.160	7.4×10^{-4}
Accel. for 10 mph	0.112	0.236	.124	5.7×10^{-4}
Traction at Rest	0.123	0.208	.085	3.9×10^{-4}

The locked wheel braking and the acceleration data were taken at 30°F while the traction data were taken at 0°F with the snow tires and at 8°F with the studded snow tires.

Only qualitative comparisons of these data are possible because of the differences in temperature and slip ratios. The differences between the braking and traction values for the snow tires are about what would be expected from consideration of the temperature differences. The values of ΔR_s are greater than the NSC data plotted in Figure A-9. However, the values of $\Delta R_s/N$ compare quite favorably with the NSC values of 9.1×10^{-4} at 30°F and 4.6×10^{-4} at 4°F.

3. CORNERING PERFORMANCE

The only data that have been reported as this report is published are those from an exploratory program conducted concurrently with the 1966 Winter Driving Hazards program by Cornell Aeronautical Laboratory (*7*). Tests were made on ice by driving a vehicle around a 200-foot radius circle gradually increasing the speed. On-board lateral accelerometers were used to measure lateral acceleration. Skid breakaway was determined from the acceleration traces and breakaway speed used as a performance measure. Unfortunately, the CAL test data were few in number, temperature varied widely, and the results did not appear to be consistent. Consequently, the data were not considered useful for the present purposes.

Because cornering performance is a very important aspect of studded tire effectiveness, and in lieu of reliable test data, a simple analysis was made to estimate the possible cornering effectiveness from braking performance data. The important assumptions in this analysis were as follows:

1. The friction circle concept (*18*) is applicable; that is, it is assumed that the maximum force that the tire will develop by virtue of its friction coefficient or stud effectiveness coefficient is independent of the direction in which the tire is moving.

2. The car is moving at constant speed on a constant radius circle.

3. There is no traction on the rear wheels—they are freely rolling.

4. The friction and stud resistance coefficients obtained from the NSC friction trailer braking data will be applicable to cornering characteristics and are in keeping with assumption No. 1.

As a result of assumption No. 1, it follows that steer and slip angles, cornering stiffness, alignment torques, etc., of the tires do not enter the calculations and breakaway speeds can be calculated directly from the effective coefficient of the front or rear tires, whichever is lower.

The key assumption is No. 4. The braking effectiveness data were obtained with locked wheels or at 100 percent slip. In the cornering case, the wheels are not locked although there will be slip within the contact patch. The evidence is that the adhesion losses of unstudded tires will not be significantly affected by the sliding speed; hence, use of the braking data for the unstudded tires is believed to be justified. For the studded tires, however, the applicability of braking data is on considerably less secure ground. There is evidence that there are momentum exchange phenomena present which would be quite different between locked wheel braking and cornering (and presumably less favorable in the cornering case). On the other hand, in cornering, and particularly with the start of a skid, the direction of motion is not in the plane of a tire but the tire will be at a slip angle. Thus, studs which follow in the tracks of one ahead in the braking case may not do so in cornering, which should enhance the cornering properties.

Recognizing that the assumptions are on tenuous grounds, calculations were made, first for a car with highway tread tires on the front and snow tread tires on the rear,

TABLE A-7

RCAF STUDDED TIRE TRACTION RESULTS

TEST NO.	NO. OF STUDS	NO. OF LINES	ICE TEMP. °F	DRAWBAR PULL—LBS.
1	366	12	22	725
2	324	12	23	685
3	288	10	24	590
4	252	10	1	525
5	216	8	3	452
6	180	8	6	422
7	144	8	6	400
8	108	6	7	397
9	72	4	7	325
10	0	0	0	268

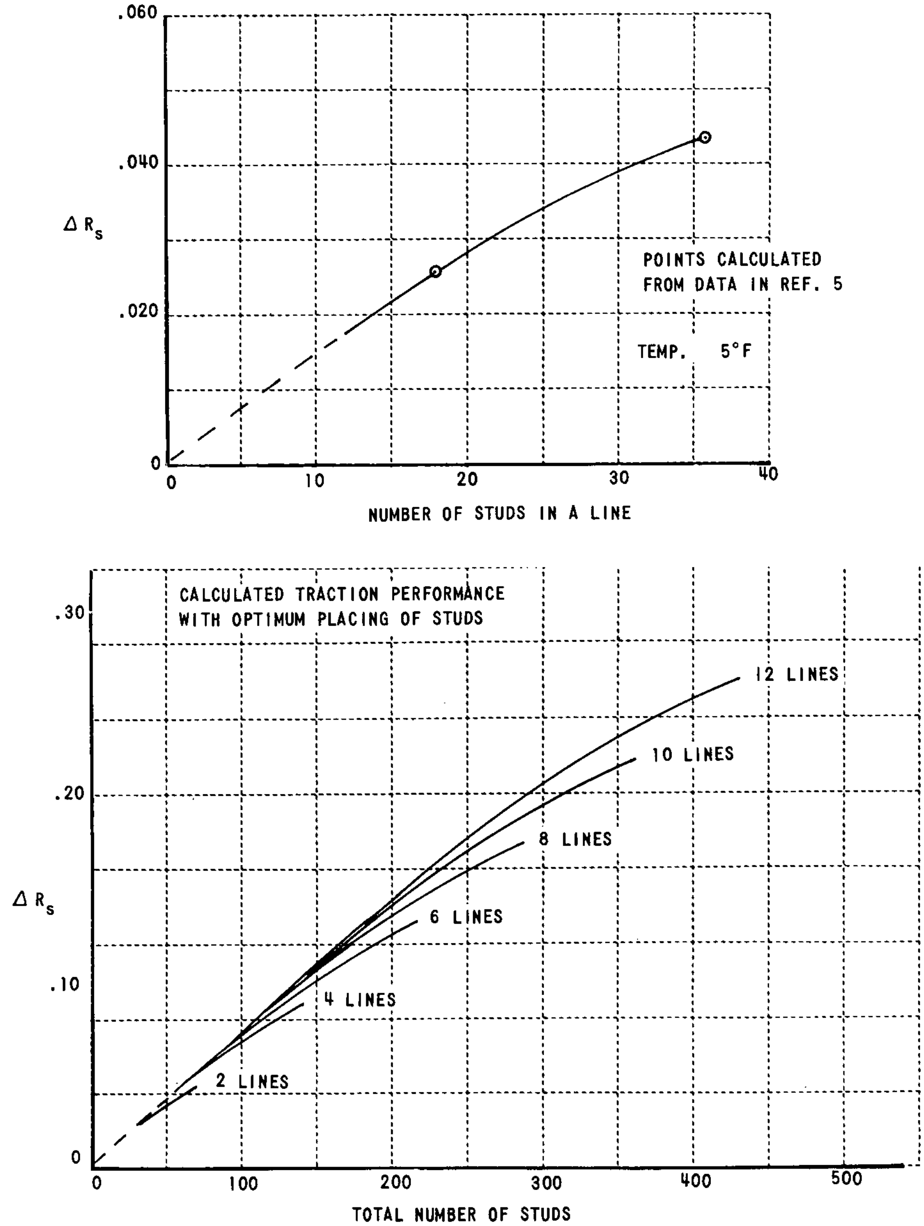


Figure A-17. RCAF traction on ice results.

and then for a car with both the front and rear tires equipped with studs. For the reference (unstudded) case, since the 1966 standard highway tread tires of Figure 6 have a lower friction coefficient on ice than the 1966 standard snow tires of Figure 7, breakaway will first occur at the front wheels. Addition of studs to all four tires * increases the breakaway speed as shown in Figure A-18, although breakaway will still take place first at the front end. This figure indicates that a significant performance gain is possible on glare ice with front and rear studded tires. For example, at an ice temperature of 30°, a car with unstudded tires in rounding a corner at 30 mph might negotiate that same corner at 40 mph without skidding. Clearly, additional experiments are needed to place cornering performance on a firm basis.

* Addition of studs to only the rear tires will not affect the breakaway speeds, since breakaway occurs at the front. On cars that breakaway at the rear end first, addition of studs to rear tires will increase cornering performance only until the critical friction is reached on the front end.

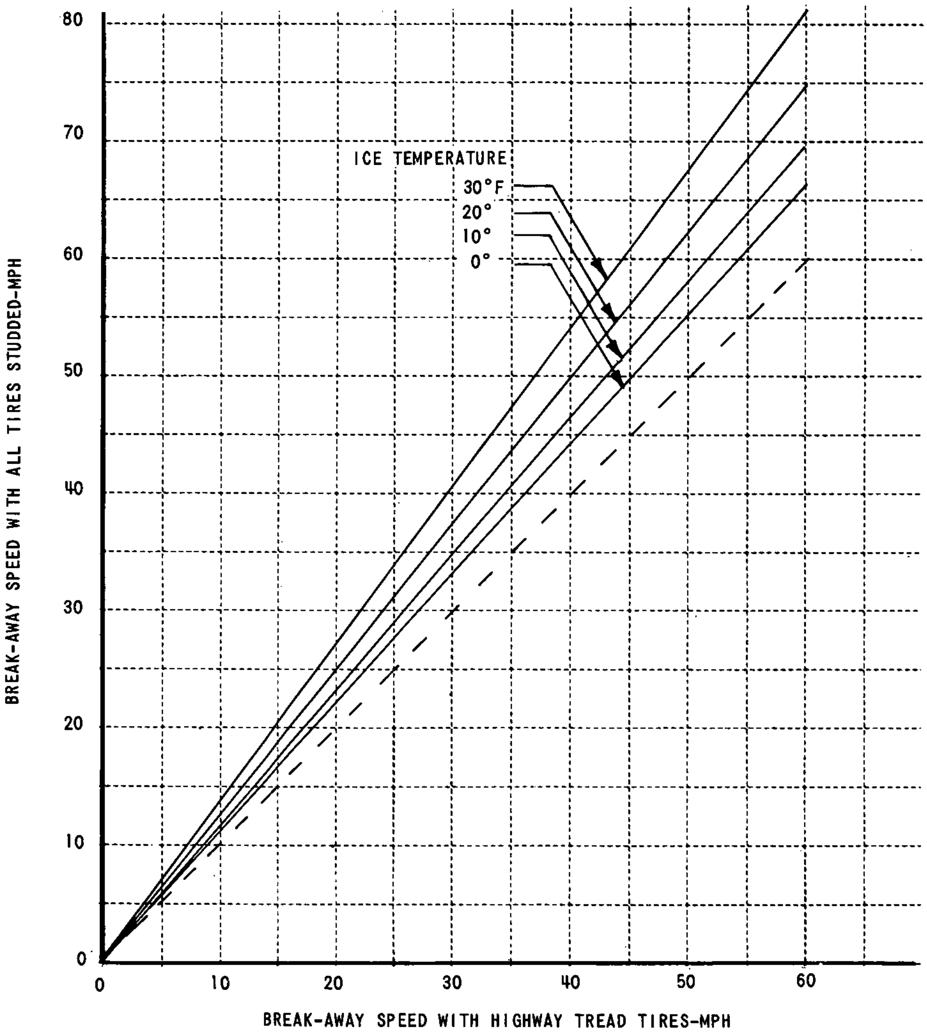


Figure A-18. Cornering effectiveness of studded tires on ice calculated from friction trailer braking data.

APPENDIX B

METHODS FOR ASSESSING PAVEMENT WEAR

The objective of this part of the project was to recommend methods of quantitative assessment of the difference in pavement wear of studded tires versus unstudded tires. This objective has been accomplished; findings are presented in the following sections and in Appendices C, D, E, and F.

TEST VARIABLES

A primary task was the identification of the elements of the damage process. These are listed in Table B-1. A discussion of their estimated importance, their interrelation, and the tests recommended for their investigation, is presented in Chapter Four.

LITERATURE REVIEW

Pilot Studies

Table B-2 lists the results of eight studies of pavement damage due to studded tires. All eight studies were preliminary and incomplete—most of them were made under pressure of time, so that some information on damage would be available on which to base recommendations to legislatures or plans for future comprehensive test programs. As a consequence, none of the individual reports could draw definitive conclusions as to the amount of pavement damage to be expected on the roads of their states. A further consequence of the preliminary nature of these studies is that the methods of damage observation and the type of test data recorded vary widely. In general, not enough potentially important test parameters were measured or recorded—hence, comparison of test results is difficult.

The major benefit to the current study of these pilot investigations is their indication of important test parameters and of certain difficulties in obtaining wear data. Therefore, we find it useful to discuss the tabulated data in terms of test parameters, rather than in terms of reported road wear as follows:

1. Test sites. The sites selected varied from straight highway sections that were open to general traffic during the tests, to proving grounds and parking lots. A drawback common to all eight investigations is that they provided information on damage to very few pavements. Variations of wear with pavement composition, its surface preparation and age were not obtained.

2. Contact mode. The pavement sections observed were contacted either in straight rolling, in cornering (that is, involving side slip), and in various degrees of acceleration or deceleration. Important differences were noted for complete skid (that is, locked wheels), spinning wheels, or various slip conditions. The contact modes were called "panic" stop, "abrupt" stop, "normal" start, etc. These descriptors are not entirely subjective, in that the speed at the beginning or end of the maneuver was specified. Significant differences in wear depth as a function of slip were indicated in those studies in which, say, panic stop and abrupt stop results could be compared. Therefore, it is concluded that specification and measurement of acceleration (deceleration) and slip are desirable in such tests.

3. Speed. Test speeds in rolling contact at the beginning or end of acceleration and deceleration varied from 10 to 55 mph. The indications from these preliminary tests are that speed in itself is not as important a variable in scratch depth as one might expect. Speed is, of course, an important factor in determining the length of skid marks. Nearly all studies recorded some test speed; in more comprehensive tests, one would want to know the speed over the test section in which scratch depth is measured.

4. Number of passes. The number of passes over the observed section is, of course, an important variable and was recorded in every one of the studies. They varied from 25 to 21,320. The former value is definitely too low. The important result is wear depth as a function of the number of passes, and it was in the measurement of wear depth at frequent intervals that the tests were deficient.

5. Mileage. If the track length and the number of passes are known, this may no longer be an independent test variable. However, in many cases, the test cars were also used on other occasions, so that total mileage of stud

TABLE B-1

ELEMENTS IN PAVEMENT WEAR BY STUDDED TIRES

Pavement
Composition
Age
Coatings
Finish
Load
Axle Load
Speed
Acceleration
Deceleration
Tires
Inflation Pressure
Type (Snow or Regular)
Age
Studs
Material
Protrusion
Shape and Orientation
Number/Tire
Environment
Temperature
Water
Salt

TABLE B-2
SUMMARY OF PILOT TESTS ON PAVEMENT WEAR

TEST SITE AND PAVEMENT	CONTACT MODE	SPEED MI/HR	NUMBER OF PASSES	MILEAGE	VEHICLE	TIRES	NUMBER OF STUDS	STUD PROTRUSION IN.	TIRE PRESSURE LBS/IN^2	TEMP. °F	WET (W) OR DRY (D)	METHOD OF WEAR OBSERVATION	WEAR DEPTH IN.	REF. NO.	REMARKS
CLOSED NEW ROAD STRAIGHT, ½ MI.LONG	NORMAL STOP NORMAL START PANIC STOP PANIC START	FROM 30 TO 30 FROM 30 TO 30	310 310 310 310	5000	SEDAN	STUDDED REG. F. STUDDED SNOW R.	70	REDUCED BY .03 DURING TESTS	32	+60 TO -10	D	VISUAL WITH STRAIGHT EDGE	X	25	LOSS OF FINISH AND FINE AGGREGATE
SAME	NORMAL STOP NORMAL START CONSTANT SPEED	30 30 50	5387	X	SEDAN	STUDDED REG. F. STUDDED SNOW R.	80 103	X	32	+40 TO -10	X	REFERENCE MARKER + 21" STRAIGHT EDGE + DEPTH GAGE 1" INTERVAL	PORTLAND CONCRETE .004-.013 AVERAGE BIT. CONCRETE .025-.061 AVG.	26	FRONT TIRES REPLACED AFTER 2600 PASSES: REAR TIRES AFTER 4700 PASSES. ROAD OBSERVATIONS INDICATE LESS DAMAGE THAN PREDICTED BY THESE TESTS.
VARIOUS PAVEMENTS	STATIC SPIN	20	27		¾TON TRUCK								.1-.2 (TYP)	27	SPIN TEST BY LOWERING SPINNING WHEEL INTO CONTACT: COMPARISON BETWEEN CHAIN AND STUDDED TIRE.
PARKING LOT	FIGURE "8" CORNERING	10-15	10,660; 21,320 AT CROSSOVER	295	1,740 LBS REAR A 1,300 LBS FRONT A .	REG. RIGHT F & R STUDDED SNOW LEFT F & R	X	X	X	X	W & D	X	.25 CROSSOVER 1.5 LEFT .05 RIGHT	27	SEVERE STUD LOSS FROM INNER ROWS.
LOOP PROVING GROUND	CONSTANT SPEED NORMAL AND RAPID STARTS AND STOPS	25	625	X	SEDAN	STUDDED SNOW (4)	52 105	.04 INCREASE AT END OF TEST	X	X	X	VISUAL PHOTOGRAPHY: PLASTER CAST: REFERENCE MARKERS + STRAIGHT EDGE + DIAL INDICATOR	.04	10	
TWO HIGH-WAY LOOPS OPEN TO TRAFFIC PC PC AND BC	CONSTANT SPEED	40 55	10,000 10,000	10,000 15,000	TRUCK, 23,000 LBS 7,000 F: 16,000 R SEDAN	STUDDED SNOW (4) STUDDED SNOW (4)	110 110			12-65 18-67	4" RAIN 2" SNOW 4" RAIN 4" SNOW	REFERENCE MARKERS + 30" STRAIGHT EDGE + DEPTH GAGE ½" INTERVAL	.07 AVERAGE OF MAX. FOR ALL TESTS	28	NOTED 77% STUD LOSS IN ONE TEST SOME LOSS OF REFERENCE MARKERS
300 FT NEW HIGH-WAY (CLOSED)	PANIC STOP ABRUPT STOP	20 MAX 4990	1,400 4,990	X	SEDAN, 2800 LBS	2 STUDDED SNOW R 2 STUDDED REG. F 4 STUDDED SNOW	50-132	0-.12 NEW (.04-.06 MANDATORY)	30	X	X	REFERENCE MARKER DEPTH GAGE 1" INTERVAL	.05 B.C. .015 P.C. .012 AVG. P.C. .026 AVG. B.C.	29	WEAR OF LARGE AGGREGATE AND DECREASE IN SKID RESISTANCE NOTED COUNT OF PANIC STOPS AT AN INTERSECTION, 1% OF VEHICLES
PC AND BC	SKID	UNIFORM --	25 --	X X	CARGO TRUCK ½TON AND TRACTOR	X	216 196	3/32 OUTER ROW 1/32 INNER ROW (INITIAL)	30	X	D	X	1/64 - 1/8 1/64 - 1/4	5	
BC AND PC OLD	SKID	30	100	X	SKID TRAILER	STUDDED SNOW	70	X	X	X	W & D	VISUAL	1/16 ON B.C. "SHALLOW" ON PC	9	

NOTES: ASTERISKS DENOTE INFORMATION NOT AVAILABLE
BC = BITUMINOUS CONCRETE
PC = PORTLAND CEMENT CONCRETE

and tire wear may be an independent variable. The extent to which the mileage on the tire influences wear as a function of number of passes did not become clear, although there were indications that this is an important test variable.

6. Vehicle. The make of the vehicle was specified in each case and vehicle nominal weights were also stated or could be readily ascertained. However, actual vehicle weight and axle load (or load per wheel) should be known if the relation between stud pressure and pavement damage is to be derived. An increase in wear with vehicle weight was found in German studies (*31*), which are discussed in detail in the second part of this section, and which indicated that scratch depth is directly proportional to stud pressure.

7. Tires. In most tests, the make and type of tire (whether conventional or snow, etc.) was described. On the basis of the test results, it is believed that for pavement damage assessment, this is a secondary variable, less important than contact pressure, stud protrusion, or details of stud insertion.

8. Stud material. In all the tests, tungsten carbide was the stud material, presumably carbide grade No. II though not stated implicitly. Since there are other carbide grades and other stud materials, investigation of this variable should be included in any future comprehensive tests.

9. Number of studs. The number of studs per tire is probably important in pavement damage, when considered along with other variables such as protrusion and contact pressure that determine the penetrating force per stud. In the tests reviewed, the number varied from 52 to 216 (the latter for truck tires), and no meaningful deductions can be made as to the importance of the number of studs in pavement damage.

10. Stud protrusion. This has been recognized as an important studded-tire-performance variable because protrusion length affects the energy absorbed by pavement or ice. The same reasoning would seem to hold for pavement, although here the cutting depth is less and, to the extent that the studs skid over coarse aggregate, as has been shown to occur in some of the reported tests and in the CAL single stud tests, protrusion length becomes irrelevant. (The CAL single stud tests discussed below and in Appendix C also provided information on the importance of stud shape and orientation relative to the pavement surface.) Table B-2 indicates that protrusion varied initially from 0.00 to 0.12 in. and remained constant or was reduced by substantial amounts (0.03 in.) during some of the tests. But not all reports contained information on stud protrusion. In view of the probable importance of protrusion to wear depth, it would be important to monitor protrusion as the tests progress, so that variation of wear rate with protrusion can be taken into account.

It should be noted here that at least one state (*29*) mandates protrusion length within limits of 0.04 and 0.06 in. On the other hand, according to tire stud industry standards to be adopted for 1967/68, protrusion lengths vary from 0.062 to 0.095 in. for passenger tires and from 0.116 to 0.150 in. for truck tires, if nominally specified tire core depths and over-all stud lengths are assumed.

11. Tire pressure. This variable was not recorded in all tests. It is, again, not an important independent variable as such. As stated earlier, the pressure exerted by the stud is the important variable, and that is a function of tire pressure, axle load, contact area, and the dynamics of the contact. However, since determination of contact area and contact dynamics would constitute a sizable separate program recording of tire pressure, size and axle load would contribute toward analysis and prediction of pavement damage.

12. Environment. Pavement temperature and its cover (water, snow, ice, oil, or dirt) can be pooled as environmental conditions. As indicated in Table B-2, these conditions were not recorded in most instances. Their control, such as that of snow, ice, and dirt, would be easily accomplished. Knowledge of pavement temperature and water, snow or ice cover would be of great help in extrapolation and comparison of results.

13. Method of damage observation. Methods of observation varied widely from visual only to depth gage traverses over a specified track width with specified measurement interval. In the latter case, the more elaborate studies employed reference markers embedded in the pavement which served as supports for the straightedge. In some cases, the reference markers were elevated above the pavement and their shifting led to loss of confidence in (or discard of) some of the wear measurements. None of the measurements was performed in such a manner that its probable error could be estimated.

14. Wear depth. In view of the stated uncertainties about test variables, the wear depths as measured in the listed studies should not be pooled, averaged, or otherwise compared. Two of the studies contain plots of wear depth vs number of passes, which are not in agreement. One finds a linear relation, whereas the other finds a saturation effect, (wear depth diminishes and eventually ceases with increasing number of passes). Though not questioning the specific findings, generality cannot be assumed for either. These results are influenced by variables discussed earlier, such as stud protrusion and pavement condition (the hardness and composition gradients of the pavements for which the data were obtained); what is required is more information on these variables. Certainly, such wear curves, with full knowledge of the significant variables contributing to their shape, will be of great help in predicting cumulative pavement damage.

A Comprehensive Study

Following a pilot study in 1963 in which the possibility of significant pavement damage was indicated (*30*), in 1965 the German Federal Government sponsored a comprehensive investigation which was conducted by the Technical University of Berlin under the supervision of Professor B. Wehner (*31*).

The earlier work (*30*) was conducted on an especially constructed dished test ramp over which the vehicles rolled back and forth in pendulum fashion. This method was abandoned in the comprehensive tests (*31*) because vehicle velocity was low and could be varied only within narrow limits, and the vehicles tracked so well that the studs tended to follow previously cut grooves. The later tests were therefore conducted on a road test loop which was closed to other traffic.

A particularly interesting feature of Wehner's tests (both series) is the use of pavement core specimens from actual roads. In the second series, a total of 178 pavement cores representing 30 pavements of various composition were tested. The cores had a diameter of 9 in. and their smooth and secure embedment in the test course was an essential part of the test preparations.

In two test series, a total of 39,000 round trips were made by two passenger cars equipped with four studded snow tires each. In the first series, the cars were unloaded; in the second series, they were alternately loaded and unloaded. The following variables were controlled: Axle loads were measured for front and rear axles of both cars; the loads varied only over 22 percent range, however. Tires were switched and stud protrusion was measured every 600 miles, since stud protrusion tended to increase during the pavement wear tests. A protrusion of .06 to .08 in. was maintained by driving each car daily for 80 miles at constant speed on a race course. Tire pressures were maintained within close limits and stud pressure was estimated. The pavement cores were distributed over the four test locations of the loop (straight, curve, acceleration and deceleration) according to random number tables. By this method, some test conditions were replicated and systematic test errors were eliminated. The width of the tire tracks was carefully monitored, so that extrapolation of wear results to actual road traffic would be more meaningful. Wear was observed visually by means of stereoscopic photography. In addition, wear was measured at 418 points of each core specimen by means of a stylus gage which sat on three reference markers which, in turn, were embedded in rectangular concrete plates holding the specimens as seen in Figure B-1. The stylus consisted of a .6-inch-diameter wheel which traversed the core in two lateral directions. The stylus was spring loaded in the vertical direction and its final position was registered by relay on one of 50 counters. The depth interval of these relays was .008 in.

The stylus position of the instrument itself was repeatable to .002 in. within 95 percent confidence limits. The smallest wear depth interval that could be measured within 95 percent confidence limits was .010 in.

Typical results are shown in Figure B-2. Wear was increasingly severe from straight driving (at 37 mph) to cornering (300 ft radius at 25 mph), acceleration (from 5 to 10 ft/sec^2) and deceleration (from -10 to -15 ft/sec^2).

Lateral acceleration in the curve was estimated at 3.6 ft/sec^2 and, based on the ordering of wear depth with acceleration, the *(31)* estimated expected wear at curves of other radii and at inclines.

On the basis of the test loop results, the report also provides an order-of-magnitude estimate of pavement wear under traffic conditions. The estimate is made for a two-lane road of 25-ft width. The wheel track width on the test loop was 1.3 ft and typical observed wheel track width on a two-lane road was 2.0 ft. A Gaussian distribution of the passes over both widths is assumed (Fig. B-3) and, taking into consideration that the measured width of the core

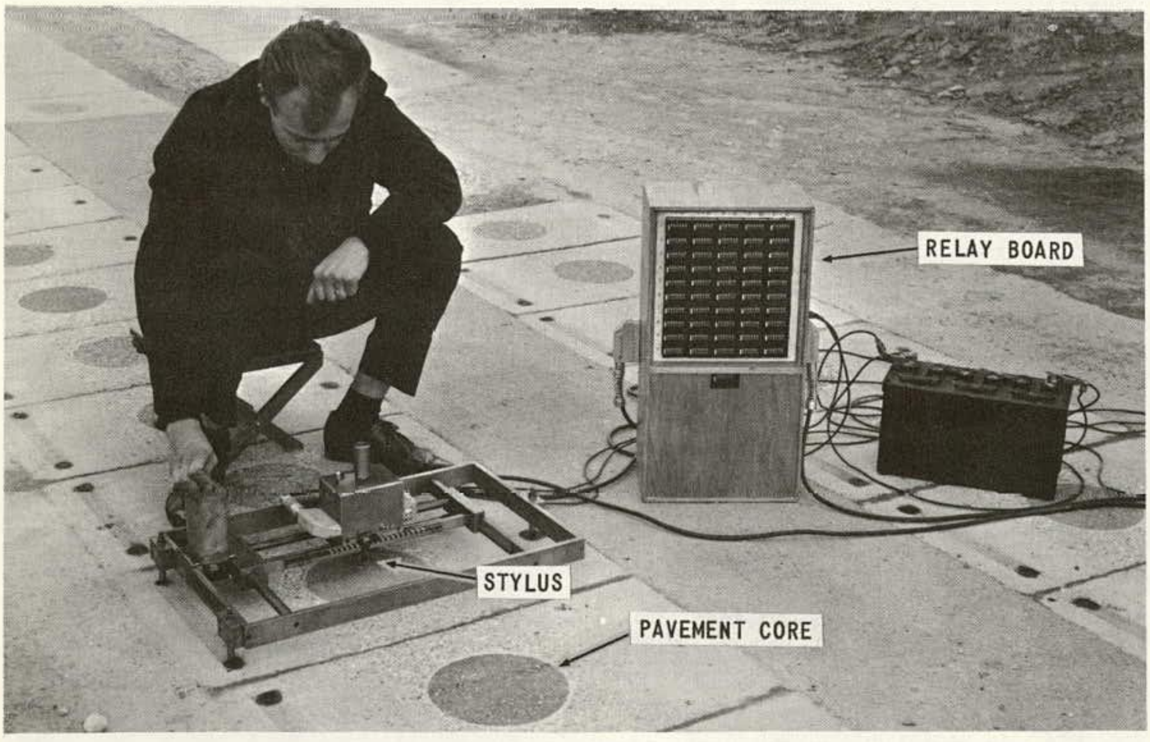


Figure B-1. Wear and roughness meter (Wehner).

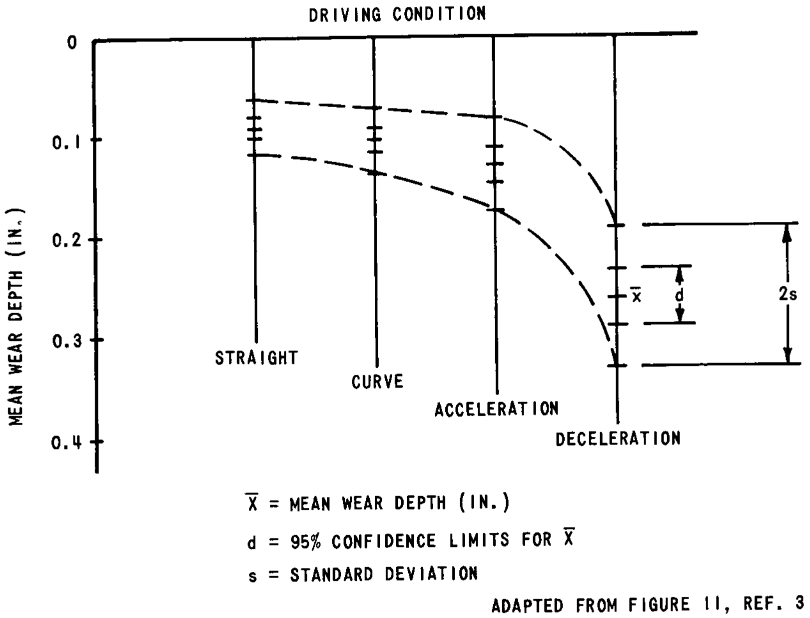


Figure B-2. Mean wear depth of all pavements after 27,000 passes with unloaded vehicles.

specimens is 0.6 ft, the proportion of the passes which will go over the 0.6-ft central part of the 1.3-ft track width is computed as 45 percent. Since, as shown in Figure B-3, on the test loop a 0.6-ft wide strip was touched by 63.2 percent of all passes, 70 passes on the test loop will cause the same wear as 63/45 (70) ≈ 100 passes on the two-lane road.

Wehner's estimates of wear depth are simplified by the assumption that trucks are not equipped with studded tires. On the basis of the proportionality between wear depth and number of passes, he provides a nomograph on which wear depth can be read for total traffic count and proportion of stud-equipped vehicles in the count for four use conditions. The use of such a nomograph is illustrated by the dotted line in Figure B-4; one enters with the known traffic count on the upper left, goes horizontally to the percentage of studded vehicles and then down to the several wear graphs.

We should note here that this estimate of road wear does not take into account vehicle weight, wet or dry conditions, panic stops, variation in stud and materials or protrusion. Nevertheless, the graph illustrates the application of test loop data that are more comprehensive than the pilot studies cited earlier.

THE CUTTING ACTION OF SINGLE STUDS

The review of the literature on pavement wear by studded tires illustrates that the amount of wear is determined by the interaction of many variables. In order to gain an understanding of the nature of this wear, it was considered instructive to study the cutting action of single studs. The main objective of this study was to determine how material is actually cut from pavement by a stud and whether there

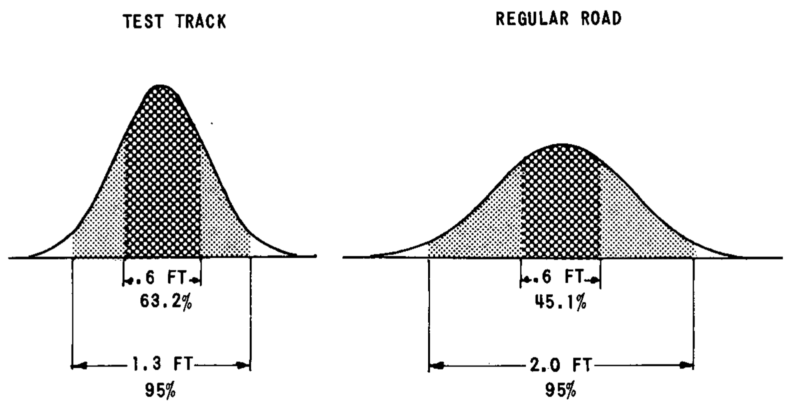


Figure B-3. Gaussian distribution of contacts.

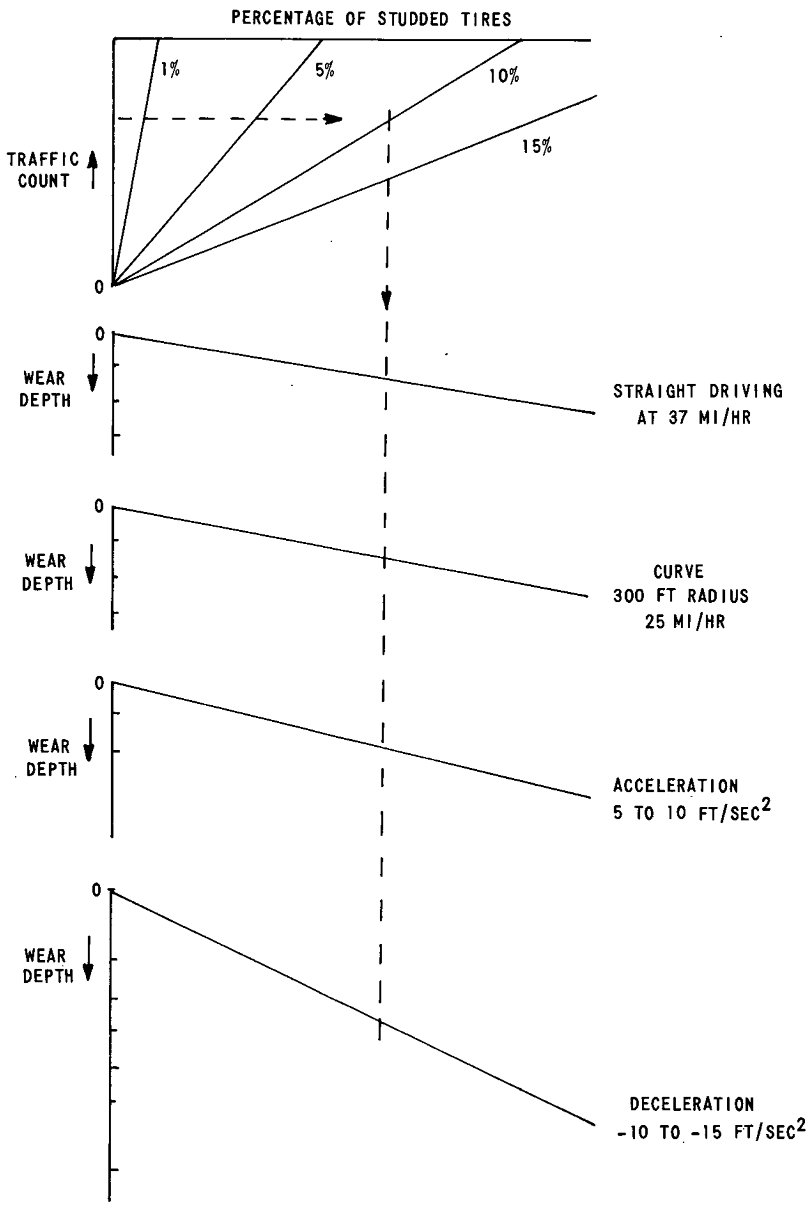


Figure B-4. Wear nomograph.

is any indication of damage beyond the immediate removal of some material.

The tests were conducted in a milling machine on which single studs were mounted in fly-cutter fashion. The setup simulated skidding of a stud on pavement at speeds of 4 and 24 mph. The studs were springloaded with forces similar to the force required to push a stud back into the tire. The pavement specimens used, the test configuration and the test variables are described in Appendix C. A photograph of five pavement cores is shown in Figure B-5; wear treads from single studs are clearly visible on the surface of four of the cores.

The most important results of the more than 50 test runs were as follows:

1. Under all conditions tried, the studs cut grooves of rectangular cross section, reproducing their projected cylindrical area; in other words, under our test conditions, there was no significant breakage of material on the sides of the groove. Close-ups of wear tracks cut in the top surfaces of 3 cores are shown in Figures B-6, B-7, and B-8.

2. The strength of the core material was high enough so that, in all cases, the studs were deflected up by a significant amount; this upward deflection took place through compression of the spring in the stud housing and through deflection of the disk and of the milling machine spindle. Typically, the studs cut the groove three times at the low speed, and 20 times at the high speed setting; even when many more contacts were made, the studs were still riding

Figure B-5. Pavement cores.

the grooves when the machine was shut off—there was no indication of the spark-out that occurs in grinding.

3. The material removed from the pavement by the studs was clearly observable as a fine dust, indicating brittle failure.

4. For a 0.030-in. machine setting, the maximum depth of the grooves varied from 0.010 to 0.025 in. The ranking of the cores according to depth of cut is:

Soft concrete—top surface	Greatest depth
Bituminous concrete	↓
Hard concrete—top surface	
Soft concrete—bottom	
Hard concrete—bottom	Least depth

This ranking is based on pooling and averaging of measurements for several cuts and on measurements at several lines across a groove.

5. The grooves in the top surfaces were deeper than those in the bottom surfaces of the same cores, as shown in the ranking of groove depths above. This variation is believed to be due to a combination of two causes: (a) the top surfaces contain finer and softer aggregate that is more readily cut, and (b) the top surfaces were rougher than the bottom surfaces (which were saw cut); the surface roughness would contribute toward generating impact failure of individual particles, rather than failure under steady-state load.

6. The grooves, particularly of bottom surfaces, indicate that the studs tend to skid over hard aggregate.

7. No significant difference in groove depth cut by the three stud materials was found for the test conditions. (It must be emphasized here that this finding is limited to experiments and cannot be generalized to the cutting action of any tire studs on any pavement under any condition of acceleration, slip, or velocity.)

8. No significant change in groove shape or depth was observed when two cores (one hard, one soft portland cement) were immersed in salt water for 24 hours, frozen at 0°F for 12 hours, and then cut after drying and attaining room temperature. Again, this was only a rather brief and simple experiment aimed at detecting gross differences in pavement failure due to secondary damage.

9. The magnitude of the spring force did not make a significant difference in groove depth, within the test range. In evaluating this finding, it must be remembered that there was also elastic deformation in the rotating disk and in the spindle bearing; the magnitude of this "residual spring force" was not measured.

10. A dark discoloration was noted, in varying intensity and uniformity, on stud surfaces and in the grooves. The discoloration, which looks like a smeared deposit, is noticeable on the studs as soon as the zinc or cadmium coating is removed by diamond dressing, grinding or road wear. The discoloration was noticed much less when a stud was ground and positioned so as to have a 15° clearance angle on its bottom surface; the discoloration was pronounced

when the stud was reversed, so as to drag on the groove bottom with a clearance angle of − 15° as shown in Figure B-9.

Because of limitations of project funds and since this phenomenon was not clearly related to the magnitude of pavement damage, it was not investigated further to see, for instance, whether a chemical reaction product forms that would give a clue as to the temperature on the sliding interface. However, further investigation of this problem may be of interest to the stud manufacturers because it could guide optimization of stud materials.

Another finding noted on examination of Figure B-9 is

Figure B-6. Wear tracks in bituminous concrete.

Figure B-7. Wear tracks in soft P. C. concrete.

the appearance of many transverse lines across the grooves cut with the high drag force (negative clearance angle). It is not possible to distinguish clearly between voids in the concrete opened by the cut and the opening of hairline tensile cracks. It is noteworthy, however, that these lines were found to be most numerous in the grooves cut with the highest drag force. Project time and funds did not permit further exploration of this phenomenon, but we recommend its separate investigation under the general heading of secondary damage.

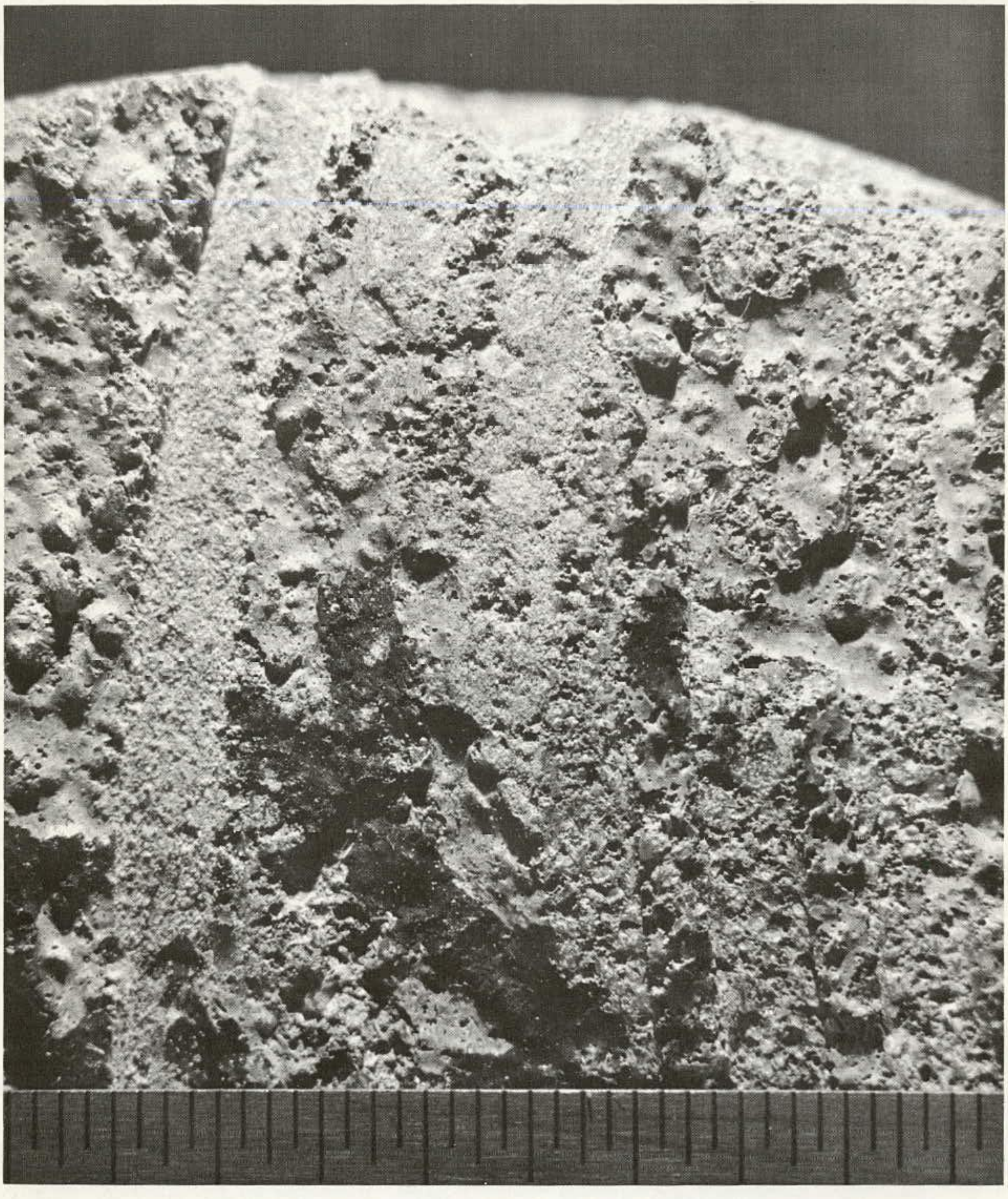


Figure B-8. Wear tracks in hard P. C. concrete.

WEAR AND ROUGHNESS DETERMINATION

The development of appropriate methods for measuring wear and roughness of pavement was the primary task of the project. Determination of wear expressed as the thickness of material removed from a given pavement measured in a traffic area during a winter season is, of course, information required by the highway official to determine the need for repair and it is essential in cost effectiveness studies on the use of studded tires. Since it was a foregone conclusion that gross observation of suspected wear areas over long time periods is not the best way to assess road damage, it was also recognized that very accurate wear measurements were required which permit measuring small wear in brief tests, the results of which can be extrapolated to prolonged exposure conditions. Roughness measurements are important also, because in the early stages of wear, the difference between initial and worn pavement roughness is the only indication of the total wear to be expected over long time periods. Further, roughness measurement may be

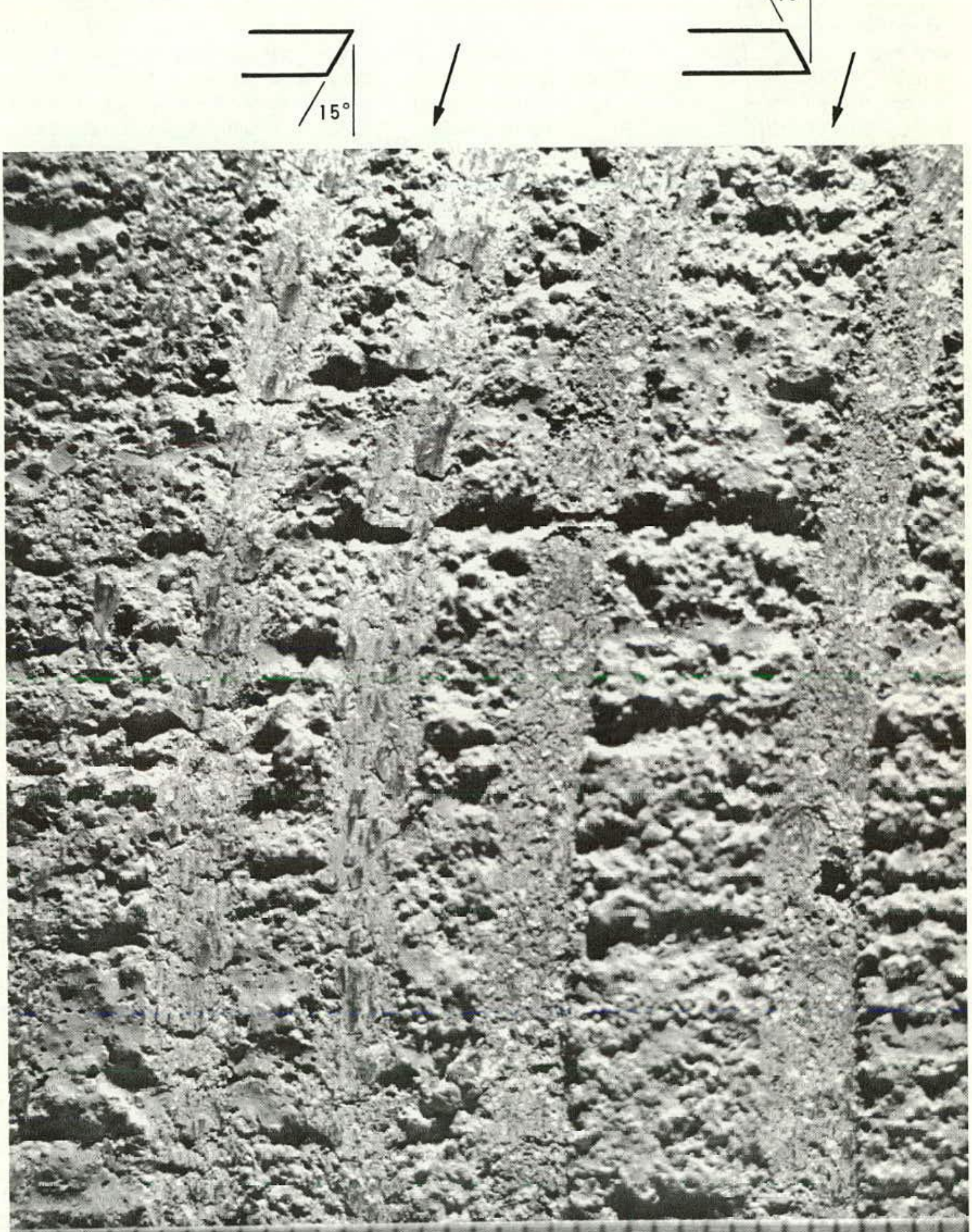


Figure B-9. Wear tracks by studs with various clearance angles.

an important input to determine skid resistance changes due to studded tire action.

The literature survey indicated that very few applicable methods of wear measurement were available; most of the methods found were for roughness determination only. On the basis of the survey, it was concluded that a special instrument was needed capable of accurately measuring wear and roughness of pavement. Therefore, such an instrument was designed and a breadboard model was constructed. Roughness and wear measurements demonstrated the appropriateness of the design. Also, for gross monitoring of suspected wear areas, simpler methods for determining wear only were conceived.

The following discussion presents the results of a literature survey on wear and roughness, and describes a wear and roughness meter designed by CAL as well as outlining ideas for monitoring gross wear. Appendix D introduces wear and roughness terminology, describes a breadboard model of the wear and roughness meter, gives tests performed to demonstrate its capabilities, and presents conclusions as to the specification for a final model of the instrument.

Literature Survey

The methods of wear and roughness measurement are divided into four categories: depth gauges, instruments based on depth gauges, the outflow meter, and photogrammetry.

1. Depth gauges. Several of the pilot studies previously discussed measured wear by depth gauges, dial indicators, scales, or feeler gauges applied from a straightedge resting on reference markers in the pavement (*10, 26, 28, 29*). In others of these pilot studies, the straightedge was applied directly to the pavement, so that only roughness was measured.

The terms "mean wear depth" and "roughness mean height" are defined in Appendix D. In principle, one can obtain a surface profile record and, therefrom, the mean wear depth d_w and the roughness mean height R_a by such methods. They all involve making depth measurements at regular intervals across the pavement, and then drawing the profile and finding d_w and R_a. It is even possible to arrive at R_a and d_w analytically from a tabulation of the depth measurement (without drawing the profile). However, this analytical method provides no information on the distribution of the roughness peaks or the worn pavement portions.

The equipment cost of this method is the lowest of all those discussed. The main cost item is common to all methods that include wear measurement—properly installed reference markers, as discussed earlier. Once these reference markers are installed, the expense for depth gauges and straightedges or a suitable reference frame is low. However, the operating cost is high, because this method is laborious. Also, when lengthy measurements have to be taken under adverse weather conditions, the required precision of measurement will be hard to maintain. Therefore, any of the wear and roughness determinations that are based on manual depth measurement at many stations are not recommended.

An interesting instrument developed by the Texas Transportation Institute and called "Texturemeter" can give a measure of gross surface roughness (*32*). The device senses relative variation of surface height at fifteen equally spaced points along the datum. Fifteen identical, spring-loaded, pointed plungers acquire the same height variation as the road at these fifteen points. A sliding string threaded through identically placed eye holes in each plunger takes a shape which roughly approximates the shape of the surface. The string length will increase as the relative height variation between all of the plungers becomes greater. A dial gauge measures the total increase in string length taken up by the plunger array; this reading can be correlated to slope variance along the datum. The device, in its present form, was designed to measure surface variance or texture on a comparative basis. It does not produce the mean line, or measure the mean wear depth.

Several more or less refined instruments for pavement roughness evaluation have been developed in conjunction with research on skid resistance. One of the more recent of these is the pavement profile tracer developed at Pennsylvania State University (*33*). However, none of these instruments provides a measure of wear depth.

The stylus instrument developed by Wehner (*31*), which was discussed earlier, does store data from which the required roughness and wear data, as well as a profile curve, could be extracted. The method has the advantage of having been tried successfully in a pavement wear study. The principal drawback, compared to the instrument designed by CAL, appears to be its lack of a direct profile visualization.

2. Replication methods. By these methods, the profile is merely transferred to an instrument or to the laboratory for processing. Plaster casts and film replication belong in this category. One of the pilot studies (*10*) used the former and achieved good profile rendition. Such methods are no better than the measurement method that follows. If a height gauge is used, then the method only offers convenience, because a height gauge could also be used on site. If a film replica is used, then optical roughness instruments become applicable and a gain in accuracy can be achieved. Film replicas are, of course, flexible and do not lend themselves at all to wear measurement. Plaster casts could be so used if the reference markers, or unworn pavement, are part of the cast; however, it would seem that such casts would have to be rather large. Moreover, the objection of high operating cost that was made for depth gauges still holds.

3. The outflow meter. This instrument was developed for the study of hydroplaning on wet surfaces (*34*). Its principal element is a transparent plastic, cylindrical tube, to one end of which a thin neoprene ring of square cross section is cemented. This device measures the drainage ability of the road surface under a rolling tire at the squeeze-film zone of the contact area. The measurement is made by placing the gasket end of the cylinder in contact with the road surface and filling the cylinder with water. Various weights can be attached to the cylinder to allow

measurements under different contact pressure loads. Water will drain out at a rate depending on the size of the channels and voids between the rubber and the road surface asperities. Measuring the flow rate and knowing the areal density of surface asperities and water temperature, a mean hydraulic radius (MHR), can be computed. MHR is a valid measure of the drainage ability of surfaces (*35*) and is approximately proportional to the maximum asperity height. Since the drainage rate depends on the product of the number of asperities or channels under the rubber ring and the fourth power of the total cross-sectional channel area, such drainage measurement will not determine either parameter uniquely, nor can the spacing factor or plateau area be determined from a drainage measurement.

Thus, roughness parameters depending on asperity height, asperity density, and plateau area cannot be uniquely determined by the outflow meter. To determine asperity height and plateau area, some kind of profile study must be made beforehand by means of photography or stylus measurement. The instrument is apparently well suited for surface drainage studies, but not for wear or roughness measurements. Another difficulty involves the requirement that the pavement surface be of uniform flatness and roughness; scratches and deep grooves, as may be expected for stud damage, would give inconsistent values. However, since the drainage ability of the road has a critical effect on the behavior of vehicle tires on wet roads, the outflow meter should be of value for determining the skid resistance of pavements that are worn by studded tires.

4. Photogrammetry. Photographs have been made of road sections as a means of assessing damage by the change in surface appearance. Such photography is a useful tool since it can show wear artifacts such as stud grooves and fracture pits as well as changes in road texture. Precision stereoscopic photography could, in principle, provide all of the quantitative information one would require, if accurate reference level points are clearly present in all pictures. However, a rather elaborate precision stereo-reader or plotter system would be needed to obtain depth and surface profile from a pair of stereo photographs. A precision stereo photography system capable of doing such close up work is not commercially available at this time. Commercial systems—the Zeiss SMK Stereometric Camera, for example—would require expensive modification in order to meet our requirements. As currently designed and marketed, that camera has a minimum working distance of 6 ft and, at this distance, one can resolve only 0.08 in. in depth. For our purposes, the depth resolution would have to be improved by an order of magnitude. Moreover, the plotting of surface profiles from a stereophotographic pair is tedious and requires further special equipment and operator skill and judgment.

In conjunction with skid resistance research, Sabey (*36*) refers to a photogrammetric technique that apparently would provide the necessary precision and detail; however, all the reservations stated above as to the need for wear reference marks and the laboriousness of the method would still seem to apply.

In view of these inherent characteristics of photogrammetric methods, it is concluded that it is not advisable to develop a photogrammetric instrument for road wear measurement.

Wear and Roughness Meter

The instrument designed under the current contract meets the requirements for wear and roughness determination by measuring mean wear height and mean roughness, and by providing visually a plot of the surface profile from which maximum scratch depth and distribution of peaks can be observed.

The instrument is contained in a light-tight case with an internal tripod support frame. Two of the legs are placed on recessed reference pins that straddle the wear track; one of these legs has a conical cavity, the other a V-slot, so as to accommodate expansion or contraction of the pavement reference base; the third leg rests on the pavement. Within the case, a horizontal array of identical sensing plungers is mounted with freedom to slide in the vertical plane only (Figure B-10). The plungers are pointed at the bottom; their top surfaces have a mirror finish and are inclined at 45° to the vertical axis. Light from a tubular lamp, whose housing can be moved vertically by a graduated screw, is collimated by a parabolic mirror and deflected by a small 45° mirror through a horizontal slit of width w; the light beam is then reflected by the top surfaces of the plungers toward the photo cell, which is as long as the stack of plungers, has a width $10w$ and is inclined at a 5.7° angle to the vertical. This inclination serves to magnify the width of the collimated beam from the plunger by a factor of ten.

When the plunger bottoms contact a flat plate with a smooth surface, the light from the illuminator is projected by the plunger tops as a parallel band with smooth edges on the photocell. When the plungers contact a rough surface, the light pattern at the photocell reproduces the surface profile with a vertical magnification of ten. A 45° mirror projects the light scattered horizontally by a translucent screen which is coated onto the photocell so that the profile can be viewed directly from the top by an observer.

The photocell is attached to the lamp housing, so that when the collimated light source (lamp, parabolic mirror, small deflecting mirror, and slit) is moved vertically, the optical path remains constant. When the plungers contact a flat plate that is in contact with the legs of the instrument the collimator can be moved vertically until the light beam just covers the width of the photocell. A maximum meter reading is obtained when the contacting plate is smooth. When the contacting plate is rough, the maximum meter reading is less and the difference between the two maxima is the roughness mean height of the second plate. The meter dial can be ruled so as to read roughness R_a directly to the nearest 0.001 inch.

Wear height d_w is read on the counter actuated by the micrometer screw that is moving the collimator housing. The instrument is first rested with its legs on the reference markers of an unworn pavement; its spring-loaded plungers will contact the pavement; next, the collimator is adjusted in height until the roughness meter indicates a maximum.

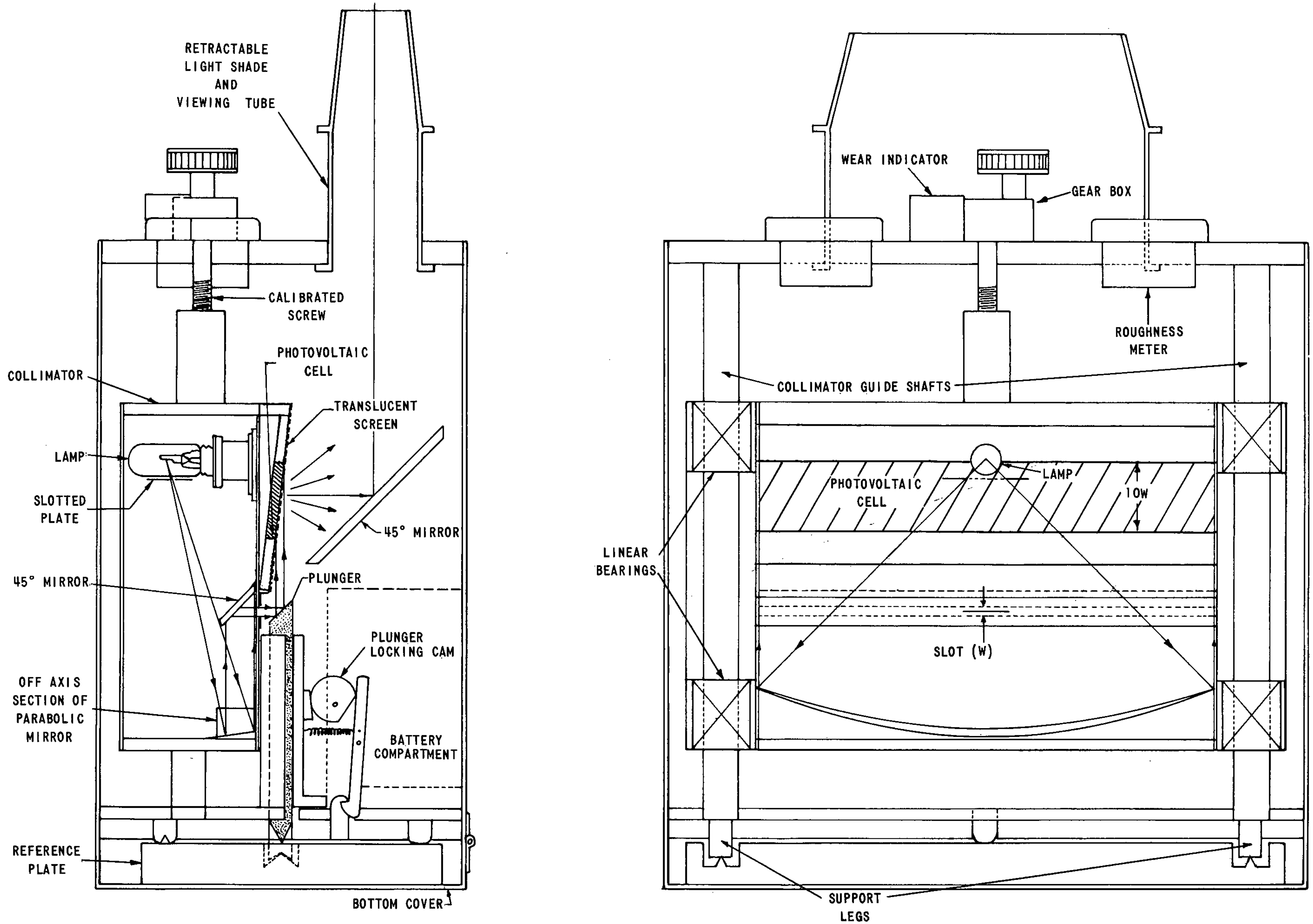


Figure B-10. Wear and roughness meter schematic.

Now the counter is set to zero (or its reading noted). When the same pavement is worn, a maximum roughness meter reading can again be obtained. The difference in counter settings is an indication of wear height; the counter can also be made so as to read directly to the nearest 0.001 inch.

Method of Total Wear Measurement

Consideration has been given to two relatively simple schemes whereby total road wear, from any selected time onward, may be measured. The merit of these schemes would reside in their simplicity of installation and operation. They are not recommended as substitutes for the meter previously described, which provides more information. However, they may complement the meter in monitoring road wear.

Figure B-11 shows a method requiring a prepositioned reference index set similar to that required for the road wear and roughness meter. It can be seen that this technique converts a volume measure to an area by the expedient of squeezing a predetermined volume of soft material between the roadway and a reference plate. It can be seen that, as the roadway wears, the geometry is such as to cause a lesser squeezing of the fixed volume of measurement material when pressed by the reference plate. Shown in the drawing are two postulated imprints taken before and after wear. The difference in areas should correlate with total wear which has occurred between these two readings.

The second method lends itself to interpretation of total wear in the field without the need for instruments. Figure B-12 shows one such method of a family of many. Depicted is a pattern of variable depth holes drilled in a section of pavement upon which it is desired to determine future total wear. Hole depths are staggered with a depth difference depending upon resolution desired in wear determination. Holes are flat bottomed and filled with different colored road material to prevent edge collapse and to facilitate reading. Once such a pattern is placed, a reading involves a simple count to determine the number of remaining holes. The implacement of the hole pattern will require precise, but simple, equipment and its advantage resides in the ease of readout.

RECOMMENDED TESTS

The objective was to determine the test methods most suitable for measuring the extent of pavement wear attributable to studded tires and for comparing it with damage due to other causes such as vehicles with tire chains. The fact alone that wear due to studded tires must be isolated and compared with wear from other causes rules out an open-road section as the test location. A further disadvantage of open-road tests would be that the variables listed in Table B-1 could not be controlled; in particular, such tests would have to be restricted to very few variations of pavement composition and age. Once the effect of the various variables on pavement wear is known, it is possible to predict cumulative damage to actual roads based on estimates of the magnitude and frequency of occurrence of the test variables (see Appendix E). Then, open-road tests or measurement of wear after a specified number of general traffic passes can be used to test the applicability of the field test results to local traffic conditions.

The argument that many road materials should be tested also applies to a closed test loop. We recommend the method employed by Wehner (*30, 31*); that is, to bring the road to the test course, in the form of pavement core specimens.

While it is beyond the scope of the present program to consider test techniques in detail, consideration should be given to using skid trailers either in place of, or in conjunction with, cars. The possible advantages of using a properly designed skid trailer center around both the convenience and the excellent parameter control and measurement prospects. For example, it seems likely that the tire slip ratio (and/or angle) are fundamental highway wear parameters. Whereas the slip is difficult to control with a vehicle, it could readily be measured and controlled with a skid trailer.

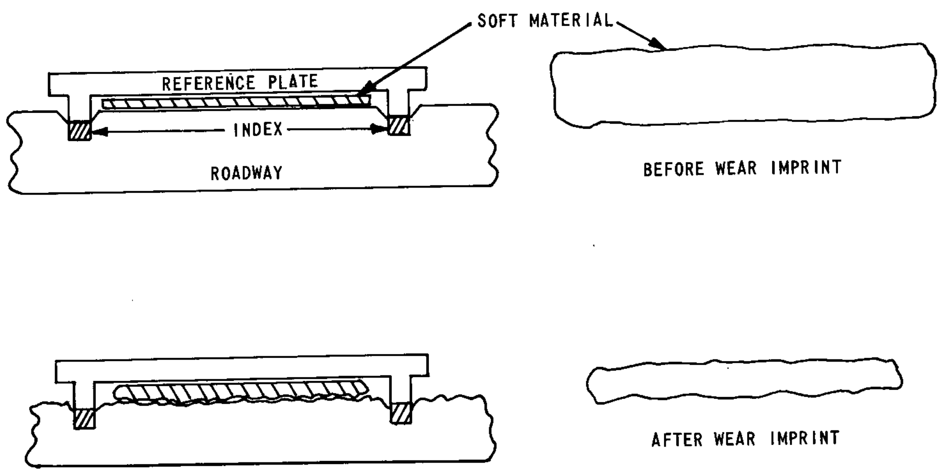


Figure B-11. Total wear measurement.

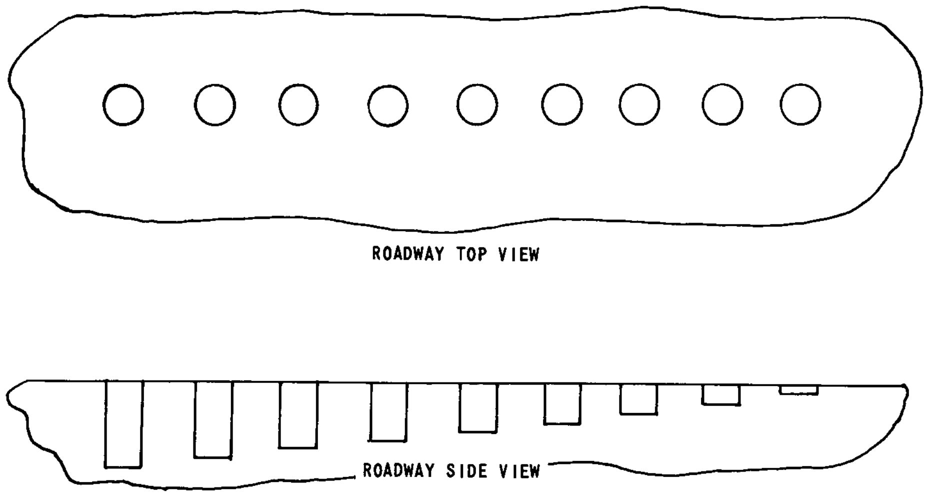


Figure B-12. Total wear measurement.

Field tests might also be conducted with special rigs such as a wheel mounted on a radial arm riding over a circular track. But this technique is not recommended because it would make extrapolation of results to open-road situations more difficult. It is, however, recommended that accelerated wear tests run on a special test rig precede closed loop tests.

Accelerated Test Rig

The accelerated test rig recommended is attractive for a number of reasons: (1) convenience (located indoors); (2) ability to control and measure test variables; (3) economy, and (4) reference or control pavement compositions can be developed which will permit rapid evaluation of future changes in variables such as new stud materials.

In the recommended tire test rig, the steel rim of the conventional drum is replaced by concrete segments, as shown in Figure B-13. A hydraulic actuator brings the tire in contact with the drive wheel after the desired test speed has been attained and then controls the contact pressure. A brake can lock the driven wheel or produce any desired amount of slip. Both wheel spindles are equipped with tachometers (not shown). The drum is wider than the tire and lateral movement is provided for the latter, so that wear grooves can be distributed across the pavement, and starting and running conditions can be identified for measurement. The CAL wear and roughness meter can be adapted for use on the rig by extending two radial arms from the wheel which serve as reference pins.

Since test rig masses and loads will be different from those encountered in vehicles, care must be exercised in simulating deceleration. The following relations can be used to scale results:

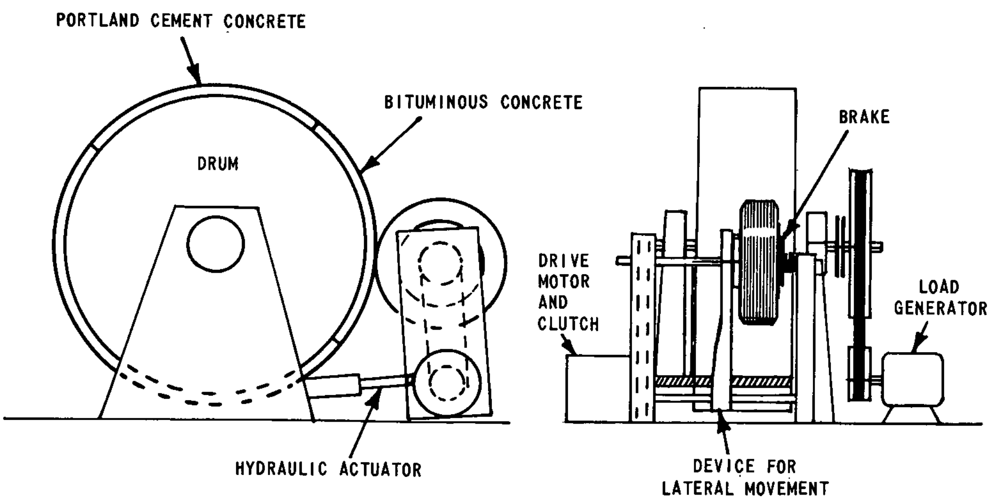


Figure B-13. Accelerated test rig.

deceleration for vehicle:

$$a_v = \mu g \quad \text{(B-1)}$$

deceleration for test rig:

$$a_t = \mu \frac{R^2 N}{I} \quad \text{(B-2)}$$

in which

μ = Coefficient of friction (kinetic)
g = Acceleration of gravity
R = Radius of the drum
N = Normal force (force between tire and test wheel perpendicular to the interaction surfaces)
I = Moment of inertia of the drum

In addition to its capabilities for the accelerated tests to be described, the rig will also provide a valuable reference basis. The portland cement and the bituminous concrete mix used for the rig should be specified as a fine mix that can readily be reproduced (or better yet, a large number of test segments are produced initially). The fine aggregate has the advantage of producing a uniform wear pattern that can easily be measured. After field tests are completed and standards are set, newly marketed stud materials, new tire designs and other variables such as stud shape or protrusion can easily be tested and classified by comparison with wear measured with standard studs and tires in previous tests.

Field Test Loop

A level test loop with minimum dimensions such as those shown in Figure B-14 is recommended. This test course should be in a region with winter climate. The design is based on the loop used by Wehner, but omits his mildly curved section (300-ft radius). The curved section produced wear that was intermediate between that in the straight-away and the acceleration section. Such wear information is also obtainable by knowing relative slip, as discussed earlier.

Three test stations are recommended: A for constant speed, B for acceleration, C for deceleration. At each section, there are a minimum of 10 test cores per wheel track mounted as shown in Figure B-15. Each 10-in. diameter pavement core is cemented with its top flush in a 30 × 18-in. concrete plate. The plates are aligned in the wheel tracks of the test loop and are cemented in carefully prepared road beds. They are aligned in two rows that are separated by the track width of a passenger car.

The number of offset parallel tracks is not prescribed here because it depends on the over-all size of the planned experiment, which in turn depends on the number of pavement materials to be tested and other factors beyond the scope of this report. However, it is recommended that an early determination be made of the maximum number of cores to be used in a test series and then install them all in place, in two or more parallel tracks for reasons of economy.

All three test sections should be covered by a roof in order to control environmental factors. Station A should, in addition, be provided with infrared radiation heaters, so that the pavement temperature can be raised to 140°F. This station should also be used for observing the effect of repeated freezing and salting on wear.

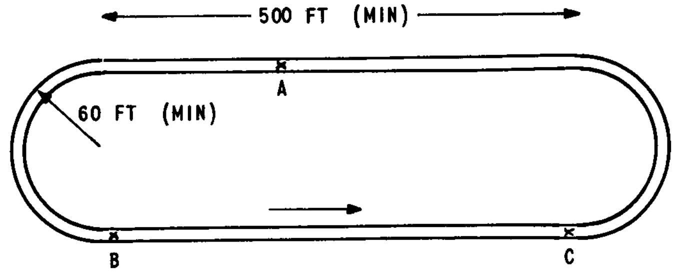


Figure B-14.

It should be noted that the field tests are, in a sense, also accelerated because wear will take place faster than on normal roads. Moreover, information on wear can be obtained more rapidly than on roads, due to the accuracy of the wear measurement made possible by the meter and the reference markers—which will permit meaningful wear measurements after comparatively few vehicle passes.

Test Variables

It is instructive now to discuss what is currently known about the variability and range of the test variables, and what must be determined by test. Further, we are now in a position to recommend the test method; that is whether "accelerated" (in the wheel test rig) or "field test" over the test loop. In Table B-3, the variables from Table B-1 are re-listed with the recommended test method and then each variable is discussed. Note that the list has been expanded to include traction aids, because the wear tests must provide a basis for comparisons between wear due to studded tires and other causes.

1. Pavement. Pavement composition is an important variable. Most of the pilot studies used two pavements; one portland cement concrete, the other bituminous concrete. Wehner (*31*) used a total of 30 different varieties of portland cement concrete, bituminous concrete and asphalt. He obtained a relative ranking of the 30 varieties in which average wear varied from 0.5 to about 1.7 of the average of the wear in all pavements. His data did not reveal any characteristic differences in wear behavior according to composition.

Our recommended approach is to use fewer than 30 pavement varieties in the field tests and to put emphasis on determining how sensitive pavement composition is to variation in the other test parameters. The two control pavement compositions used in the accelerated test rig should also be represented in the pavement cores, so that accelerated test results can be extrapolated.

Pavement age should be combined with composition as a field test variable. It will be important to know how the wear behavior of, say, a 5-year-old portland cement concrete differs from that of a new and a year-old pavement of the same composition.

Only one of the pilot studies (*26*) included sealer coats

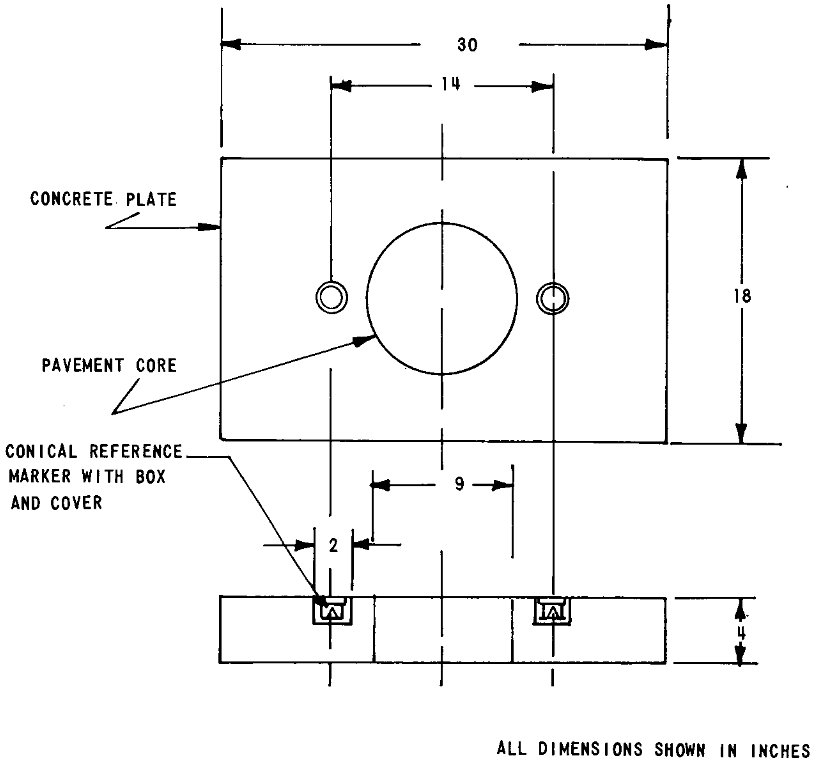


Figure B-15. Pavement insert.

TABLE B-3

TEST VARIABLES AND RECOMMENDED TEST METHOD

TEST VARIABLE	RECOMMENDED TEST ACCELERATED	FIELD TEST
Pavement		
Composition		x
Age		x
Coatings	x	
Finish	—	—
Load		
Axle Load	x	x
Speed	x	
Acceleration		x
Deceleration	x	x
Tires		
Inflation Pressure	x	
Type (Snow or Regular)	x	
Age	x	
Studs		
Material	x	
Protrusion	x	x
Shape and Orientation	x	
Number/Tire	x	
Other Traction Aids		
Tire Chains		x
Environment		
Temperature		x
Water		x
Salt		x

as a test variable and little effect due to rapid wear of the coating was found. It is recommended that such protective coats be subjected to accelerated screening tests in the indoor test rig, where their sensitivity to load and other variables could be determined inexpensively.

The original finish of the pavement has an effect on wear rate until the finish marks are removed. This effect is not significant if pavement repair is expected to be necessary only when pavement has to be replaced in some depth. If the loss of finish is of interest from the point of view of skid resistance, then frequent measurements of the mean roughness value and observation of the roughness profile in field tests of such coatings are recommended.

2. Load. Most of the pilot tests were run with passenger cars and axle loading was not recorded. The Canadian tests (*5*) included a truck and found deeper pavement scratches in their cursory tests. As was discussed in the literature review, in more comprehensive tests, Wehner (*31*) found a proportionality between axle load and wear depth. However, his range of axle load was only 22 percent and, between measuring periods, one-half of the tests were run with increased load and one-half without, for an average load increase of only 11 percent.

The actual range of axle loadings varies by an order of magnitude and it is recommended that there be accelerated tests of wear rates over that range. If, for a given material, such as the fine-grained control material recommended, wear rate can be established as a function of axle load, then field tests can be run at only, say, two axle loads which do not have to be extremely far apart. Prediction of traffic wear can then be made on the basis of number of passes and vehicle weight.

It is further recommended that, in the tests, the interdependence of axle load, tire pressure, contact area, number of studs per tire, stud protrusion and shape be recognized and its magnitude be determined. It is concluded from examination of reports and from our own tests that, as in a cutting process, the pressure of the stud on the pavement and the shape of the stud have a strong influence on the volume of pavement removed per pass (see Appendix F). Tire pressure has an influence on the magnitude of the contact pressure and its variation as a given stud touches the pavement, deflects, and becomes more or less pushed back into the tire. The importance of stud protrusion is most readily visualized for material that is much softer than the studs, say, soft ice; the more the stud protrudes, the more it will penetrate and the more ice it will remove on skidding or rolling.

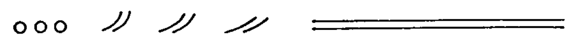
The importance of stud shape can be appreciated by comparison with the importance of tool shape in cutting processes. The single stud tests indicated that cutting action differed significantly when studs had relief angles of + 15 and − 15 degrees. Further, from observation of worn studded tires, we know that the protruding ends of studs sometimes are near hemispherical. This shape apparently comes about by softening due to high contact temperature—hence, such studs may also have somewhat different strength or ability to penetrate hard pavement. For a given length of skidding on the pavement, rounded studs do less work than cylindrical studs with square ends. More detailed analysis of the exact influence of contact geometry on pavement volume removed would be possible if preground and carefully oriented studs are used; however, in view of the lack of control of shape in actual use, and the likelihood that a given piece of pavement is passed over by studs in a random variety of shape and orientation, we recommend investigation only of studs with flat ends and studs with hemispherical ends in these tests.

3. Speed. There is no indication in the available test reports, and none was obtained in our single stud tests, that speed is an important variable in depth of pavement wear by studded tires. (The length of a skid wear track in a panic stop is, of course, proportional to the square of the velocity; however, we are concerned here with the depth of stud penetration.) The CAL single-stud skid tests were made at speeds of 5 and 25 mph. Wehner (*31*) used 25 mph and 37 mph in cornering and straight driving tests, and in the various pilot studies speeds (straight driving, start of braking or terminal speed for acceleration from standstill) ranged from 20 mph to 50 mph. Our assertion that speed is not a strong variable is also based on metal cutting experience, where it is found that cutting forces are but little affected by cutting velocity.

It is recommended that accelerated speed tests be performed; for instance, axle load should be tested in conjunction with speed to obtain a series of curves as shown in Figure B-16.

If the expected small speed effect is realized, then considerations of safety, convenience and reproducibility will determine the speeds selected for field tests. If the effect is large for the selected slip condition, then the interrelation of speed with the other test variables must be investigated in more detail in field tests.

4. Deceleration and acceleration. Typical wear marks on pavement for straight driving (rolling), decelerating (slipping), and sliding vary as shown from left to right:



The marks left by rolling are about the diameter of the studs; the slip marks are curved, their length depending on the magnitude of relative slip,* and their separation depending on the arrangements of the studs in the tire; skid marks are continuous and are straight, unless the vehicle corners or veers.

It is reasonable to expect that the depth of the marks depends on instantaneous stud pressure and their length on relative slip, and on the variation of the coefficient of friction between stud and pavement. Tire friction is known, qualitatively, to have the trend shown in Figure B-17.

On the basis of the foregoing reasoning, and in the conformance with the results of Wehner (Fig. B-2), we expect the trend depicted in Figure B-18.

If the shape of these curves, including the speed dependence, can be established in accelerated tests, then the field test task is vastly simplified. Measurements can then be made at rolling speed and one reproducible condition, deceleration, will suffice to determine the wear rate for the gamut of deceleration conditions. Locked wheel stops, which are hard on vehicles and tires—in addition to the pavement—need then not be employed.

In Wehner's tests (*31*) wear at the acceleration test site was not as severe as that at the deceleration site. In interpreting his results, it is noted that acceleration magnitudes ranged from 5 to 10 ft/sec², whereas deceleration ranged from − 10 to − 15 ft/sec². Here again, the establishment of the trend in accelerated tests would reduce the number of different acceleration tests in the field, while the ability to predict wear for the traffic accelerations would be greatly enhanced.

* Slip ratio is defined as $1 - \frac{\omega_b}{\omega_{fr}}$, where ω_b is the angular velocity of the wheel in the braked condition and ω_{fr} is the free-roll angular velocity.

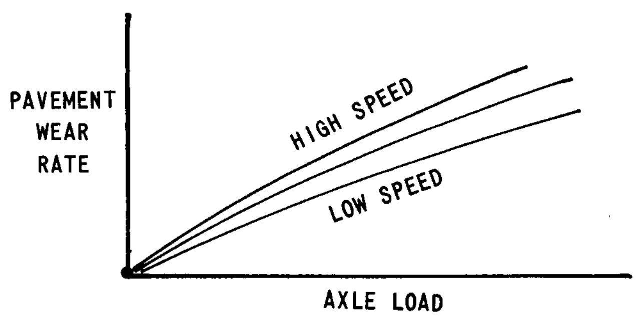


Figure B-16.

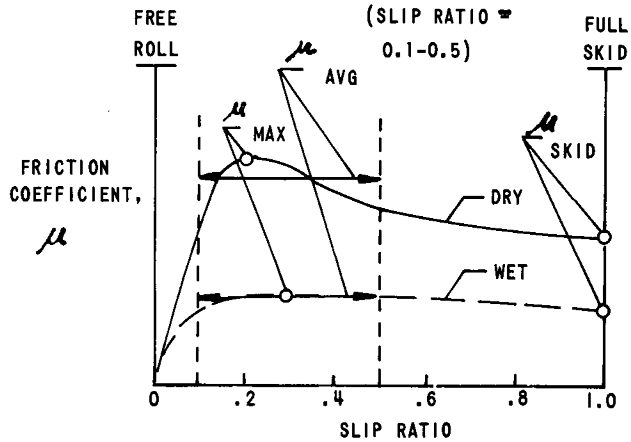


Figure B-17.

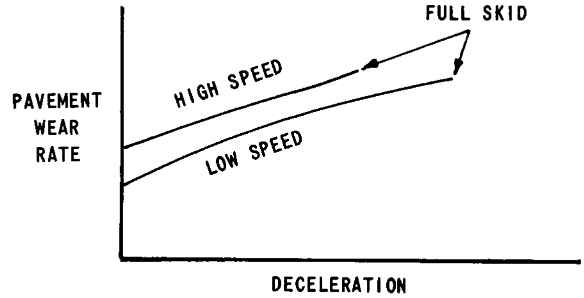


Figure B-18.

5. Tires. The relation of tire inflation with stud pressure and, thereby, with wear has already been discussed. The accelerated test rig is recommended as the means to check out how strong a variable tire pressure is, and how well it must be controlled in the field tests.

There are many types of regular and snow tires on the market; all may conceivably be equipped with studs. These tires differ by a multitude of properties such as cord material, number and type of plys, tread pattern, tread depth, rubber hardness, and others. It is believed that rubber hardness and tread depth, as represented in extremes by snow and highway tires, are the important tire variables that determine road wear by studded tires. (Note that stud variables are treated separately below.) Again, the accelerated test rig is the recommended device for determining the difference in expected road wear between studded highway and studded snow tires, and also for verifying our contention as to the relative unimportance to pavement wear of the other tire variables.

As discussed in our survey of the pilot tests, one state report (*26*) found a saturation effect with age as shown in Figure B-19.

In contrast, Wehner reported a linear relation between wear rate and number of tire passes.

We believe that tire age or mileage, as such, is not an important variable and that stud protrusion and shape (as discussed) has a much stronger effect on pavement damage. Stud protrusion varies with age, but is a strong function of tire use; treads tend to wear faster than studs in fast highway driving and, conversely, studs tend to wear more rapidly than treads during deceleration and acceleration. As mentioned earlier, Wehner ran his test cars daily over a race course, in addition to the field test loop, in order to keep stud protrusion constant as the tires aged. However, his report contains only qualitative information on this aspect of his tests. Moreover, we know that control of relative wear rate between tire and studs is a primary concern to the tire makers and we can therefore expect variations in the relative wear of studs and treads of studded tires on the market in the future. Consequently, the establishment of a wear-mileage curve as shown in Figure B-20 is advocated in the accelerated test rig, if the other test variables, such as stud protrusion and shape, are measured, then such a curve may serve three useful purposes: (1) it will make possible the rapid screening of new tire products to ascertain whether they differ essentially from others; (2) it will indicate the number of miles that tires should be run in field tests; and (3) it will make possible better estimates of traffic road damage.

6. Studs. Composition, protrusion, number per tire, shape, and orientation are stud variables whose effect on pavement wear must be considered. Note that this list does not include number of flanges, method of seating, and other factors which determine, say, stud loss but are not related directly to pavement wear.

Tungsten carbide, the currently most prevalent stud material, is manufactured in three grades of wear resistance. Grade I is intended for truck tires, Grade II for regular snow tires, and Grade III for retreads. The wear resistance of these carbides, rather than their indentation hardness, determines their effect on the skid resistance of vehicles. Wear resistance is measured by a number of industrially accepted tests (including ASTM No. P-112) in which the studs are rubbed against a specified abrasive-charged wheel, for a prescribed number of turns of the wheel (or a prescribed total contact length, or length of contact time at a given surface velocity), and under maintenance of a specified contact pressure. The weight loss of the studs is the basis of their grade classification.

Carbide wear resistance, determined as described, is not directly related to the pavement wear caused by the studs. Single stud tests of Grades II and III indicated no evidence of a significant difference between these grades in pavement wear. Because, under conditions which more closely resemble pavement loading, differences in wear rate may be found, including various stud materials in the accelerated wear tests is advocated. The reason for the recommendation is that information on small differences in wear of the advocated fine-grain control paving will be a guide in evaluating other stud materials that may be commercially introduced in the future.

The importance of stud protrusion has already been discussed and its eventual inclusion, along with axle load in a stud pressure term, has been advocated. The fact that current nominal stud and hole specifications permit wide

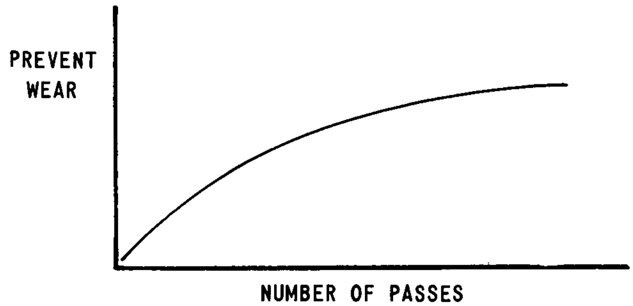


Figure B-19.

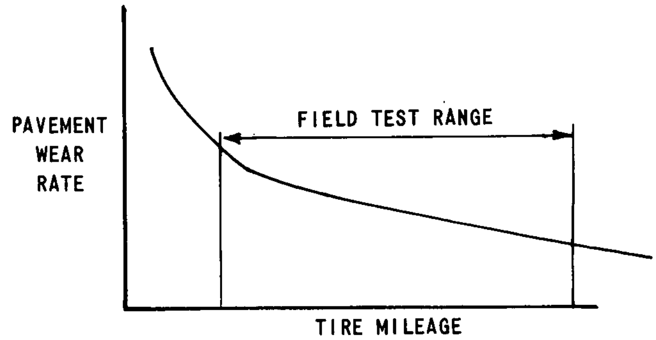


Figure B-20.

variation in the protrusion of studs from new tires has already been mentioned. Stud protrusion may change rapidly during tests; if it is measured frequently during, say, locked wheel tests, the effect of two variables—protrusion and sliding—can be determined simultaneously.

Stud shape and orientation affect the cutting forces and the energy necessary to remove a given amount of pavement material. Single stud tests indicated a significant change in stud behavior, depending on the inclination of the flat end of the stud to the pavement (corresponding to the face relief angle of a cutting tool). Moreover, some worn studs have assumed a hemispherical surface. The effect on pavement wear rate of these variations can readily be screened in accelerated wear tests.

The number of studs and their peripheral and transverse arrangement on the tire, together with axle load, inflation pressure, and contact area determines stud pressure. Screening tests of tires with the most radically differing stud arrangement can establish the influence of the variable on wear.

7. Environment. Temperature, water and salt are the most important environmental factors that must be taken into account in the test program and in making predictions on traffic road wear based on test results. Other influences, such as dirt and oil, should be carefully eliminated in the test program. They will, of course, introduce uncertainty into the prediction of expected actual road wear, but their quantitative consideration would make the test and prediction process too difficult and costly.

8. Tire chains. A proper basis of comparison of road wear due to studded tires and other traction aids can only be arrived at by test. Tire chains as the traction aid are advocated; wear due to tire-chain-equipped tires on dry pavement should be determined, as a minimum, with the following variables: pavement composition, axle load, and deceleration.

A maintenance cost comparison must, of course, be based not only on wear per pass, but also on expected actual number of passes, according to the mathematical relations outlined in Appendix E.

9. Temperature. We must distinguish at least three temperature zones: pavement, stud tip, and rubber.

Pavement temperature is held to be the most important of these, especially in the case of bituminous materials. Pavement surface temperatures are estimated, conservatively, to vary from $-20°F$ to $+140°F$. (The upper limit is based on summer conditions and is considered appropriate, since not all users will remove their studded tires during summer months.) The strength of bituminous pavements varies widely over this range; in fact, poured asphalt becomes viscous at the higher end of this temperature range, and while studs will "cut" asphalt at such temperatures, they are not expected to remove material; instead, the asphalt will probably flow back into the cut after passage of the vehicle. The strength of aged portland cement is not so temperature sensitive over the above range. Recommended is establishment of the test loop and the test season in part of the country in which low temperatures are encountered, with provision for heating at one of the test locations, so that the temperature sensitivity of the wear rate can be established for each pavement core material.

The observed hemispherical end of some studs indicates that pavement-stud interface temperatures may be very high; so high that the stud material softens. The dark smudges left in our tests by single studs that were dragging over concrete at a negative relief angle indicate the possible occurrence of a high-temperature chemical reaction. We hold, however, that these interface and stud temperatures are only transient, that they do not affect the pavement with which they are in brief contact only, and that therefore stud temperature need not be monitored in road wear tests.

The rubber temperature in the vicinity of the stud is affected by the stud through conduction, since the heat conduction path is continuous, unlike the path to the pavement. The raised rubber temperature may affect tire life and the stud holding power of the tire, but not the road wear action of the studs; therefore, rubber temperature need not be a test variable.

10. Water. The pavement may be dry, wet, or ice covered. While some of the reported tests did keep track of the number of test days during which each of these conditions prevailed, no measurements of the accompanying wear rate are available. We recommend that, in the field tests, wear rate be monitored separately under each of these conditions. In the case of ice, temperature must also be

recorded; what is of prime interest here is to know the ice condition under which some pavement cutting can also occur.

11. Salt. Our single stud tests were inconclusive as to the importance of salting and freezing cycles on the stud wear resistance of pavement. We recommend a more thorough investigation for the field test. Pavement age should also be a variable in these tests.

APPENDIX C

SINGLE STUD TESTS

The purpose of the single study tests was to furnish information on the nature of pavement damage by studded tires. The tests have provided inputs to the specification of field tests by which the extent of this damage can be determined.

Three types of pavement cores were provided by the New York State Department of Public Works. All of the cores met NYS DPW materials and construction specifications. Information on these specimens is given in Table C-1.

Tungsten carbide studs of carbide Grades II and III from Kennametal, Inc. and carbide Grade II, from Studebaker Corp., were tested. Only one stud length, 0.480 in., was tested, since length per se is not a significant factor in damage. (Stud length may determine the mobility of the stud in the tire which may be quite important, however; also, stud protrusion is believed to be important to the damage process and has been found important for skid resistance on ice.)

The test configuration was chosen so as to partially simulate locked wheel braking at various velocities. The simulation is only partial because the studs generated circular, rather than straight, skid marks on the pavement, and because they were spring loaded in the axial direction only. Figure C-1 indicates the test configuration schematically and Figure C-2 is a photograph of the setup. The studs are held by an adjustable spring, so as to protrude 0.06 in. from a housing; the housing is affixed to a disk which is provided with a balance weight and a central arbor, so that it can spin at high speed in a milling machine. The pavement core is clamped by a V-block which is fastened to a milling machine table. The core is clamped at a slight angle (approximately ½°), so as to provide gradual entry of the stud into the core. The table of the (vertical) milling machine has lead screws which permit positioning the pavement cores within 0.001 in. in three directions and the milling head has a fast lead screw which permits rapid engagement of the rotating stud to a preset depth.

After a number of trials, the following procedure was adopted: The core was positioned under the path of the rotating stud; the milling machine table was raised until an impact sound indicated that the study just began to touch the high edge of the core; then, the stud was rapidly lowered by 0.030 in. and retracted again.

TABLE C-1

PAVEMENT CORE SPECIFICATIONS

MATERIAL	NO. OF SPECIMENS	AGE (YEARS)	TRAFFIC EXPOSURE	SIZE (IN.)
Concrete (Soft) Limestone Coarse Aggregate (+⅛ Particles) and a Relatively Soft Fine Aggregate	3	1	None	4 Dia. × 3
Concrete (Hard) Traprock Coarse Aggeg. and Long Island Silica Sand Fine Aggregate	2	1	None	4 Dia. × 3
Bituminous Concrete Limestone Coarse Aggregate and Fine Aggregate Containing 50% Soft and 50% Hard Particles	3	3	5,000 Vehicles/day	6 Dia. × 3

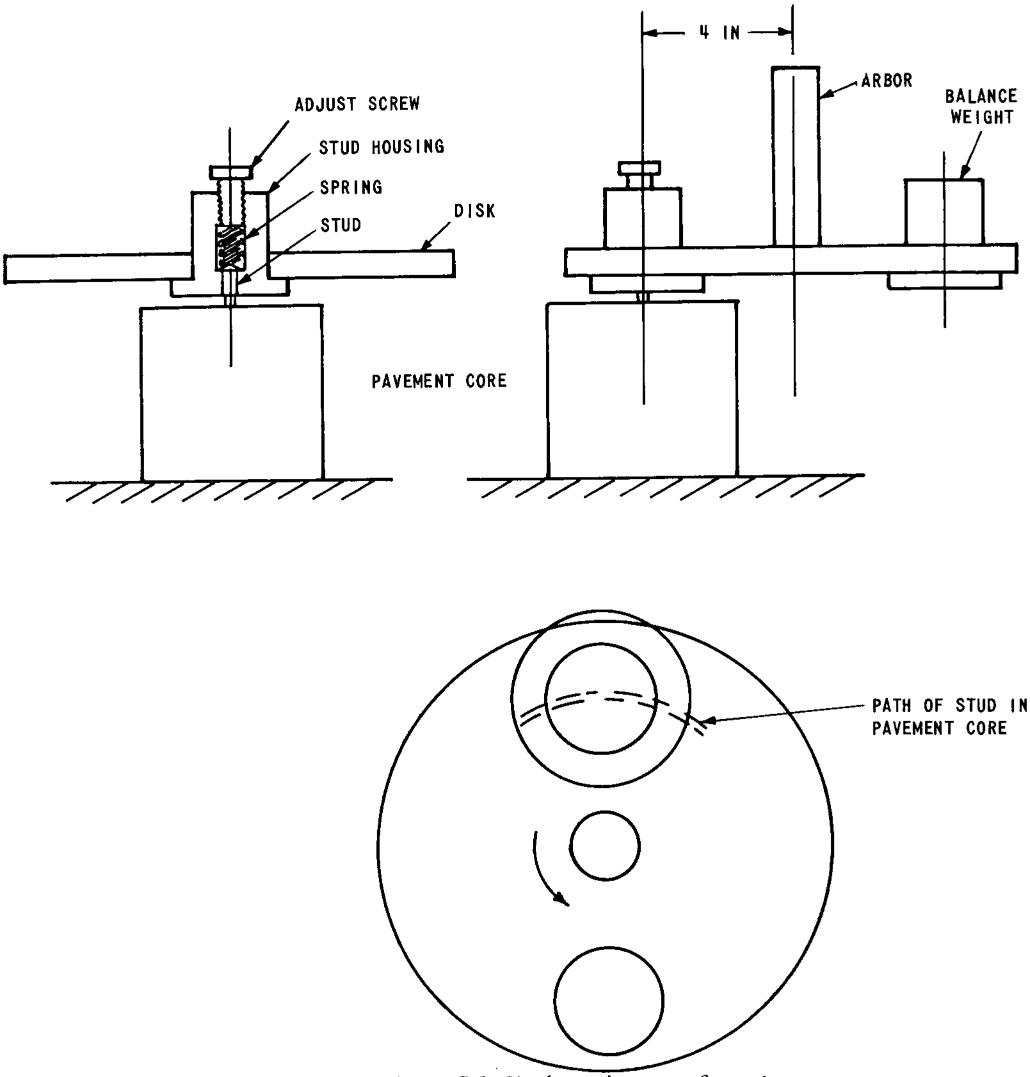


Figure C-1. Single stud test configuration.

Test conditions and variables were as follows:

Cutting Velocity:	24 mph and 4 mph
Depth of Cut:	0.030 in. max. (nominal)
Spring Force:	30 lbs., 50 lbs. and infinite (stud fixed)
Stud Configuration:	Single flange Over-all length 0.480 in. Insert Diameter 0.10 in.
Stud Material:	Carbide Grade II (2 makes) Carbide Grade III (1 make)
Stud Condition:	As received Diamond dressed Used on pavement Inclined at ± 15°
Pavement Material:	Soft portland cement (top and bottom) Hard portland cement (top and bottom) Bituminous concrete (top only)
Pavement Condition:	As received After exposure to salt water, freezing and thawing

The results of these tests are reported in Appendix B.

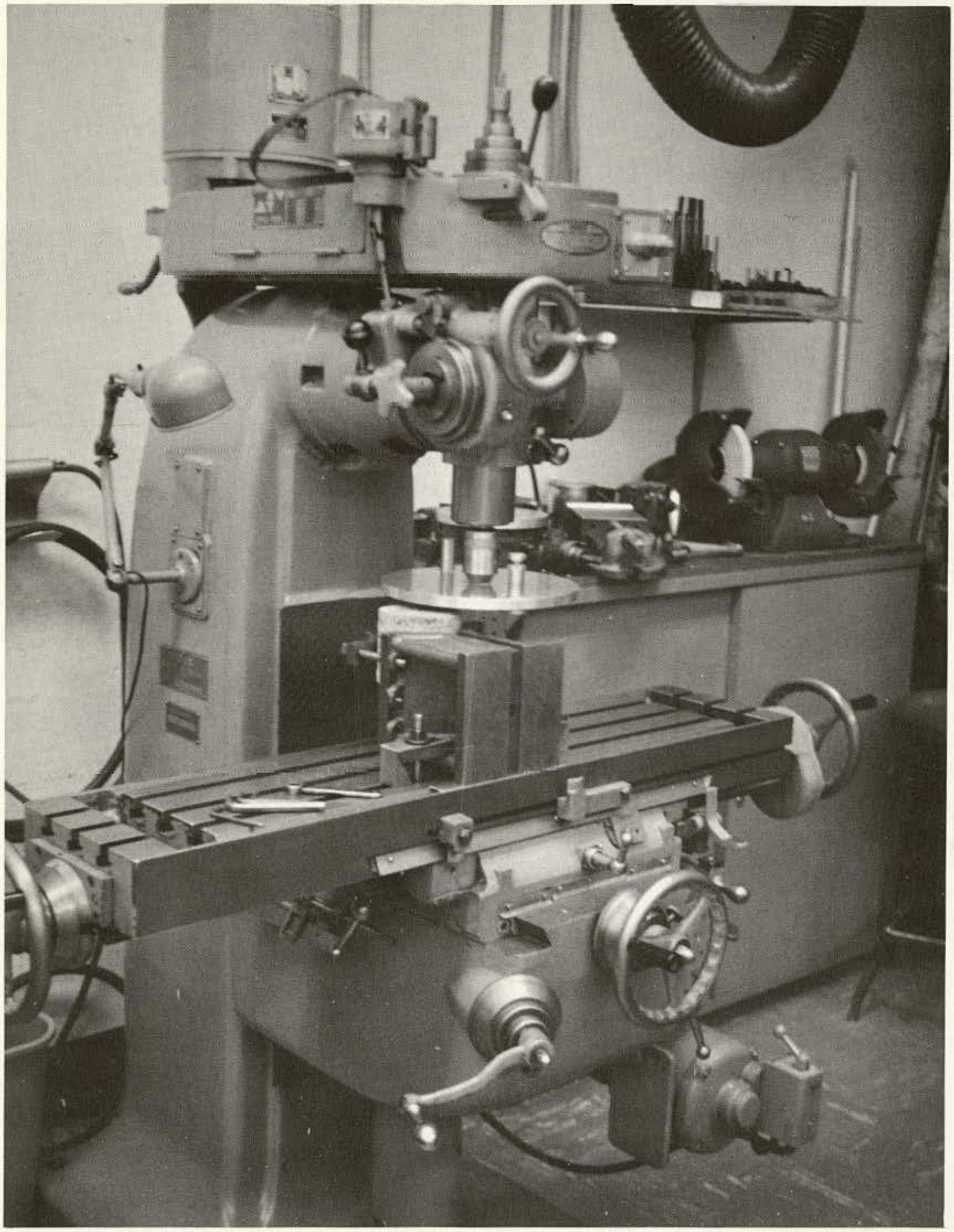


Figure C-2. Single stud test set-up.

APPENDIX D

WEAR AND ROUGHNESS MEASUREMENT

The need for determining wear (how much material has been removed from a pavement) *and* roughness (the description of the resulting pavement profile) is described in Appendix B, as is the recommended method for measuring wear and roughness. In this appendix, we define roughness and wear terms, describe the breadboard model, the tests performed to demonstrate its capabilities, and present specifications for a prototype instrument based on our test experience.

WEAR AND ROUGHNESS TERMS

Mean Wear Depth, d_w: This is the vertical distance between the mean line of the initial surface profile and the mean line of the worn surface profile. The mean line or mean profile line is defined as the straight line drawn through the surface profile in such a way that the areas encompassed by the surface profile above and below the line are equal and minimum (see Fig. D-1) (*37*).

Roughness Mean Height, R_a: This is defined and evaluated as the average arithmetical distance of the surface profile from the mean line within the base length L (*37*). R_a equals AA in the American Roughness Standard.

$$R_a = \frac{1}{L}\int_{\chi_a=0}^{\chi_a=L} y_a d\chi_a = \frac{\Sigma^n y_a}{n} = \frac{y_1 + y_2 + \ . \ . \ . \ y_n}{n} \qquad \text{(D-1)}$$

This way of evaluating or comparing roughness in a quantitative way is purely statistical, is reliable and is

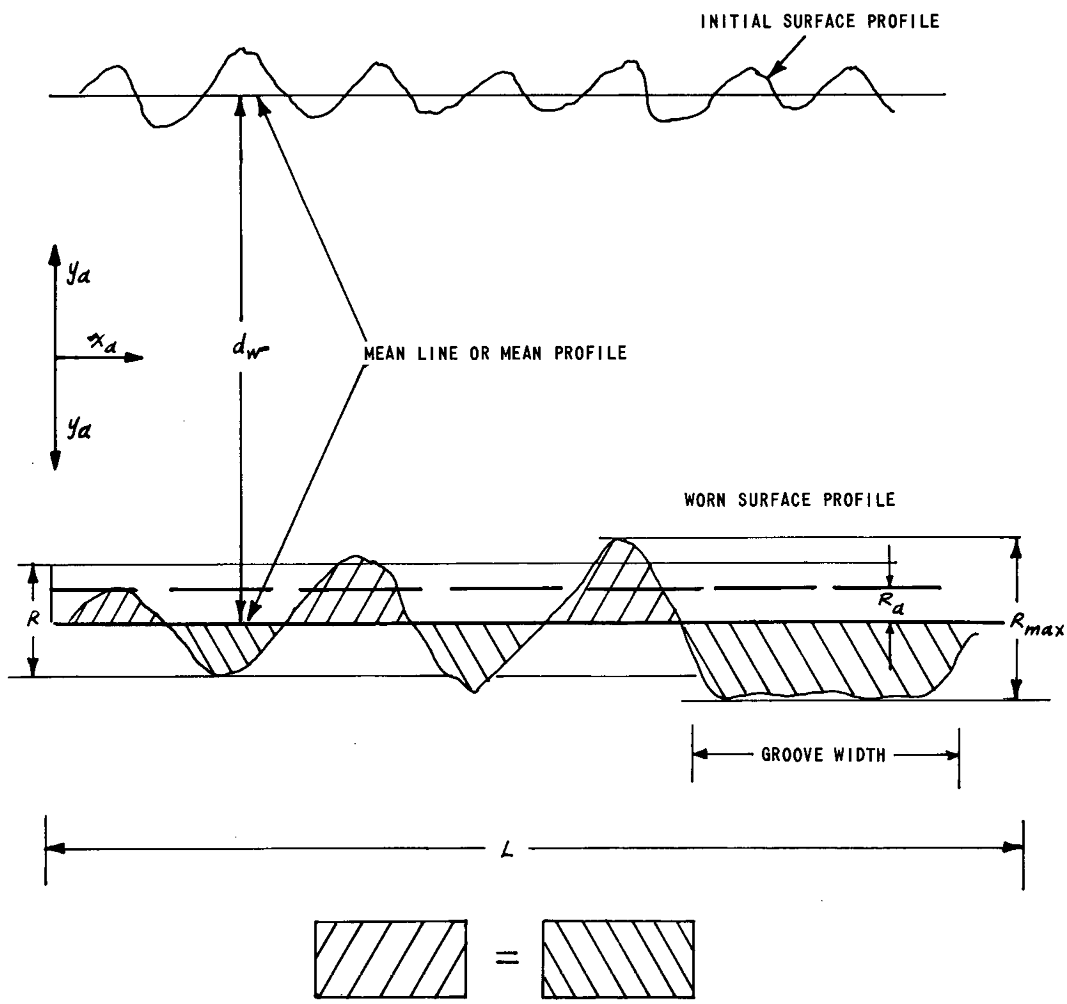


Figure D-1. Terminology.

virtually an international standard. L, the base length, must be large enough to include all irregularities which are fundamental to road roughness and wear; that is, L must be large enough to include grooves and pits due directly or indirectly to studded tires or to other causes.

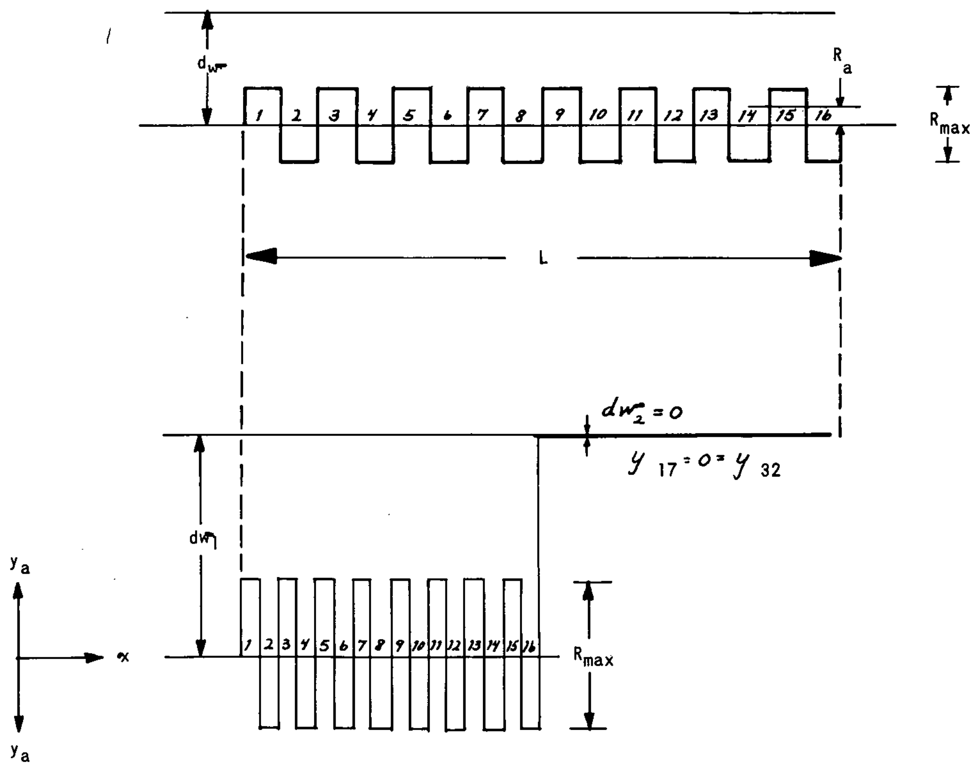
Surface Profile Record: Ideally this would be a true profile plot of the surface cross section taken along a basis or datum line. Profilograms are usually made by moving across the surface with a stylus-displacement sensing system. From such a profile record all basis roughness and surface characteristics can be obtained.

We should note here that an important aspect of surface roughness measurement is, in current practice, not properly recognized; that is the spatial distribution of the roughness peaks. Theoretically, the two surfaces sectioned in Figure D-2 have the same wear and roughness dimensions d_w and R_a, though visual inspection indicates drastic differences. Only the maximum peak to peak roughness value will also be larger when such profile irregularities occur for equal R_a and d_w. In the case illustrated the mean profile line has a discontinuity, but less drastic cases in which the mean profile line remains continuous can readily be visualized. In the absence of quantitative recognition of the importance of peak distribution, the complete profile record must serve as qualitative indication of the wear and roughness pattern. The number of peaks, though not their distribution, is included in a roughness measure proposed by D. F. Moore, ("A Note on the Mathematical Representation of Surface Roughness," WEAR, 9, 477, 1966.)

CONSTRUCTION AND TEST OF A WEAR AND ROUGHNESS METER BREADBOARD MODEL

A simple model of the wear and roughness meter was constructed and the feasibility of the design described in Appendix B was demonstrated. Figure D-3 shows the model which contains 28 plungers, the complete collimator, and the photocell, in a workable bench setup; the instrument sits on a V-block to which a pavement core is clamped; a flat and smooth calibrating plate can be interposed between pavement core and plungers.

Because of the severe limitation of funds on this program the breadboard model was made with fewer plungers than desirable and the plunger lengths and their 45° mirror



$$d_w = \frac{dw_1 + dw_2}{2} = \frac{dw_1}{2}$$

$$R_a = \frac{y_1 + y_2 + \cdots y_{32}}{32}$$

Figure D-2. Surfaces of nominally equal mean wear depth and roughness mean height.

surfaces were not of high accuracy. In spite of these shortcomings, wear was measurable to 0.002 ± 0.001 in. The roughness of a pavement specimen was measured as 0.012 ± 0.0025 in., which is within the random error to be expected for 28 data points, about 20 percent in our case. Figure D-4 is the roughness profile of this pavement core photographed as it would be seen by an observer through the viewing opening.

The roughness measurement was compared to a point by point profile measurement of 120 points made with a sharp-pointed dial indicator and using a milling machine table to obtain uniform spacing between measuring points. The mean roughness value was calculated as 0.013 ± 0.001, an expected random error of less than 10 percent.

The following describes the method by which the capability of the breadboard model for roughness measurement was established: the output current of the silicon photovoltaic cell is directly proportional to the amount of light reaching it from the thin translucent diffusing screen. As the collimator–detector configuration is moved in the direction necessary to obtain a mean profile reading, the cell output will increase linearly as the profile pattern covers progressively more of the cell. When the mean pattern position with respect to the cell is reached, the signal will be a maximum. If the plungers are perfect in construction and alignment and rest on a smooth surface, the maximum signal will have its greatest possible values as shown in Figure D-5. However, due to plunger imperfections our breadboard model gave a curve as shown at (1) in Figure

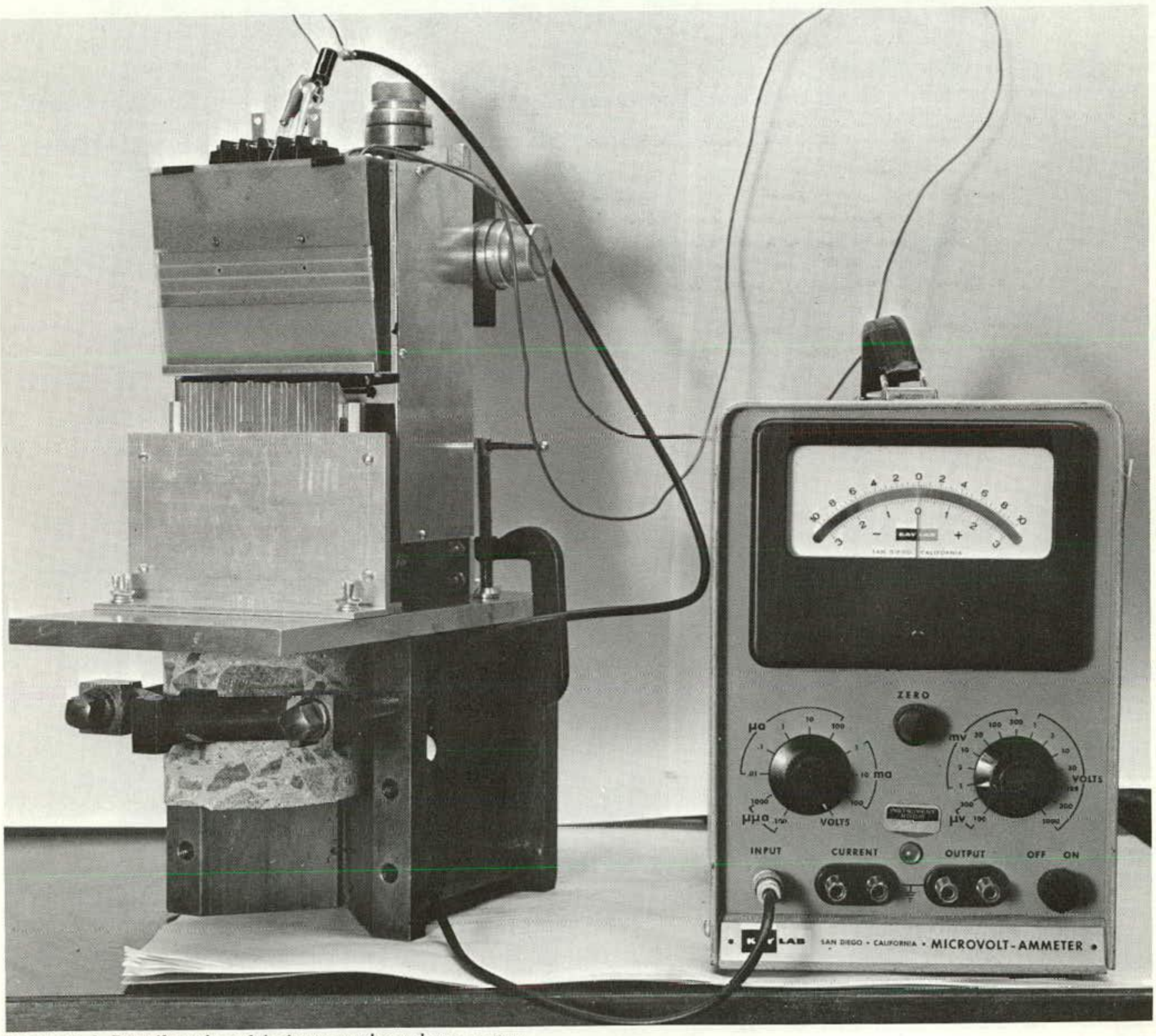


Figure D-3. Breadboard model of wear and roughness meter.

D-5. The intercept of the peak height with the ideal triangular plot indicated a systematic error equivalent to a roughness mean height of $R_a^* = 0.008$ in. Therefore, any roughness of less than $R_a = 0.008$ in. could not be measured. However, since this error is a systematic one (i.e., it is the same for all measurements) roughness values greater than 0.008 in. were measurable. Curve *2* in Figure D-5 shows the type of curve obtained with a rough

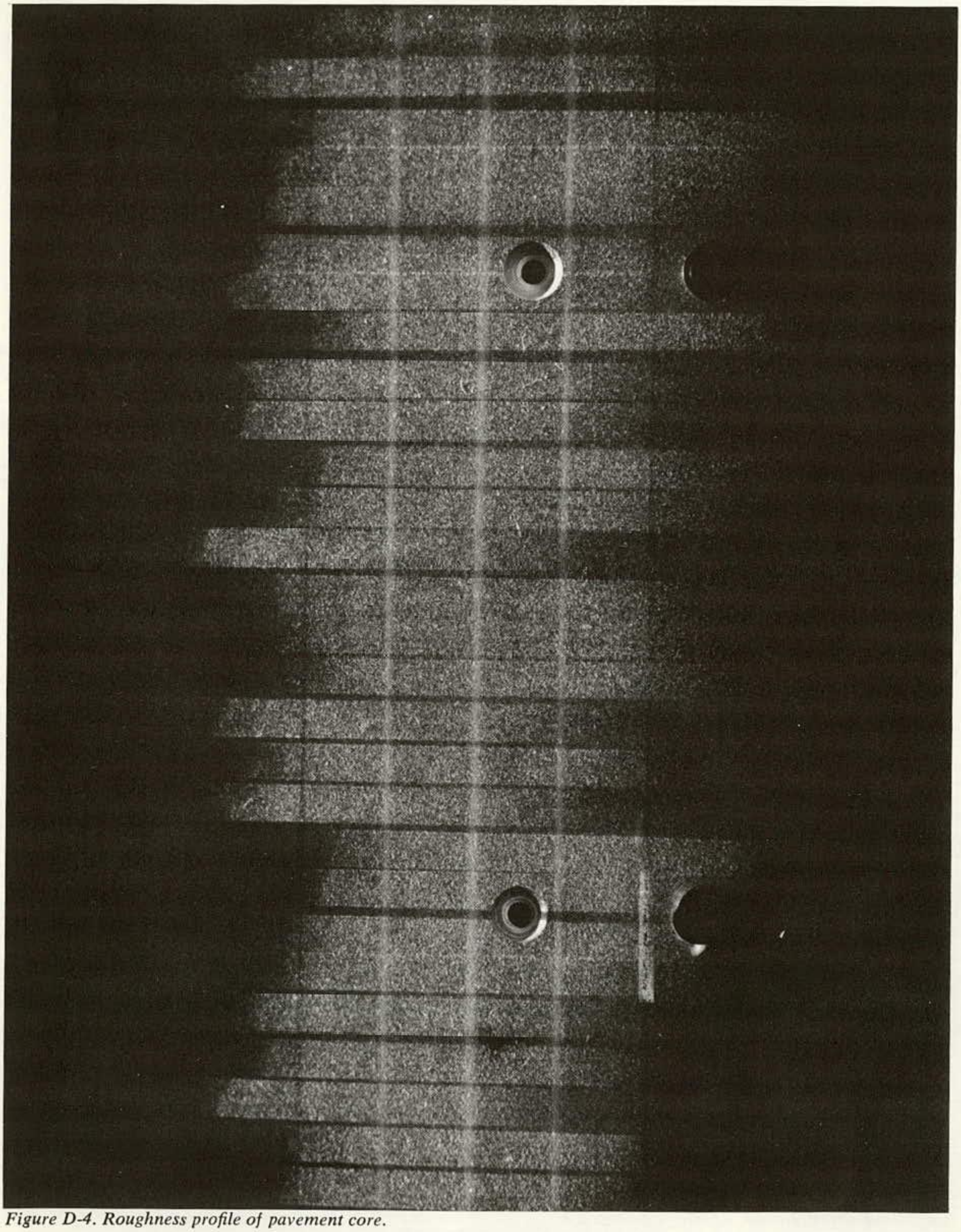


Figure D-4. Roughness profile of pavement core.

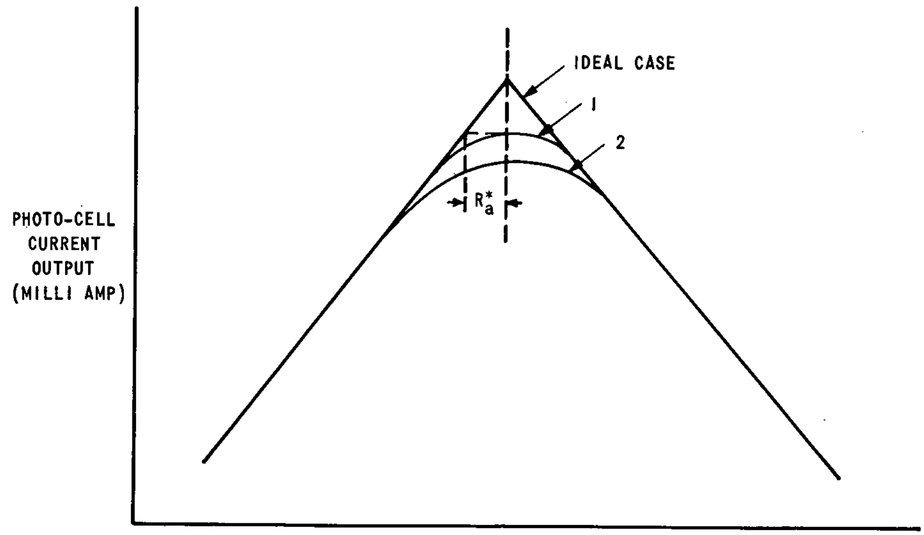


Figure D-5. Calibration of breadboard model.

concrete core contacting the plungers (e.g., $R_a = 0.012 \pm 0.0025$).

Figure D-6 shows diagramatically how the meter output signal as a function of collimator screw travel is interpreted to obtain both d_w and R_a. Curve (a), Figure D-6 is a reference curve that was obtained by placing a smooth surface in contact with the underside of the mounting plate. This reference curve was found to be well reproducible. A road core sample placed with its mean surface profile an arbitrary distance d below this plate gave rise to curve (b) in Figure D-6. R_{ab} was determined by taking the maximum meter reading for curve (b) and locating its horizontal intercept on either side of curve (1), point (3) in Figure D-6. The collimator travel distance between point (3) and point (1) or the vertical symmetry line of curve (a) is the roughness mean height, R_{ab}. If to simulate wear a similar but rougher road sample were placed in the prototype with its mean profile at a lower level (d_w) then specimen curve (c) would result. The collimator screw travel between the maximum points of curves (b) and (c), i.e., (2) and (2′) would be indicated by the counter as d_w. The roughness R_{ac} of the second sample would be determined as with the first sample by noting the travel distance corresponding to the horizontal separation of points (3′) and (1).

Once an instrument is calibrated, the graphs shown in Fig. 4-6 do not have to be determined and the operator only has to measure maximum cell output values—points (1), (2) and (c). With the roughness values R_a found on curve (1), the cell output ammeter can be ruled so as to read directly to the nearest 0.001 inch. Any variation in light level caused by lamp and battery aging can be corrected from time to time by using a roughness standard surface and adjusting the lamp current.

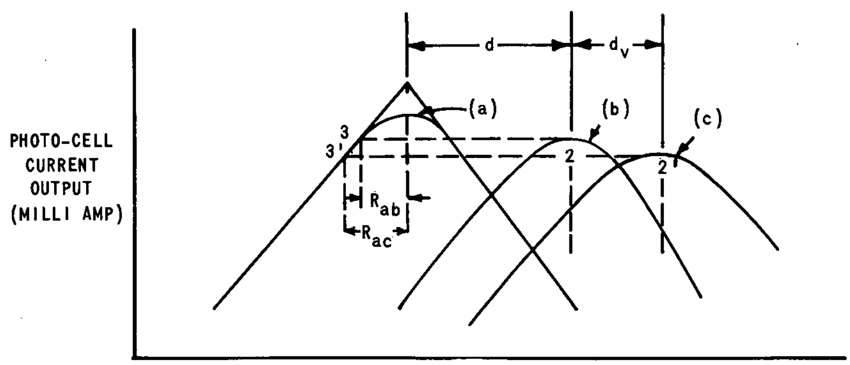


Figure D-6. Illustration of measurement.

THE DUAL-CELL METHOD

The breadboard model was originally conceived and constructed as a null instrument with two matched photocells separated by distance 10w as shown in Figure D-7. In this design mode, a null-meter connected in parallel to the photocells reads zero when the light beam from a rough or smooth surface is exactly centered between the cells; the wear height, d_w, is read on the counter at that time. A second meter is connected in series with the photocells and their combined output, when the first meter reads null, is an indication of roughness mean height, R_a.

In spite of the elegance and self-calibrating feature of the null method this construction was abandoned when the following disadvantages became evident.

The 45° reflecting surfaces of the plungers of the model were not well aligned and were not very good mirrors (they were only mechanically buffed aluminum); consequently, they scattered some light in random direction. More of this light hit the lower photocell, introducing a mean line shift when indicating null. Wear height measurement could be made within 0.001 in., but good roughness measurement was not possible. While it was realized that better plunger alignment could be obtained and better mirrors could be made by metallurgical or electrical polishing methods, it was felt that some residual scattering would always be present and would be worse if the mirrors became dirty.

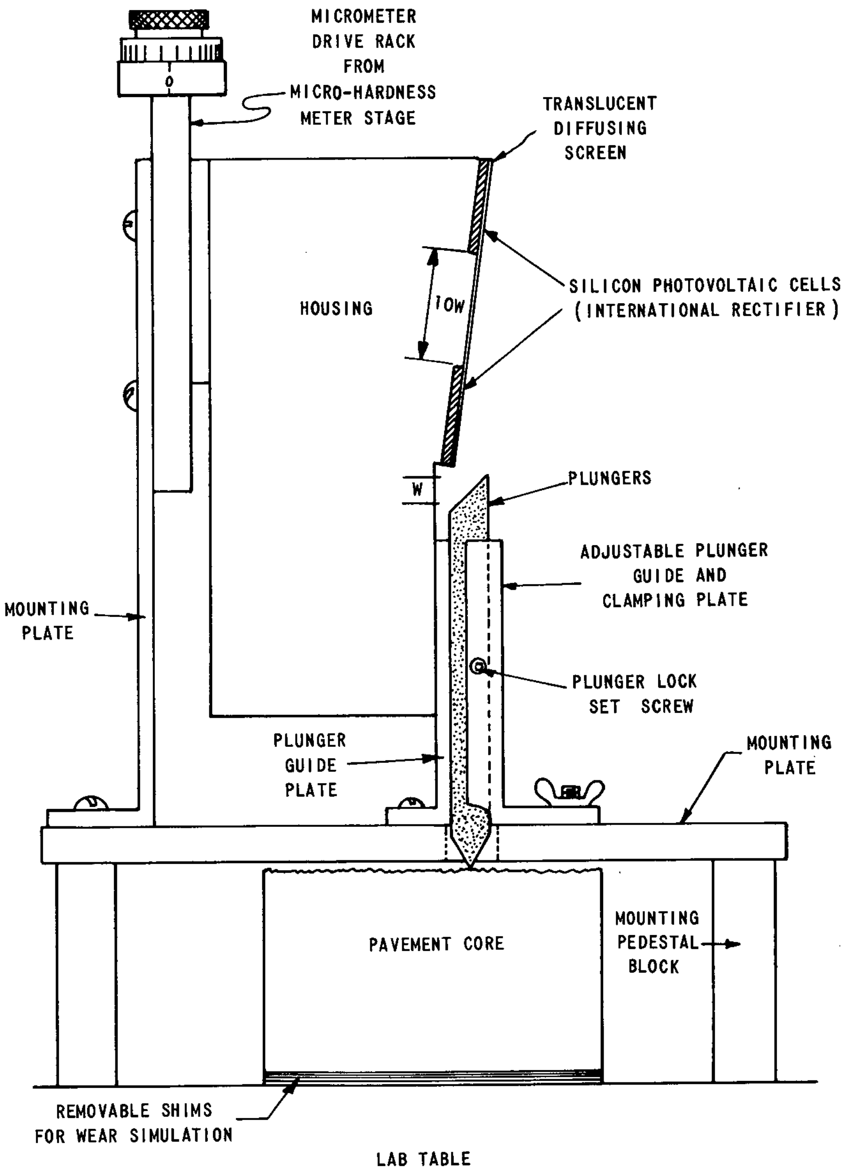


Figure D-7. Breadboard schematic (dual cell).

Further drawbacks of the null-method are its higher cost because two matched cells are required. Therefore, the single cell mode of operation was adopted.

TOLERANCE REQUIREMENTS

In order to make dependable and consistent road wear and roughness measurements the instrument should be capable of measuring wear differences of 0.001 in. and mean roughness differences of 0.002 in. with a measurement precision of 10 to 20 percent. To achieve this the following instrument parameters and tolerances should be met:

The number of plungers should be 200 covering a distance of about 10 in. This will keep the random sampling error below 10 percent. Plunger thickness will then be 0.050 in. The maximum relative angular error between individual plungers and between plungers and the mounting slide plate should not exceed 1 minute of arc. Plunger length should be uniform to within 0.001 in.

To obtain 10 to 20 percent precision in R_a readings, the spread in the vertical direction of the light beam leaving the slit should not exceed 4 minutes of arc. The measurement of d_w, the mean profile height, is not affected by systematic errors in the collimating system.

APPENDIX E

MATHEMATICAL RELATIONS BETWEEN WEAR VARIABLES

The following relation can be defined:

$$\delta_{ls} = d_{mat}\, c \qquad \text{(E-1)}$$

Here

δ_{ls} = depth of pock mark or longitudinal groove produced by one pass of a studded tire

d_{mat} = a groove depth that is characteristic for pavement composition, age, finish and any protective coatings

c = a wear coefficient

This wear coefficient can be further defined as

$$c = c_L \cdot c_t \cdot c_s \cdot c_e \qquad \text{(E-2)}$$

in which

c_L = wear coefficient of load
c_t = wear coefficient of tire
c_s = wear coefficient of studs
c_e = wear coefficient of environment

The following variables have been identified as affecting the magnitude of d_{mat} and c.

d_{mat} Pavement
- Composition
- Age
- Coatings
- Finish

c_L Load
- Axle Load
- Speed
- Deceleration
- Acceleration

c_t Tires
- Inflation Pressure
- Type (Winter or regular)
- Age

c_s Studs
- Material
- Protrusion
- Shape
- Number/tire

c_e Environment
- Temperature
- Water
- Salt

Since c_L, c_t, c_s, and c_e may have values that vary with N_s, the number of passes by studded tires, we may write first

$$N_s = N_{s_1} + N_{s_2} + N_{s_3} + \ \ldots\ N_{s_n}$$

and for a given pavement material and N_s passes the groove depth becomes:

$$d_{ls} = d_{mat}\, [N_{s_1} c_{L_1} c_{t_1} c_{s_1} c_{e_1} + N_{s_2} c_{L_2} c_{t_1} c_{s_1} c_{e_1} + N_{s_3} c_{L_2} c_{t_2} c_{s_1} c_{e_1} + \ \ldots\ N_{s_n} c_{L_n} \ldots] \ * \qquad \text{(E-3)}$$

The total wear along a longitudinal line is due to the passage of N wheels

$$N = N_s + N_c N_r \qquad \text{(E-4)}$$

* It must be recognized that Equation (E-3) represents the simplest possible predictive model, i.e. one containing only terms for linear considerations of the coefficients. Non-linearities and interdependencies of the coefficients that are found in the field test analysis must be taken into account by separate linear terms. Alternate models, e.g. $c = c_0 e^{a+bT}$ may be more inclusively representative of actual wear. Since, however, at this time the magnitude of these coefficients is not known at all, the multi-term linear model of Equation (E-3) appears to be best suited for the present purpose.

in which

N_c = number of wheels equipped with chains
N_r = number of regular, unstudded wheels

and

$$d_1 = d_{mat}\ (N_s c + N_c c_c + N_r c_r) \qquad \text{(E-5)}$$

in which

c_c = wear coefficient for chained tires
c_r = wear coefficient for regular tires

Finally, d_w the depth of wear on a line across the traffic direction can be expressed as

$$d_w = d_1 a \qquad \text{(E-6)}$$

where a is a factor such that $0 < a < 1$ which is determined from information on the distribution of wheel contacts across the pavement, as indicated in Figure B-3. Determination of the variability and interdependence of d_{mat} and the coefficients c_L, c_t, c_s, and c_e constitutes the major task of the field tests. The magnitude of these coefficients must be determined for various values of the listed variables. Once the coefficients are known, actual pavement damage can be predicted based on estimates of traffic count (N_s, N_c and N_r) and on estimates of traffic variables such as types of vehicles, loads and environmental conditions which determine the products of N_n, c_{L_n}, c_{tn}, c_{sn} . . . that must be summed.

From the foregoing one might conclude that a vast number of tests will be necessary to predict pavement damage with some accuracy. Actually, the task can be reduced by early recognition of the less sensitive coefficients and by establishment of the magnitudes of the coefficients as a function of groups variables that can then be graphed. Some of these relations can be established by accelerated (indoor) tests. Field tests will then only be needed to establish numerical values of the variable at a few points.

APPENDIX F

THE MECHANICS OF PAVEMENT WEAR BY STUDDED TIRES

The discussion of the variables in Table B-3 indicated that more fundamental parameters than axial load, speed, and acceleration control the mechanics of pavement wear by studded tires. These fundamental variables cannot readily be measured directly. Discussion of a simple, two-dimensional model of the mechanics of the wear process will, however, aid in appreciating the interrelation between the measured variables.

Consider a free-body-diagram of a stud during cutting action neglecting couples and assuming equilibrium of forces as shown in Figure F-1.

The stud is held by an axial spring force S_1 and circumferentially by springs S_2 representing the elastic behavior of tire and vehicle. N is the normal component of the force between pavement and stud. Normal pressure on the pavement is found by dividing N by the stud contact area $a_1 = \frac{1}{4} d^2 \pi$.

F, the horizontal component of the force between stud and pavement, is shown in two parts. F_1 is the force that does work in cutting pavement, F_2 is a friction force that acts on the stud-pavement contact surface.

When the tire is in near-rolling contact, say, when driving on level ground at constant speed, F is small and most of the work is done by N and S_1. The cylindrical depressions that are typical of studded tires at constant velocity, result when $S_1 > N$.

Actually, however, a slip will take place within the contact patch of a non-rolling wheel and the amount of relative slip increases with acceleration or deceleration of the vehicle to a maximum of one for the locked wheel case.* Slip affects the horizontal force F:

$$F \propto M a s$$

* The magnitude of relative slip, s, as indicated earlier, is $1 - \frac{\omega_a}{\omega_r}$ where ω_a is the actual wheel angular velocity and ω_r the free rolling angular velocity.

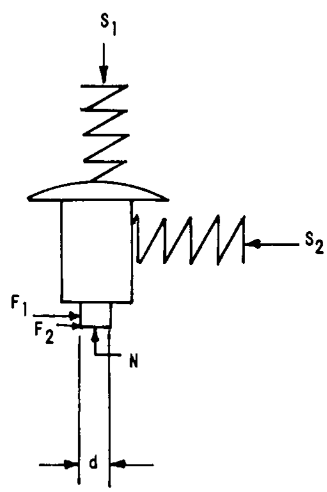


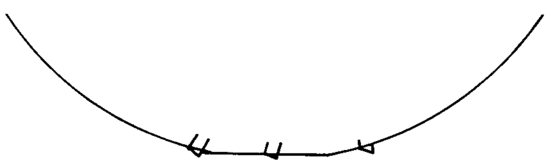
Figure F-1.

in which M = accelerated (decelerated) mass
a = acceleration (deceleration)
s = slip parameter

The resultant force between stud and pavement is the vector sum of F_1, F_2 and N. Depth of penetration and amount of pavement removed are affected, in the case of the slipping wheel, by N, a, F, a_2 and f; here a_2 is the horizontal projected area of the penetrating portion of the stud and f is a shape and orientation factor.

The horizontal projected area of the stud exerts pressure on the pavement in the direction of stud movement and is responsible for compressive and shear stresses in the pavement. The shape of the stud determines the distribution of these stresses. In customary approximate punch design calculations uniform stresses are assumed and the required energy is calculated as the product of contour length of punch (stud), material thickness (pavement penetration) and shear strength of the material.

The orientation of the stud with respect to the pavement surface is determined by the kinematics of the configuration and by the dynamics of the contact event. Kinematic parameters are tire diameter, static stud protrusion and pavement profile. The dynamics of the contact are more complex and involve the size and shape of the tire-pavement contact area and the orientation of the stud with respect to the tire. The diagram below indicates that the orientation of stud to the groove which it is cutting changes as it proceeds through the cutting zone.



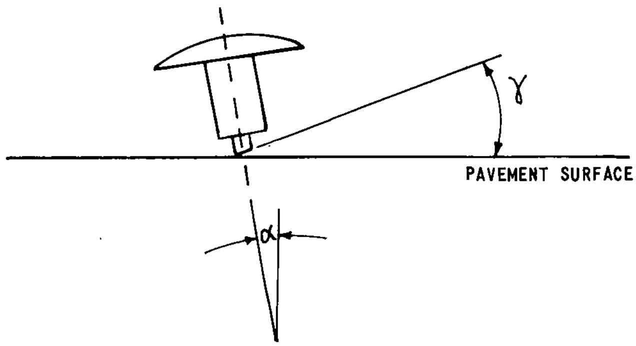


Figure F-2.

The range of values that this shape factor can take must be determined experimentally. In Figure F-2, the angle α between the front of the stud and the normal to the pavement surface corresponds to the "rake" angle in cutting mechanics; when cutting ductile materials this angle has a strong influence on the force required to produce material failure. The importance of γ, the relief angle, was demonstrated in our single stud tests.

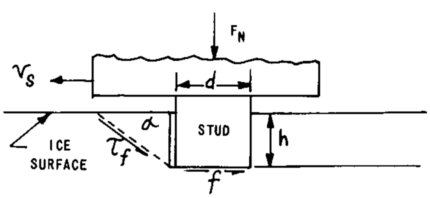
Actual stud contact is of course a multiple event, i.e., there is usually more than one of the spring mounted studs in contact with the pavement. The normal force per stud will be governed by axle load, number of studs, tire pressure, tire contact area, stud geometry and orientation and the spring force on each stud. Correspondingly, the friction and cutting forces developed are a function of the number of studs in contact, their total contact area, the total rubber contact area and the respective coefficients of friction.

APPENDIX G

STUD-ICE MECHANICS

The authors were unable to find in the literature any analysis of stud-ice mechanics. Although it was beyond the scope of the present program to conduct theoretical studies of the resistance mechanisms of studded tires moving on ice or snow covered surfaces, it is apparent that an understanding of the physical processes would be extremely useful in correlating data, particularly between the various modes of operation (i.e., traction, rolling, cornering, and braking). In Appendix A a very simple model was used in the estimation of cornering effectiveness from correlated braking data.

In this appendix, a preliminary physical model is proposed on the general matter of stud resistance forces. Assume that by some mechanism a single stud has penetrated a distance, h, into the surface of an ice covered highway and that a slip velocity, v_s, between the stud and the ice is present. Further assume that the gouging action of the sliding stud is one of shear failure in which small pieces of ice are continuously sheared off in planes intersecting the



ice surface, leaving a track or groove in the ice of width, d. The proposed mechanism thus neglects several effects of unknown importance including: plastic flow, stud-tire casing interaction, momentum transport, frictional heating-melting phenomena, etc.

The total shear failure area will be equal to the area of the inclined shear surface plus the area of the sides of the trough:

$$A \approx d(h \csc \alpha) + 2(h/2)\ (h \cot \alpha) \approx h(d + h \cos \alpha) \csc \alpha \qquad \text{(G-1)}$$

The total shear force acting parallel to the failure surface is then

$$\tau_f A = \tau_f h\ (d + h \cos \alpha) \csc \alpha \qquad \text{(G-2)}$$

where τ_f is the ultimate shear stress of the ice.

The component of shear force in the direction of motion is

$$\tau_f A \cos \alpha = \tau_f h\ (d + h \cos \alpha) \cot \alpha \qquad \text{(G-3)}$$

The total stud force opposing motion is then:

$$F_s = F_N \mu_s + \tau_f h\ (d + h \cos \alpha) \cot \alpha \qquad \text{(G-4)}$$

where F_N is the normal force on the stud and μ_s is the coefficient of friction between the stud (tungsten carbide) and the ice.

Assuming $\alpha = 45°$,

$$F_s = F_N \mu_s + \tau_f h\ (d + \sqrt{2}/2 \cdot h) \qquad \text{(G-5)}$$

It is of interest to examine the magnitude of the terms in Eq. (G-5). Assume a stud diameter of 0.10 in. From (*38*), τ_f is approximately 105 psi and independent of temperature; from (*11*), approximately 35 pounds of axial force is typically required to push a stud into the tire so that it is flush with the surface. Assuming an initial protrusion of 0.060 inch and that the tire acts like a linear spring, F_N and h would be related as follows:

$$F_N = 35 - 583\ h \qquad \text{(G-6)}$$

If a friction coefficient between the stud and ice (μ_s) of 0.10 is then assumed, Eq. (G-5) becomes

$$F_s = (3.5 - 58.3\ h) + 105\ h\ (0.10 + 0.707\ h) \qquad \text{(G-7)}$$

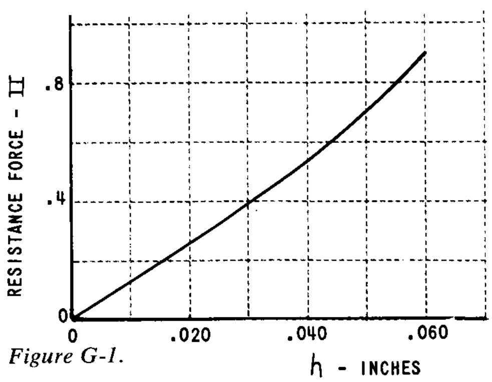


Figure G-1.

The variation of the second term on the RHS, which is the shear force, is shown in the accompanying Figure G-1. It may be seen that the first term on the RHS which is the stud-ice friction term will vary linearly from 3.5 pounds when the stud is fully compressed ($h = 0$) to 0 when the stud is fully extended ($h = 0.060$). Thus, the total force acting on the stud in the direction of motion will be greater when the stud is fully compressed than when it is fully extended. Although the total resistive force on the stud may be greater for increased compression of the stud, it must be realized that the studs will be carrying an increased portion of the total wheel load so that the total frictional force between the rubber and the ice will be reduced. Whether the total friction will be increased or decreased will depend upon the relative values of stud/ice and rubber/ice friction coefficients. It should be noted here that according to frictional melting theory of sliding on ice (*20*) the thermal conductivity of the slider will affect the friction coefficient (in general the greater the conductivity, the higher the friction coefficient). In this respect the stud material could affect the total stud resistance.

The foregoing analysis, while recognizing that F_N and h are not independent variables, does not give any indication as to what the actual groove depth will be. This is likely to be a complex problem depending upon the geometry and cutting action of the stud, the penetration hardness of the ice, frictional and pressure melting, plastic flow phenomena, etc. Since ice is a solid which flows plastically under an applied stress the "hardness" as measured by any indentation methods must depend upon the time of loading and its physical significance must be interpreted with caution. Bowden (*21*) has presented data on the hardness of ice as determined by one of the standard indentation hardness testing methods. While the authors do not suggest that Bowden's data may be used to estimate the penetration of a flat ended stud into ice, the variation found with temperature on a qualitative basis is probably significant and the numbers themselves are of interest. The hardness values when plotted against the logarithm of the loading time at constant temperature were found to be linear over a range of two orders of magnitude. Since the shortest loading time was 2 seconds and values of the order of 0.02 seconds will be significant in the studded tire case, Bowden's data were extrapolated to this value. The results, plotted in psi against ice temperature represent to first approximation an indentation pressure and are shown in Figure G-2. It may be seen that ice temperature is an important variable with the ice (not unexpectedly) becoming softer as the temperature is increased. In contrast to such strength properties as ultimate tensile, compressive and shear strengths which do not appear to be a function of temperature (*38*). It is also noted that the values are from one to two orders of magnitude greater than the shear and compressive strengths of the ice—not unlike many other crystalline materials.

It was noted above that 35 pounds force had been reported as necessary to fully compress a stud into a tire. With an 0.10 inch diameter stud, this force gives a unit pressure of 4,500 psi, which is greater than the hardness only at the higher temperatures. Again recognizing that caution must be used in applying the penetration hardness data to the stud problem, it does suggest that cutting action in addition to static penetration is important in the resistance process. A more refined theoretical approach to the stud resistance problem might logically commence with the application of metal cutting technology. The analysis of forces on a worn cutting tool by McAdams and Rosenthal (*39*) would appear to be directly related to the present problem, for example.

The preceding analysis of a single stud assumed that it was operating on smooth ice. Consider next, under high slip conditions, that a stud in the contact patch follows in the same groove cut by its predecessor. For the second stud to add resistance (assuming that any pure friction between it and the ice is exactly balanced by friction lost between the rubber and the ice), it must increase the depth of the groove (do more cutting). Since the second stud travelling in a groove will be further extended from the tire than the one initially cutting that part of the groove, the axial force tending to push it into the ice will be diminished. It is shown in (*39*) that a minimum unit pressure is required for cutting to occur, and that the cutting rate is determined largely by the extent to which the unit pressure at that time exceeds this minimum or critical pressure. Thus, the contribution of the trailing studs will be reduced although not necessarily to zero. This behavior was verified by the RCAF and the Swedish data.

The variation of the friction coefficient with wheel slip ratio has been discussed extensively in the literature, (*12*) for example, and elsewhere in this report. It was noted that in dry pavement braking the coefficient rises from 0 at no slip to a maximum value at some relatively low value of slip (typically between 8 and 20 percent). It seems generally agreed that on the front side of the curve that the apparent wheel slip is due to the tire carcass stiffness. For a studded tire operating on ice and assuming some depth of stud penetration of the rolling wheel, this characteristic will not be altered as brakes are applied. As braking is increased and the tire/stud-ice forces increase to the point that the ultimate shear strength of the ice is exceeded, a net tire-ice slip velocity will be developed and grooving will commence. At this point a departure from linearity would be expected; however, the effective coefficient should increase at least until the slip is great enough that where a groove made by one stud sliding in the patch ends (because the stud moves out of the patch), it will be continued up by another stud in the same line on the tire coming into the

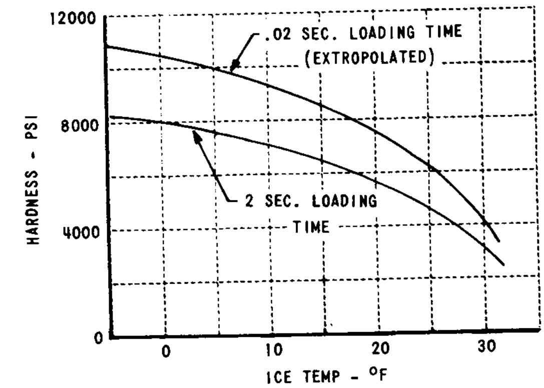


Figure G-2.

patch.* At still higher values of slip, grooves will overlap and whether further increases in effective coefficient will be realized depends upon the cutting effectiveness of the trailing studs as discussed above.

The general arguments for braking should also apply to traction for low values of slip. The limiting cases of locked wheel skidding (in braking) and spinning in place (in traction) are quite different, however. In locked wheel braking the same part of the tire is doing work on continuously changing ice. In stationary spinning, a continuously changing part of the tire is doing work on the same patch of ice; studs will traverse the same grooves and very soon the only cutting will be due to melting of the ice surface by the heat generated by the spinning tire. Thus, the effective breakaway friction coefficient would be expected to not be too different, perhaps slightly less, than the locked wheel braking coefficient. If the vehicle does not move forward exposing new ice, it would be anticipated that the effective friction coefficient or drawbar pull would diminish once wheels began to spin.

* Neglecting carcass stiffness effects, the slip ratio at which this condition will be reached can easily be determined. Assuming that the contact patch subtends a 30° segment of the tire, with only 12 studs in single lines, continuous grooves will not be cut until 100 percent slip has been reached. Increasing the number of studs in single lines to 24, 36 and 48 studs reduces the slip required to 50, 33 and 25 percent respectively. Clearly an "optimum studded tire" would be one in which no more or no less than a given number of studs were used in a single line. If a stud is fully effective anywhere within the contact patch and the assumption of 30° is valid, this number would be 12.

APPENDIX H

REFERENCES AND ANNOTATED BIBLIOGRAPHY

Annotations are included for reports concerned with stud effectiveness, since only that phase of the program called for a critical review of the literature.

1. "Report on 1963 Winter Test Program," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Gaylord, Mich.

   The primary results of the 1963 program were related to efforts to obtain data on the effect of weather variations on the coefficients of friction between passenger car tires and the ice, and on actual locked wheel stopping distances on ice. Data were taken over an ice temperature range from —3.5°F to +18.5°F on ASTM E-17 rubber highway and snow tread tires. This report presents detailed information on the equipment used (friction trailers and vehicles), test procedures, data spread, data reduction procedures and test conditions (ice temperature, air temperature, radiation, etc.). This was the first year that systematic data were taken on the reference ASTM E-17 rubber tires.

2. "1964 Passenger Car Tests," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Gaylord, Mich.

   The 1964 program was primarily an extension of that run in 1963, with data obtained at higher temperatures (up to 32°F.) A good description of the Tennessee Highway Research Skid Trailer, which had not previously been used is included along with information on the General Motors and Portland Cement trailers. Along with the reference highway and snow tires, the first data taken on studded tires by the NSC were taken.

3. "Passenger Car and Friction-Trailer Tests," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Stevens Point, Wis., *Final Report, 1965*.

   A complete report on the 1965 program which had objectives of (1) collection of data to evaluate effect of environmental variations (ice temperature, air temperature, solar radiation, and winds) on data, and (2) evaluation of performance of studded tires. ASTM E-17 rubber highway tread and snow tires were tested on friction trailers and cars over a range of ice temperatures from —10°F to +32°F. New and used highway tires with and without studs and new and used snow tires with and without studs were tested, again on friction trailers and vehicles. Four different manufacturers supplied tires. The number of studs varied between 63 and 108. A considerable amount of locked wheel braking data were obtained with much valuable information. Program suffered to some extent in that too few data were taken on too many tires. Limited traction and packed snow tests were made. The former study was too brief to obtain significant results on the latter, the condition of the packed snow course led to such nonrepeatabilities that no conclusions could be drawn.

4. "Passenger Car and Friction-Trailer Tests," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Stevens Point, Wis., *Final Report, 1966*.

   An extensive series of tests was made on glare ice to evaluate effectiveness of studded tires. Friction trailers and passenger cars were used to measure locked wheel braking characteristics (friction coefficient and stopping distances) on ice ranging in temperature from 6°F to 32°F of both highway and snow tread tires with and without studs. ASTM E-17 rubber tires were used to correlate 1966 data with those taken in previous years. The number of studs varied from 48 to 144. Tires with porcelain studs were also tested. New and used tires were tested and a limited investigation of protrusion length was made. On vehicle tests only the rear tires were studied. This report contains some of the most significant data available on braking performance of studded tires on ice. Data are also included from vehicle and skid trailer tests on braking performance of studded tires on wet and dry bare pavement.

4a. WHITEHURST, E. A. and EASTON, E. H., "An Evaluation of Studded Tire Performance," *Highway Research Record, Number 171, 1967,* also presented at the 46th Ann. Meeting, HRB, (Jan. 1967).

   This report contains a summary of the studded tire performance test results obtained in the National Safety Council Winter Driving Hazards programs of 1964, 1965, and 1966, the details of which are reported in (*2*) and (*3*). Skid trailer coefficients of friction, vehicle stopping distances and limited traction test results are presented for various tires (highway, snow, studded, unstudded, new, worn, etc.). Most of the data presented are for an ice temperature of 25°F. This paper was released as this report was being published. Although not referred to in the text, it is included here for completeness.

5. SALOSIS, J. L. A. and COUSINS, A. R., "Evaluation-Studded Tires," *RCAF Central Experimental and Proving Establishment Report No. 1782,* (June 1965).

   Reports braking, acceleration and drawbar pull investigations made to evaluate operational characteristics of studded tires on a cargo truck and an aircraft towing tractor. Tests were made on glare ice and dry asphalt and concrete pavements. Braking and tractive accelerations were measured with an on-board accelerometer and drawbar pull from a dynamometer. Braking and traction tests were made with unstudded tires and tires (four wheels) containing 216 studs. Drawbar pull tests made with unstudded tires and tires containing from 72 up to 360 studs in rows varying in number from 4 to 12.

   Measurements were made of both tire and stud wear over 5000 miles of driving. Considerable information on installation techniques is included as well as observations on the effect of the studs on various pavement surfaces.

6. "Dubbade Dack-Friktionsmatningar Med Nydubbade Vinterdack-Vintern 1962-1963, Forslitningsprov Med Dubbade Vinterdack-Sommaren 1963," *Statens Vaginstitut, Stockholm, Special Rapport 21.*

   Reports a research program on studded tires conducted by the National Swedish Road Institute. In the winter of 1962-1963, the frictional properties were investigated on the three most popular studs in use in Sweden at that time. Friction trailers were used in which the amount of slip could be controlled at various values as well as at 100 percent (locked wheel). Tests were made on smooth ice and compacted snow. The number of studs in a tire was varied between 0 and 364 spotted in up to eight different lines. Data were taken at two speeds—20 and 60 km/hour (12.4 and 37.3 mph). Stud effectiveness of lines located at different distances from the edge of the tread and at different slip ratios were studied. A program was run on bare roads to examine stud wear and retention.

7. PULLEY, A. L. and DELL'AMICO, F., "Performance of Studded Tires on Ice," CAL *Report No. VJ-2204-V-1,* (Mar. 1966).

   Presents results and analysis of vehicle tests conducted by CAL at Stevens Point, Wisconsin, concurrent with NSC WDH program in 1966. Vehicle braking, acceleration and cornering in steady turns were studied on clean smooth (glare) ice over a temperature range of 1°F to 30°F. New and used unstudded and studded highway tires on the front wheels and snow tires on the rear wheels were used in various combinations. Data were measured by on-board instrumentation and a fifth wheel to give longitudinal and lateral accelerations, vehicle speed and displacement, brake pressure, steering angle and yaw rate. Results presented are in the form of stopping distance, calculated "effective friction coefficient," forward speed and lateral acceleration at breakaway in cornering and time to accelerate. One of only two sources of performance data with studs on all four tires.

8. W. P. MILLER, II, "The Winter Tire Stud," *Highway Research Record No. 136,* also presented at the 45th Ann. Meeting, HRB, (Jan. 1966).

   This paper included nontechnical descriptions of the working principles of the tire studs, installation practice and historical background on the usage of studs in Europe, Canada and the United States.

9. BURNETT, W. B. and KEARNEY, E. J., "Studded Tires—Skid Resistance and Pavement Damage," *Highway Research Record No. 136,* also presented at the 45th Ann. Meeting, HRB, (Jan. 1966).
   "Effect of Studded Tires on Skid Resistance and Pavement Wear," State of N. Y., Depart. of Public Works, *Physical Research Report RR-65-3,* (May 1965).

   These two reports contain the same information and are identical except for minor differences. A skid trailer was used to obtain "friction coefficients" a 7.75 x 14 snow tire and a similar tire containing 67 tungsten carbide studs. Tests were made at 30 mph on new and old bituminous and concrete pavements both wet and dry, on ice at temperatures above 30° and below 20° and on "packed snow." "Average friction coefficients" are presented in a table for the various conditions tested.

10. BURKE, JOHN E. and MCKENZIE, L. J., "Some Tests of Studded Tires in Illinois," *Highway Research Record No. 136,* also presented at the 45th Ann. Meeting, HRB, (Jan. 1966).

   Locked wheel braking tests were made using a stationwagon on a dry portland cement concrete surface. Stops were made for speeds of 10, 20 and 30 mph. At each speed, five stops were made with the following tire combinations: (1) four standard passenger car tires (sizes unspecified), (2) two studded snow tires (103 to 108 studs) on rear and two standard tires on front, and (3) four studded snow tires. Five runs were made at each condition and average stopping distances are tabulated. No data are reported using unstudded snow tires.

11. CARLSTEDT, R. L., "Report on Tire Studs for Passenger Cars 1964," Kennametal, Inc., Latrobe, Pennsylvania, (Oct. 1964).

   This document discusses a number of practical aspects of stud usage and particularly stud number, protrusion, retention, wear, etc. No test data or analysis are included nor are any references to such work made. While not strictly a technical report, it has been included here because it has been referred to in the literature.

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Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

THE DIVISION OF ENGINEERING is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

THE HIGHWAY RESEARCH BOARD, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.

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