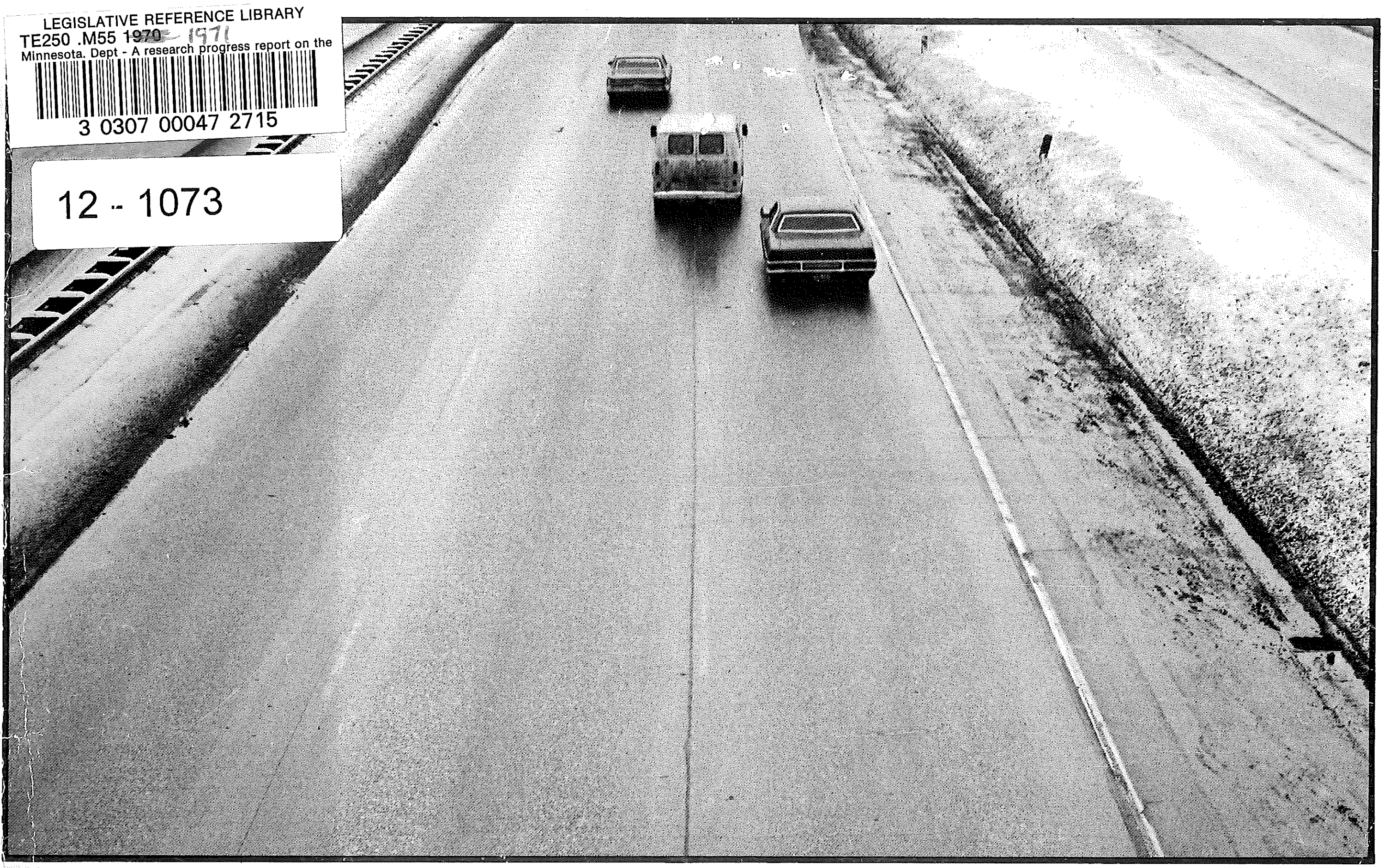
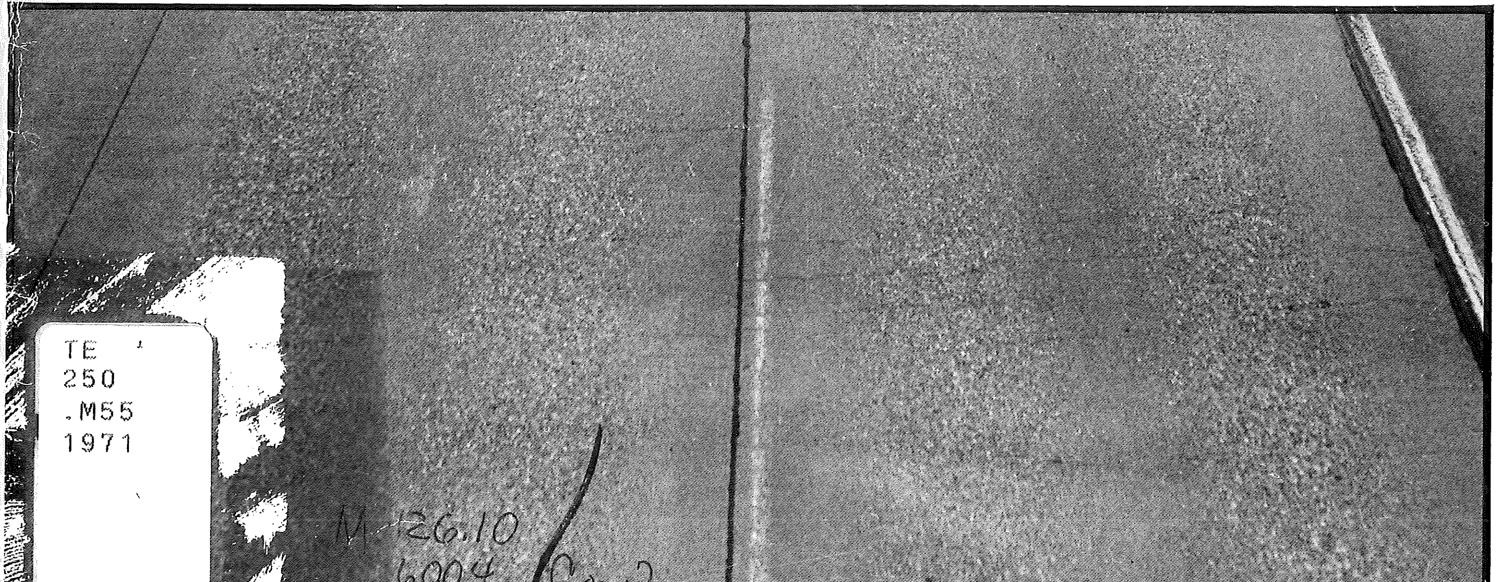


A RESEARCH SUMMARY REPORT FOR THE MINNESOTA LEGISLATURE

THE EFFECTS OF STUDDED TIRES

THE MINNESOTA DEPARTMENT OF HIGHWAYS

MARCH 1971



A Research Summary Report

on the

EFFECTS OF STUDDED TIRES

prepared for

The Legislature

State of Minnesota

by the

Minnesota Department of Highways

Supported in part by the states of
Illinois, Iowa, Michigan, New York,
North Dakota, Pennsylvania, Utah and
Wisconsin

March, 1971

FOREWORD

The 1969 Legislature of the State of Minnesota under Minnesota Statutes, Chapter 169.72, directed the Commissioner of Highways to conduct an in-depth study on the safety and pavement-wear effects of studded tires. This, the final report of that study, summarizes the research efforts and the results. The report is prepared for the specific use of the 1971 Legislature.

The Commissioner of Highways is indebted to the many organizations that cooperated in providing information: The American Oil Company for conducting the pavement-wear tests; Kennametal Corporation for furnishing and installing studs in test tires; Cornell Aeronautical Laboratories for the accident study and analyses; the Minnesota Highway Patrol and other offices of the Department of Public Safety for accident reporting and survey coordination; and the many city police departments for supplementing accident reports with data required for the study. Participating cities were Brooklyn Center, Duluth, Edina, Grand Rapids, Mankato, Minneapolis, Richfield, Rochester, Roseville, St. Cloud and St. Paul.

Special thanks are due those states that contributed funds for defraying part of the project costs: Illinois, Iowa, Michigan, New York, North Dakota, Pennsylvania, Utah and Wisconsin.

The content, findings, and conclusions expressed or implied in this report are those of the Minnesota Department of Highways. They do not necessarily represent the views of the organizations providing data for the report or the cooperating states.

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SUMMARY OF FINDINGS

Pavement Wear Aspects

1. Since studded tires were legalized in 1965, the average percentage of passenger vehicles equipped with studded tires increased to about 40 percent during the winter of 1969-70. Surveys during the winter of 1970-71 indicated a slight drop in use to approximately 37 percent. If studded tires are legalized indefinitely, ultimate use is expected to rise to 60 percent by the winter of 1973-74.

2. Pavement wear measurements show that pronounced wheel path wear was virtually non-existent on high-type roadways prior to the introduction of studded tires in 1965.

3. The severity of surface wear on the basis of wear measurements is directly proportional to the amount of studded tire traffic.

4. In the laboratory tests, the average terminal wear rate for the various conventional bituminous wearing courses ranged between 0.75 and 0.91 inch per million studded tire passes. For the conventional concrete pavements the range was 0.30 to 0.47 inch per million studded tire passes.

5. The laboratory tests disclosed that the amount of stud protrusion beyond the face of the tire tread significantly affected wear rates: the greater the protrusion the more the wear within the range of protrusions measured at the test track.

6. The laboratory tests using unstudded snow tires with applications of salt and sand at a subfreezing temperature of 25 deg. F. produced virtually no wear.

7. A comparison of laboratory test results showed that studded tires without sand and salt abraded the pavement specimens more than 100 times as rapidly as unstudded tires with sand and salt.

8. In combination with studded tires, sand or salt individually contributed incrementally to the total wear of the test-track pavements; with unstudded tires salt alone produced no measurable wear, and sand alone produced a measurable but insignificant amount of wear.

9. Some new pavement compositions tested in the laboratory were more wear-resistant than conventional Minnesota pavements, but the proportionate increase in the cost of the materials generally exceeded the indicated reduction in wear.

10. A wear-rate ratio of 5.5 to 1 was established between the test track wear rates and the measured rates of wear on highway surfaces. This relationship is approximately the same for all pavements studied.

11. Studded tires have damaged pavement surfaces, particularly on those highways with high traffic volumes. Continued use of studded tires will nessitate substantial repairs in addition to those expected during the normal service life of the pavements.

12. Using criteria defined in this report, with the continued use of studded tires it is estimated that damage repair of pavements and bridge decks due to stud abrasion and the use of more wear-resistant pavements for new construction would amount to $55 million on the trunk highway system by 1980. The cost study shows, however, that no expenditures would be incurred until 1973 after which annual expenditures would gradually accelerate to $12.6 million in 1980. The damage cost would increase significantly after 1980 when the wear depth on medium-volume roads would have reached the point of repair.

Safety Aspects

The following summary represents a compilation of findings, including those drawn from the Cornell Aeronautical Laboratory (CAL) study plus those developed from Minnesota Highway Department records and observations from other sources. The CAL study covered 5½ months of the two periods in 1970 when studded tires were legal. It included 4,500 accidents involving 7,150 autos. Vehicles other than autos were excluded from the study. About 60 percent of the approximately 99,400 accidents and about 44 percent of the approximately 987 traffic deaths in 1970 occurred during the 6½ months when use of studded tires was legal.

1. Exposure to driving on snowy and icy roads depends on the type of road and regional location. Questionnaire returns as analyzed by Cornell Aeronautical Laboratory showed that six percent of all driving during the study period occurred on roads completely covered with ice, snow, slush, or frost. Another six percent occurred on mostly covered roads, and 18 percent on roads with scattered cover. This means that 70 percent of winter driving was on bare roads - about six times the amount of driving that occurred on icy roads as established by the Highway Department. From the Department records over 95 percent of 1970 winter freeway driving was on bare pavement, less than 2 percent on ice. On the other hand, on township roads less than 50 percent of 1970 winter driving was on bare surfaces, and about 30 percent on ice or packed snow.

2. Twenty-one percent of the accidents reported in the CAL study were precipitated by sliding on ice, snow, slush, or frost. This infers that about 13 percent of all Minnesota accidents in 1970 could have been precipitated by sliding on icy or snowy roads. Of all single vehicle accidents in the study period, 30 percent were said to have been precipitated by sliding. Considering all accident vehicles in the study, 14 percent were involved due to their own sliding. (This figure is low because the group of all accident vehicles includes those which were stopped or were suddenly imposed upon.) Accidents precipitated by sliding are more apt to be single-car accidents.

3. Of all traffic deaths in the sample of accidents, 12 percent resulted from accidents generated by vehicles which triggered (precipitated) the accident due to sliding on snowy or icy roads. This infers that six percent of all 1970 traffic deaths occurred in accidents triggered by sliding on such roads. Accidents generated by sliding also accounted for 13 percent of the A-level injuries, 15

percent of the B-level injuries, and 17 percent of the C-level injuries. (A-level injuries are the most severe and C-level the least serious, as judged from visual indications.)

4. The estimated rates for triggering an accident more than doubled as road conditions changed from little or no cover to completely covered, in spite of increased driver caution evidenced by decreased severity. Department records substantiate this finding.

5. Comparing trigger vehicles involved due to sliding with trigger vehicles which were not, the sliding vehicles were involved in less severe accidents as measured by impact speed and resultant vehicle deformation. This presumably resulted from reduced travel speeds on slippery road surfaces. In general, accidents triggered by sliding on snowy and icy roads are less severe than non-sliding accidents, involve fewer vehicles, cause fewer and less severe injuries, and cause less property damage per accident.

6. While the use of studded tires varies regionally and locally, vehicles using studded tires accounted for about 38 percent of the winter driving in Minnesota during 1970.

7. Vehicle performance on ice is significantly enhanced by the use of studded tires, but such performance falls far short of that on bare pavement with any type of tire.

   Vehicle stopping performance on glare-ice improved by 10 to 30 percent through the use of studded tires; however, vehicle stopping performance on ice with or without studded tires is inferior to vehicle stopping performance on bare road surfaces by five to six times.

   Vehicle control during straight-line travel on ice may be somewhat enhanced by the use of studded tires on rear wheels; however, vehicle cornering and maneuverability performance on ice is not improved by use of studded tires unless the tires on all four wheels are studded.

   Vehicle starting traction on ice may be improved up to 30 percent and icy hill climbing ability doubled by use of studded tires.

8. Vehicle performance when aided by use of studded tires is most improved on warm, clean glare-ice. Significantly smaller improvements are obtained on other surfaces such as very cold ice, rough ice, sanded ice, snow, and slush.

9. Improvements in vehicle performance through use of studded tires on ice are much smaller than improvements obtained by sanding, deicing chemicals and chains.

10. Use of studded tires is generally detrimental to vehicle performance on bare pavements in terms of increased stopping distances and increased unintentional vehicle rotation on dry pavements.

11. Wear caused by studded tires contributes to safety hazards such as: premature loss of pavement lane markings, loss of pavement grooving for skid prevention, reduction in driving visibility due to increased splash and spray from water accumulating in rutted wheel tracks, adverse steering effects caused by rutted wheel tracks, improper placement of vehicles within traffic lanes to avoid worn wheel tracks, and possible loss of skid resistance due to surface deterioration from studded tire wear.

12. Evidence obtained from examination of official state accident statistics was not sufficiently useful to evaluate the safety effects of tire types, thus leading to initiation of the CAL study. The recent modest improvement in highway safety observed in Minnesota and nationally is attributed to the combined effects of many safety improvements to roads and vehicles.

13. When the degree to which roads were covered with ice, snow, slush, or frost was described as either scattered, mostly covered, or completely covered, the indicated likelihood of triggering an accident due to sliding was least for automobiles with studded tires and greatest for automobiles with regular tires. However, the degree of change in accident frequencies implied by the "face value" findings is slight when compared to the total number of accidents in Minnesota.

14. On roads with little or no cover, the indicated likelihood of triggering an accident, with or without sliding, was consistently lower for autos with studded tires, thus indicating a "bias" (denotes extraneous influences in the data) favoring studded tires. CAL has speculated that this bias might arise from drivers who are safety oriented choosing to use studded tires. Using procedures intended to remove this bias, the indicated likelihood of triggering an accident by sliding on snowy and icy roads during the midwinter months was less for studded tires than for snow tires and less for snow tires than for regular tires. On the other hand, during the early or late winter months the indicated likeihood was greater for studded tires than for snow tires, but greatest for regular tires. In either case, the data and procedures are not sufficiently precise to warrant a quantitative estimate of any changes in accident frequencies that may be attributable to studded tires.

15. Preimpact behavior indicators examined by CAL showed some effects of tire type, but the extent of driver influence upon the results cannot be ascertained.

    Preimpact rotation on dry roads was least for vehicles with regular tires and greatest for those with studded tires. On wet roads, both studded tires and snow tires performed slightly better than regular tires with respect to preimpact rotation. On roads covered with ice, snow, slush or frost, vehicles with studded tires had somewhat less rotation than those with snow tires, with both performing better than those with regular tires. On roads completely covered with ice or frost, studded tires performed better than snow tires, and snow tires somewhat better than regular tires.

Vehicles with either studded tires or snow tires had lower impact speeds than did vehicles with regular tires, considering vehicles triggering accidents due to sliding in zones with speed limits above 50 miles per hour.

16. Accident severity indicators examined by CAL also showed some effects of tire type, but again the extent of driver influence upon the results cannot be ascertained.

    The effects of tire type upon impact-deformation were not sufficiently great to demonstrate a systematic advantage to any one of the tire types.

    There were 23 autos with studded tires which experienced single vehicle accidents exclusive of sideswipes and rollovers; for these vehicles, none of the drivers was injured. However, when considering autos which triggered both single and multi-vehicle accidents by sliding, the advantage to drivers using studded tires persisted but was far less pronounced.

CONCLUSIONS

The legislation authorizing this study specified the scope of the investigation to be undertaken. Three specific tasks were defined: (1) "to conduct an in-depth study of the damage, if any, caused to the public highways of this state which results from the use of metal tire studs, salt de-icing materials, and other materials of a chemical or physical nature used upon said highways," (2) "to evaluate whether or not changes in asphalts, concrete aggregates, or other highway surface materials could be made to reduce the damage, if any, caused by metal tire studs and de-icing materials," and (3) to "evaluate the effects, if any, that discontinuing the use of studded tires will have on highway safety." The ensuing paragraphs are addressed to the three foregoing tasks and constitute the conclusions reached from this study.

Pavement Damage

Studded tires have damaged highway pavements by abrading surfaces and producing troughs in the wheel tracks of the traffic lanes. The degree of wear is proportional to traffic volume so that the greatest wear is observed on high-speed, high-volume roadways. The wear is sufficient to require substantial expenditures for intermediate surface repair before pavements will have fulfilled their normal service-life. Even though the wear for large mileages of the state highway system in lower traffic areas may not reach the point of surface repair within the normal service-life period, the quality of the surfaces is being impaired by studded tire abrasion.

Salt and Sand

Pavement wear measurements show that virtually all of the abrasion damage to roadway surfaces has occurred since 1965 when studded tires were first legalized even though salt had been used for snow and ice control for many years prior to that. The damage to concrete normally associated with salt is avoided by the use of "air-entrained" concrete which has been standard practice in Minnesota concrete pavements for 25 years. Air-entrained concrete is produced by adding a substance to either the cement or the mixing water which results in trapping minute bubbles of air in the mix. The entrapped air, up to seven per cent by volume, protects the concrete from deterioration due to salt and weathering cycles of freezing and thawing.

The laboratory tests conducted for this study disclosed that sand and salt in the presence of studded tires contributed some wear to specimen pavements, but virtually no wear was observed when sand and salt were used in the presence of unstudded tires. This would indicate that sand and salt increase the wear of pavements subjected to studded-tire traffic, but have virtually no adverse effect on pavements carrying unstudded-tire traffic.

More Durable Materials

The laboratory tests show that it is possible to formulate more wear-resistant pavement compositions, both concrete and bituminous, but the wear reduction achieved with specially-selected materials is counterbalanced by a corresponding increase in cost. Concrete pavements can be made more resistant by increasing the amount of cement and using the hardest, most durable stone from sources normally not in close proximity to highway construction. Thus, shipping costs, in addition to the higher cost of the stone at its source become a significant economic factor. Bituminous pavement can be made almost as wear-resistant as some current conventional concrete pavements by also using the highest quality stone aggregate with the addition of rubber and asbestos fibers in the formulations. No mixture tested was fully resistant to studded-tire wear. More specifically, on the basis of the laboratory tests the wear of the best concrete pavements could be reduced about 10 percent at a cost increase of 25 percent, and the wear of the high type bituminous pavements could be reduced about 50 percent at a cost increase of 40 to 45 percent.

Safety Effects

The effect on highway safety if studded tires were discontinued is difficult to evaluate in specific terms. Accident causation factors are variable and often as hard to quantify as they are to identify. The Cornell Aeronautical Laboratory (CAL) study, by showing a lower involvement of studded tire vehicles in sliding accidents on icy roads, confirms the test-established performance advantages of studded tires on ice-affected surfaces. At the same time the study shows that sliding accidents are less severe than other types of accidents, a fact which correlates with state accident statistics showing that wintertime accidents are generally less severe than those occurring during the remainder of the year. The CAL analysis indicates a potential increase in sliding accidents on ice-affected surfaces if studded tires had been replaced by snow tires during the study period. The resultant increase in accidents would have been slight in relation to the total number of traffic accidents in Minnesota. A more exact statement is not possible because the influence of driver characteristics and the effects of studded tires upon the precipitation of sliding accidents cannot be separated.

The indicated benefit credited to studded tires in reducing sliding accidents must be weighed in relation to the potential detrimental effects of studded tires on year-round highway safety. These would include premature loss of pavement lane markings from studded tire abrasion, loss of pavement grooving for skid prevention, reduction in driving visibility due to increased splash and spray from water accumulating in rutted wheel tracks, adverse steering effects caused by rutted wheel tracks, improper placement of vehicles within traffic lanes to avoid worn wheel tracks, and possible loss of skid resistance due to surface deterioration from studded tire wear. Traffic is exposed to most of these effects year-round, not just during the studded tire season. None of these effects, however, was covered by the CAL study, and any meaningful assessment of the effects of studded tires on highway safety should take them into consideration.

Minnesota accident records show that since 1966 there has been a modest decline in the fatal accident rate, while the overall accident rate has continued to rise at a diminishing pace. These benefits correspond with a similar national trend and are attributed by safety experts to the intensive effort to improve safety characteristics of vehicles and roads. The fact that so great an effort has not produced more improvement in accident rates demonstrates that the problem of traffic safety rests heavily upon the driver as well as upon the road and it does not appear possible from analyzing accident trends to isolate the influence of any one particular factor.

A conclusion of the effects of studded tires on highway safety at this point in time must necessarily rely to some degree on judgment. The inseparable extraneous influences involved in the data as referred to in the CAL study report, and the adverse effects of studded tires on driving safety would tend to dilute any benefits ascribed to studded tires. It seems reasonable to conclude, based on all findings as well as influences which cannot be quantified, that if studded tires were discontinued there would be little appreciable change in traffic safety in Minnesota.

INTRODUCTION

Background

The term "studded tires" refers to snow tires fitted with tungsten carbide studs which protrude from the surface of the tire tread and provide thereby, for vehicles operating on icy roads, greater traction, shorter braking distances, and improved driving stability when studs are used on all four wheels. Associated with the use of studded tires is observed pavement wear which can be severe particularly on high-speed, high-volume roads. The damage potential to pavement surfaces is a problem of growing concern not only in Minnesota but in other snowbelt states, the provinces of Canada, and northern European countries.

Studded tires were first legalized for use in Minnesota during the period October 15 to April 15 of the biennium following the 1965 legislature, subject to renewal after two years. Since that time the popularity of studded tires has grown to a point where over 40 percent of the vehicles in the state were equipped with studded tires (almost totally on rear wheels only) during the winter of 1969-70. Usage decreased somewhat during the 1970-71 season, possibly due to publicity over the studded tire issue.

During the 1969 legislative session the Commissioner of Highways expressed deep concern over the pavement wear damage being observed at various locations on the state highway system (such as shown in Figures 1 and 2) and recommended that legislation authorizing the further use of studded tires not be renewed. The legislature was faced with a dilemma: the growing use of studded tires indicated public popularity, and the advocates of studded tires stressed the benefits to traffic safety. Because of the apparent controversy the legislature decided upon a compromise course: the use of studded tires was extended for another two years until May 1, 1971 and the Commissioner of Highways was directed to conduct a study of the effects of studded tires on safety and pavement wear. This report is a final report on that investigation.

Legislation

The authority for the investigative study is covered in Minnesota Statutes, Chapter 169.72, the last paragraph, which reads:

"The commissioner of highways is directed to conduct an in-depth study of the damage, if any, caused to the public roadways of this state which results from the use of metal tire studs, salt de-icing materials, and other materials of a chemical or physical nature used upon said highways. Further, the commissioner is directed to evaluate whether or not changes in asphalts, concrete aggregates, or other highway surface materials could be made to reduce the damage, if any, caused by metal tire studs and de-icing materials. The commissioner shall evaluate the effects, if any, that discontinuing the use of studded tires will have on highway safety. The commissioner is directed to conduct the study herein prescribed and to report his findings to the 1971 session of the state legislature."

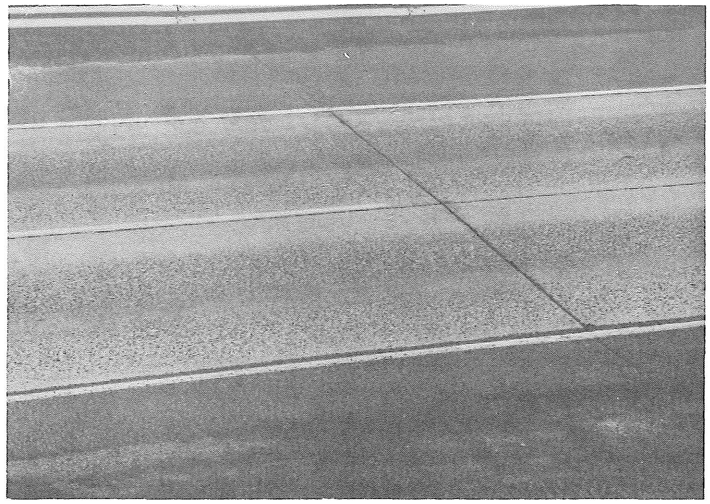
Research Tasks

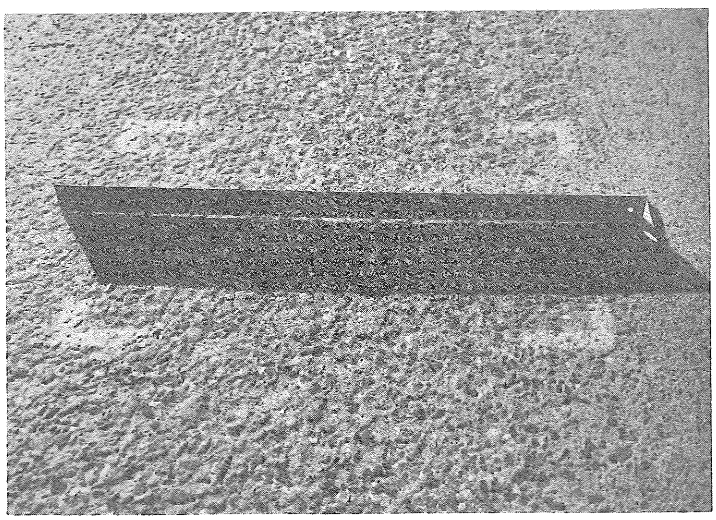
The study assigned by the legislature involved essentially three tasks: (1) a determination of the relative damage, if any, caused to pavement surfaces by studded tires, de-icing chemicals and other materials, (2) an evaluation of pavement compositions that might resist damage to the surfaces by studded tires and de-icing materials, and (3) an evaluation of the effects on highway safety if the use of studded tires were discontinued. The first two tasks were interpreted as basically interrelated, with the second being an outgrowth of the first. Implied in the work was the need for research data from controlled testing under simulated traffic conditions and a correlation of the results with actual observations of pavement wear on the state highways. The third task was considered the more complex assignment -- determining whether discontinuance of studded tires would have any adverse effects on traffic safety -- for it implied that some means be employed to analyze factually the safety effects of studded tires.

Literature Review

The Department of Highways in commencing work on the study first made a literature search of information from all available sources. The object was to fulfill the needs of the study, insofar as

Wheel Path Abrasion





Wear Depth in Wheel Path

Aggregate Severely Exposed

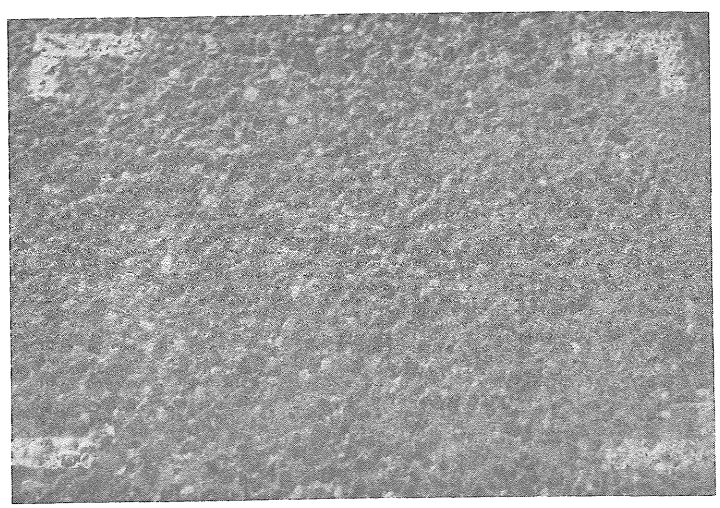
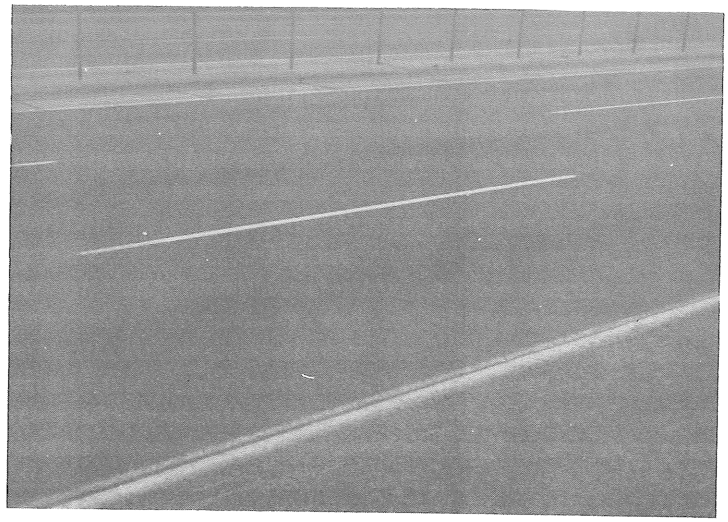
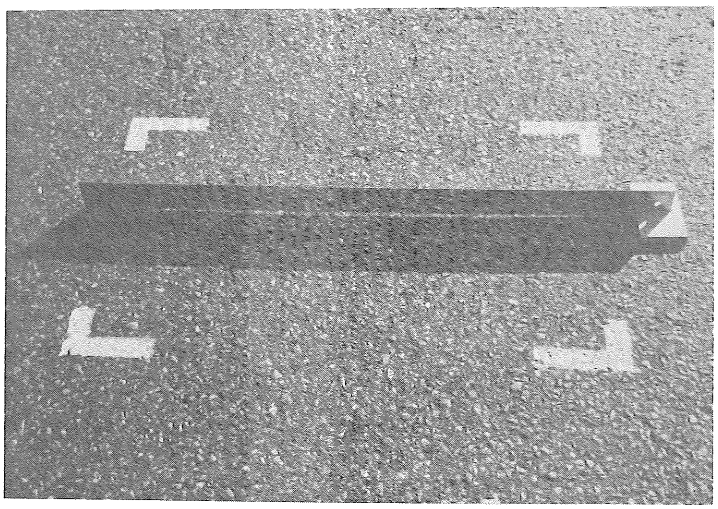


Figure 1. Concrete Pavement Wear

Wheel Path Abrasion





Wear Depth in Wheel Path

Aggregate Severely Exposed

Figure 2. Bituminous Pavement Wear

possible, from known information and to supplement with special investigations only in areas of insufficient or missing data.

Since studded tires originated in Europe and were in use there prior to being used in the United States, some research reports were available from the Scandinavian countries, Finland and Germany. These reports documented observations of pavement wear, particularly for bituminous pavements, and covered efforts to develop surface treatments that would resist more effectively the abrasion damage inflicted by the studs. (Studded tire use in the northern European countries involves up to 80 percent or more of the vehicles, most of which are equipped with studded tires on all four wheels, including trucks.)

In the United States the earliest extensive tests relating to certain safety effects of studded tires were conducted by the committee on Winter Driving Hazards of the National Safety Council in 1964 at Stevens Point, Wisconsin. These were stopping distance tests conducted on a smooth ice-covered surface to compare the relative stopping, or braking, distances required at 20 mph for vehicles equipped with regular tires, snow tires and studded snow tires under various temperature conditions. Subsequent tests have been made by the National Safety Council.

During the winters 1965-66 and 1966-67 the Minnesota Highway Department conducted pavement wear tests in the field on both asphalt and portland cement concrete surfaces using a single car equipped with studs on all four wheels. Observations were made of the wear effects produced when making abrupt starts and stops from several speeds up to 50 mph. At about the same time a few other states also undertook certain field pavement wear tests. Although these tests indicated that studs could produce significant pavement abrasion, they were too limited in scope and the results too inconclusive to warrant a recommendation for prohibiting studs.

The most comprehensive state-of-the-art study in this country was conducted by the Cornell Aeronautical Laboratory, Buffalo, New York, under the sponsorship of the National Coöperative Highway Research Program supported by state and federal highway funds and administered by the Highway Research Board of the National Academy of Sciences and the National Academy of Engineering. The report on this study, Report 69, entitled "Evaluation of Studded Tires", was published by the Highway Research Board in 1969. It covers then-known information about both the safety and pavement wear aspects.

More recently, August, 1970, the Ontario Department of Highways issued a report on studded-tire damage to pavements. The report also included a summary of a series of studded tire performance tests conducted in March and April, 1970 by consulting engineers for the Canada Safety Council. In addition, the Province of Quebec has also produced several research reports.

Data from the foregoing and any other available sources have been used in this study to the extent that the facts have application to the tasks assigned by the legislature. A specific bibliography is appended for further reference.

Research Approach

The literature review disclosed that current information was too inadequate to fulfill the legislature's assignment. Virtually no data were available on pavement wear where the abrasion effects of studded tires could be correlated with field observations. Likewise, although considerable information had become available on the performance of vehicles equipped with studded tires, particularly as to stopping distances, little had been done in a factual way to ascertain whether studded tires were making any significant contributions to traffic safety.

The Department then decided on a three-phase research program consisting of (1) continuing field surveys of studded tire use throughout the state and increasing the observations of pavement wear, (2) contracting with an independent research agency for controlled pavement wear testing of typical Minnesota pavements, both concrete and bituminous, together with treatments which might prove more resistant to abrasion. and (3) contracting with a second research agency for an accident data analysis to determine whether studded tires contribute to a reduction in accident frequency and severity.

To carry out this program required that the Department design and administer the in-house and contract research projects which would produce the basic information needed for both the wear studies and safety studies. The Department had to place the information from the research agencies in proper perspective. The laboratory wear study findings had to be correlated with road wear determined from the in-house studies. All the wear aspect studies had to be integrated for a determination of the additional road repair cost attributable to studded tires. Similarly the findings from the contract safety study had to be interpreted in relation to all known facts and conditions affecting the overall problem of traffic safety as influenced by studded tires.

The first task was assumed by the Department. After considerable searching, it was determined that the only facility capable of conducting the second phase, controlled pavement wear tests under the environmental conditions required, was a circular test track, or traffic simulator, owned by the American Oil Company and located at its laboratory in Whiting, Indiana. American Oil expressed a willingness to undertake the test program including necessary modification of its equipment to meet test conditions. An agreement with American Oil was fully executed October 23, 1969. The only research agency with apparent capability to conduct the third phase of the program was the Cornell Aeronautical Laboratory. That organization had extensive prior experience in accident data analysis and a background of knowledge about studded tires. A proposal for a research plan was solicited and ultimately accepted. Under a pre-encumbrance procedure work commenced December 8, 1969, and an agreement for services was fully executed May 4, 1970.

As the work progressed and interest in the pavement wear tests broadened, it became apparent that some film documentation was needed to inform the legislators, the public, and other parties interested in the test procedures. Arrangements for production of a documentary movie film were made with the University of Minnesota, Production Services Department. Copies of the film have been furnished to the participating States. Several copies have been retained by the Department and are available for showing upon request.

Summary of Costs

An approximation of the costs of the research program is tabulated below. Reimbursement for services by outside agencies are based on actual costs, as applied under the terms of the agreements, and the total costs shown are estimates used for contract purposes.

Department of Highways	$190,000*
American Oil Company	195,000
Cornell Aeronautical Laboratory	62,140
University of Minnesota	17,500
Total estimated project costs	$465,300

**Cumulative costs chargeable to project and administrative overhead estimated to 7-1-71.*

Participation by Other States

When the costs of the program became apparent, other states concerned about the studded tire problem were invited to share in the costs as well as in the results of the project. The response was gratifying. Eight states volunteered participation in varying amounts, and agreements were executed covering their participation. The eight states and the amounts contributed are shown below:

Illinois	$20.000
Iowa	20,000
Michigan	26,000
New York	25,000
North Dakota	12,500
Pennsylvania	20,000
Utah	12,500
Wisconsin	25,000
Total participation	$161,000

PAVEMENT WEAR ASPECTS

Scope

The primary objective of the research program was to investigate pavement wear by establishing a correlation between controlled pavement wear tests in the laboratory with observed wear measurements in the field for pavements commonly used in Minnesota. Essential to the correlation of wear rates was the number of studded-tire wheel passes required to produce observed wear both in the laboratory and the field. The number of wheel passes applied in the laboratory was merely a matter of counting, but in the field it was necessary to estimate wheel passes in terms of traffic counts and projected traffic volumes to which a studded-tire-use factor could be applied. The latter was obtained from field surveys of actual studded tire use. Thus, the pavement wear research involved use surveys, field measurements of wear, traffic surveys and laboratory pavement wear tests. Associated with the laboratory phase and field pavement wear studies was some experimentation with paving mixtures and treatments that might improve resistance to studded-tire abrasion.

Studded Tire Usage

Since studded tires were first legalized in 1965, annual surveys have been made in various parts of the state to determine the percentage of vehicles equipped with studded snow tires, unstudded snow tires and conventional highway tread tires. The surveys were made at parking lots in late December or early January and included the rear tires of passenger cars only with the exception of 1970-71 when front wheels were checked also. The latter survey indicated that the number of passenger cars with studded tires on the front wheels was negligible, about 0.1 percent state-wide. The number of trucks equipped with studded tires also appears to be negligible.

The percentages of passenger cars equipped with studded tires on the rear are shown in Table 1 for the Minnesota Department of Highways maintenance areas. Within the St. Paul-Minneapolis metropolitan area, studded tires have grown in use as shown in Figure 3. State-wide figures are similar. The results for 1970-71 indicated that the state could be divided into three general studded-tire-use areas as shown in Figure 4. The decline in studded

TABLE 1. MINNESOTA DEPARTMENT OF HIGHWAYS STUDDED-TIRE-USE SURVEY PERCENT OF CARS HAVING STUDDED TIRES

Location	1965 - 66	1966-67	1967-68	1968-69	1969-70	1970-71
Area 1A	3.6	11.7	---	44.0	46.8	38.5
Area 1B	---	20.6	---	---	44.5	46.9
Area 2A	2.5	14.2	---	38.7	44.1	42.0
Area 2B	---	10.2	---	30.8	37.2	47.2
Area 3A	---	3.9	---	21.3	30.6	29.1
Area 3B	---	8.5	---	24.2	39.9	33.0
Area 4A	---	7.4	---	18.4	35.8	30.7
Area 4B	---	5.1	---	29.5	34.2	36.3
Area 5A	3.5	9.0	22.2	31.7	40.0	37.4
Area 6A	---	5.6	---	24.2	20.7	21.6
Area 6B	---	6.6	---	22.0	20.9	15.9
Area 7A	---	8.2	---	17.3	39.4	37.4
Area 7B	---	4.3	---	22.0	35.3	34.1
Area 8A	---	10.0	---	34.7	40.7	38.4
Area 8B	---	5.8	---	25.4	31.5	38.6
Area 9A	4.0	8.8	26.0	31.8	40.0	36.0

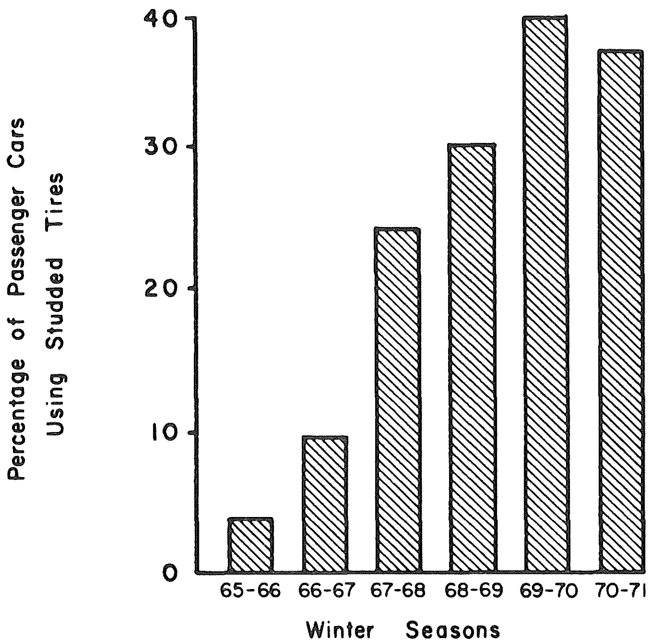


Figure 3. Studded Tire Usage Minneapolis - St. Paul Metro Area

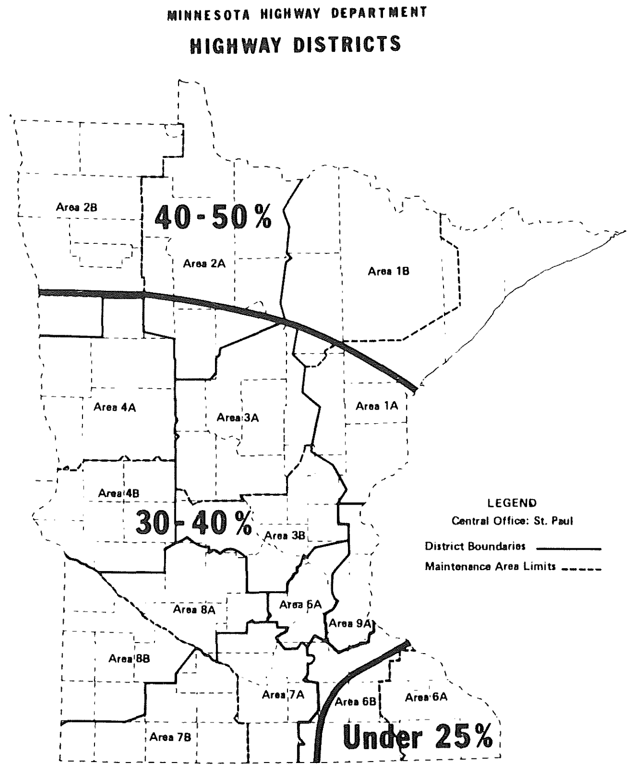


Figure 4. Current Studded Tire Percentage Zones

tire use during the 1970-71 winter was probably caused by the publicity given the studded tire issue and the possibility that the Legislature might ban the use of studded tires.

A telephone survey of tire retailers in the Twin Cities area indicated that approximately 75 percent of the snow tires sold during the 1969-70 winter were studded. A similar survey during the 1970-71 winter indicated that about 67 percent of the snow tires sold were studded. Combining this information with the results of the studded-tire surveys, and assuming that studded tires continue to be legal, it is estimated that by the winter of 1973-74, 60 percent of the passenger cars in Minnesota would be equipped with studded tires.

Field Measurements

A program was developed for measuring the amount of wear on state highway surfaces. Observation sites were chosen to include variables such as surface type, aggregate type, pavement age, traffic volume and geographic location. Initially, only six sites were established (in the winter of 1966-67), but others were added annually as wear due to studded tires became more pronounced. A total of 86 sites were ultimately included. The distribution is shown in Figure 5.

Detailed wear depth cross-sections were taken periodically at the 86 sites with the device shown in Figure 6. The frame was placed on center-punched plugs set below the pavement surface. This assured that the frame was in the same location, both horizontally and vertically, each time measurements were made. Dial gage readings were taken at one-inch intervals across a 21-inch portion of the wheel track. The amount of incremental wear that occurred during the legal period for studded tires was simply the difference between readings taken at the beginning and end of that legal period. The analyses include both the amount of wear at individual gage points and the average wear over the 21-inch width.

Another method of determining pavement wear employed the camera box shown in Figure 7. This was similar to the equipment developed by the Ontario Department of Highways. A frame with a wire stretched across was placed on the recessed plugs at the measuring point. The camera box was then placed on the pavement over the wire. A flash unit was located above and to one side of the wire, projecting a shadow of the wire onto the pavement surface. A series of five photographs was taken along the wire across the wheel track. The amount of pavement surface wear between periodic photographs was proportional to the increased distance between the image of the wire and the image of its shadow. *(Ref. 12)*

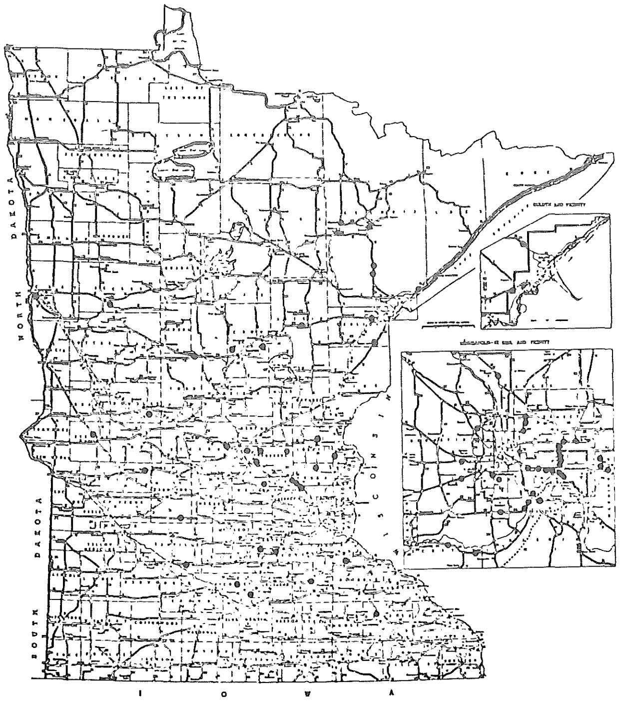


Figure 5. Location of Pavement Wear Sites

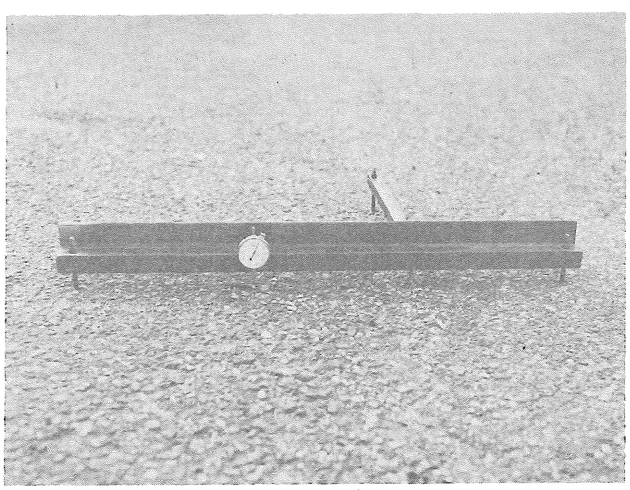


Figure 6. Dial Gage Measuring Device

Figure 7. Camera Box Measuring Device

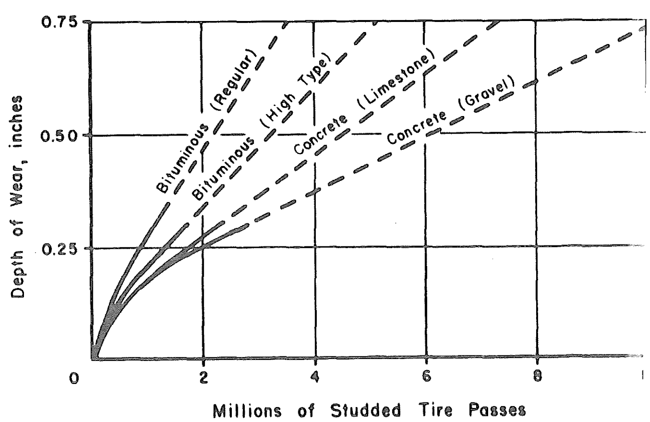


Figure 8. Wear Rates on Typical Minnesota Pavements

Prior to the introduction of studded tires, the Department had not noted detrimental abrasion damage to pavement surfaces even though sanding and salting had been practiced long before studs became legal. Therefore, the wear measurements, to be analyzed meaningfully, were related to the accumulated volume of studded-tire traffic. This was considered valid since many studies by the Department and many other agencies during the late 1940's and the 1950's have shown conclusively that the air-entrained concrete* as used in Minnesota pavements since the early 1950's, is substantially free from attack by de-icing salts. *(Ref. 5, 13)* Construction and materials inspection procedures along with construction methods employed by the Department give assurance that this type of concrete is used in pavements.

The Traffic Analysis Section of the Department calculated the total number of vehicles passing the test sites during each studded-tire season. The traffic data, coupled with the studded-tire-use survey results. provided a means for estimating the total number of studded-tire passes at each test site. The relationship between depth of wear and number of studded tire passes was then established for each location. The data points for pavements of similar surface types were combined and plotted in Figure 8. The solid-line portion of these curves represents the depth of wear that has actually occurred at the test sites. The dashed-line portion indicates predicted wear based on the laboratory-field correlation study described later in this report.

Included in the 86 wear measurement sites were experimental surfacing sections on two surfacing projects constructed in 1969. These projects were constructed to aid in evaluating conventional bituminous and concrete paving mixtures as well as relatively untried materials and mixtures which were thought to be more abrasion-resistant then the conventional mixes. The first project was a bituminous overlay on Highway 10 between Anoka and Elk River within which a one-mile section corresponded closely to Mix 1 tested at the American Oil Company test track, except that an igneous gravel was used for the coarse aggregate. The remainder of the project corresponded to Mix 2 used at the test track. The second experimental project was a portland cement concrete paving project on Highway 36 between I-35E and Highway 61 in Maplewood. Seven sections 24 feet wide by 300 feet long were constructed in the westbound roadway. The coarse aggregates used were limestone, igneous gravel and trap rock. The individual mixes corresponded to those tested at American Oil Company identified (See Table 4) as Mix 4, Mix 4 with 15 percent extra cement, Mix 4 with crushed trap fines rock substituted for natural sand, Mix 6, Mix 6 with 15 percent extra cement, Mix 6 treated with a liquid surface hardener and Mix 7.

Laboratory Pavement Wear Tests

This portion of the research was conducted by The American Oil Company *(Ref. 15)* at its laboratory in Whiting, Indiana. The Minnesota Department of Highways developed the research approach, designed the pavement mixtures, provided all materials for all pavements, and provided the necessary on-site inspections for casting the pavement specimens. The American Oil traffic simulator, shown in Figure 9, used for the test program is capable of simultaneously testing 12 pavement segments. This double-axled facility. rolled four tires in a 14-foot diameter path at a speed of 35 mph. Special mechanisms were added to distribute sand and/or salt over the pavement surfaces.

The research was designed to answer four basic questions:

1. What are the relative wear rates produced by studded tires for the most common bituminous and portland cement concrete surfacing courses used in Minnesota?

2. What are the relative contributions of sand, salt, and studded tires to total pavement wear?

3. Can surfacing courses be designed to successfully resist abrasion from studded tires?

4. Can the data collected be used for the determination of long range wear rates from studded tires on highway pavements?

**Air-entrained concrete is produced by adding a foaming agent, either to the current as manufactured or to the mixing water when the concrete is mixed, which traps minute bubbles of air (up to 7 percent by volume) in the mix and provides lasting protection against deterioration from salt and other de-icing chemicals. Air-entrained concrete should not be confused with non-air-entrained concrete commonly used in private work and subject to attack by de-icing salts.*

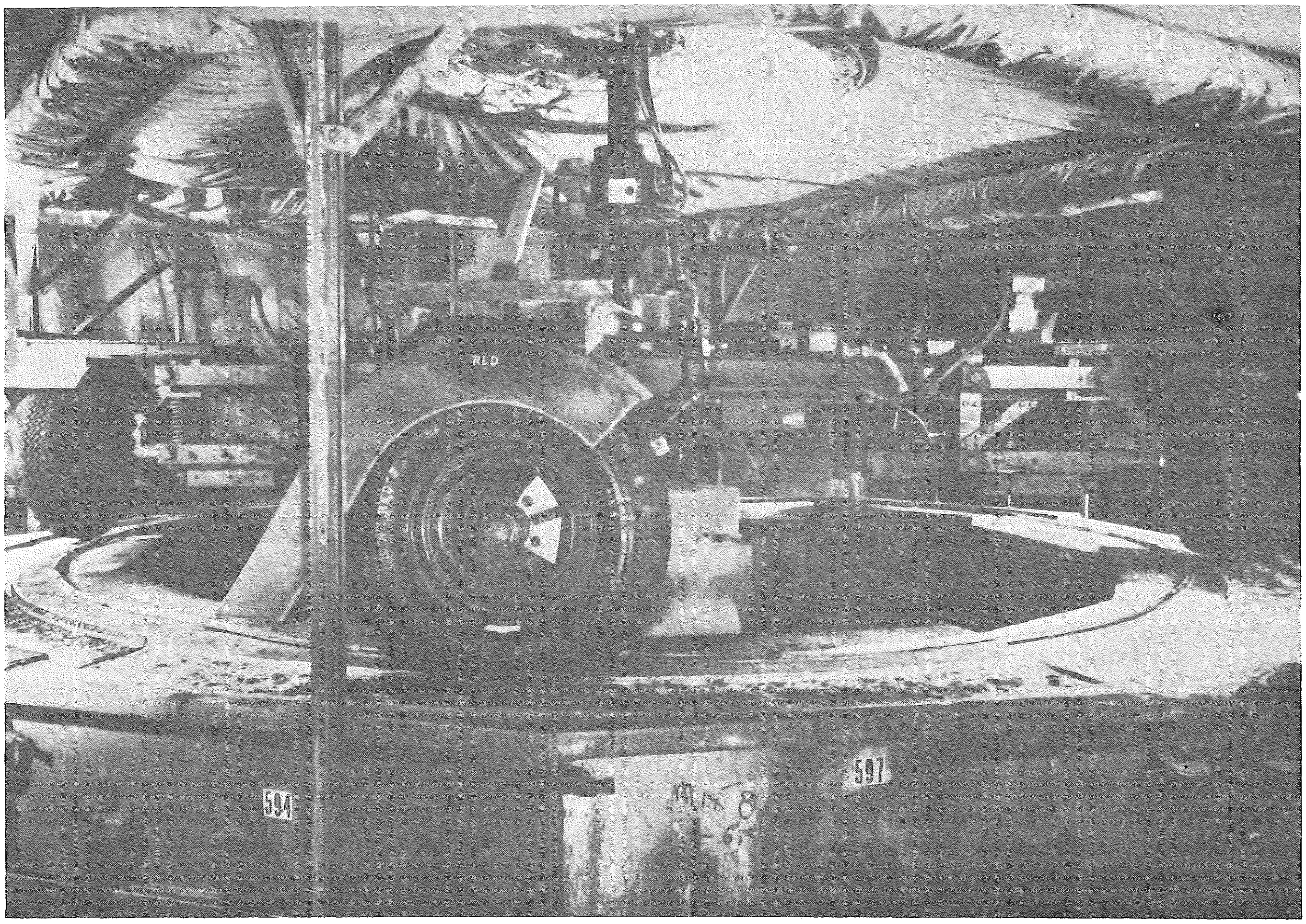


Figure 9. Traffic Simulator

Four series of tests, each series consisting of two tests, were undertaken to answer the questions. Table 2 describes the variables in the test program.

Test Series 1, 2, and 3 were conducted principally on the bituminous and concrete pavements commonly used in Minnesota. A description of these pavements is given in Tables 3 and 4. Series 4 tests were conducted on specially-formulated wearing courses to determine abrasion-resistant qualities. Descriptions of these are also shown in Tables 3 and 4. Technical data on the pavements are given in Tables A-1 through A-6 of the Appendix.

TABLE 2. LABORATORY PAVEMENT WEAR TESTS

TEST SERIES	TEST NO.	TIRE TYPES	SAND APPLIED	SALT APPLIED
1	1A	Studded tires on outer wheel path	Yes	Yes
	1B	Unstudded tires on inner wheel path	Yes	Yes
2	2A	Studded tires on outer wheel path	No	Yes
	2B	Unstudded tires on inner wheel path	No	Yes
3	3A	Studded tires on ~~inner~~ outer wheel path	No	~~Yes~~ No
	3B*	Unstudded tires on inner wheel path	No	No
4	4A	Studded tires on outer wheel path	Yes	Yes

**Not conducted*

TABLE 3. BITUMINOUS PAVEMENTS
Description

Mix. No.	Aggregates - Type & Source	Test Series
1	Coarse Aggregate - Crushed Limestone (Bryan) Fine Aggregate - Natural Sand. (Northwest) Filler - Limestone Dust.	1, 2, 3
2	Coarse Aggregate - Crushed Gravel (Plaisted) Fine Aggregate - Natural Sand (Barton) & Crushed Granite (Shiely)	1, 2, 3
3	Coarse Aggregate - Natural Gravel. (Barton) Fine Aggregate - Natural Sand (Barton)	1, 2, 3
9	Crushed Granite (Shiely)	4
10	Crushed Trap Rock (Bryan)	4
11	Crushed Granite (a) (Shiely)	4
12	Crushed Granite (a) (b) (Shiely)	4
13	Coarse Aggregate - Crushed Trap Rock (Bryan) Fine Aggregate - Natural Sand (Northwest) Filler - Limestone Dust.	4
14	Coarse Aggregate - Crushed Trap Rock (Bryan) Fine Aggregate - Natural Sand. (Northwest) Filler - Limestone Dust. (a) (b) (c)	4
15	Coarse Aggregate - Crushed Trap Rock (Bryan) Fine Aggregate - Natural Sand (Northwest) Filler - Limestone Dust (a) (b) (c)	4
16	Coarse Aggregate - Crushed Gravel. (Plaisted) Fine Aggregate - Natural Sand. (Barton) & Crushed Granite (Shiely) (a) (b)	4

(a) Asphalt contains 3% rubber latex
(b) Aggregate contains 2% asbestos fibers
(c) Aggregate contains 4% mineral filler
(d) Aggregate contains 4% mineral filler

TABLE 4. CONCRETE OR RIGID PAVEMENTS
Description

Mix. No.	Aggregàtes - Type Source	Test Series
4	Coarse Aggregate - Gravel, (Garland) Fine Aggregate - Natural Sand. (Garland)	1, 2, 3
5	Coarse Aggregate - Gravel, (Shiely Grey Cloud.) Fine Aggregate - Natural Sand (Garland)	1, 2, 3
6	Coarse Aggregate - Crushed Limestone (Shiely) Fine Aggregate - Natural Sand (Garland)	1, 2, 3
7	Coarse Aggregate - Crushed Trap Rock (Bryan) Fine Aggregate - Crushed Trap Rock (Bryan)	1, 2, 3
8	Coarse Aggregate - Gravel (Garland) Fine Aggregate - Natural Sand (Garland)	1, 2, 3
17	Fine Aggregate - Crushed Trap Rock (Bryan) Epoxy (a) (e)	4
18	Coarse Aggregate - Gravel (Garland) Fine Aggregate - Natural Sand (b) (h)	4
19	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand (f) (g) (Garland)	4
20	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand (h) (Garland)	4

(e) A two component epoxy resin & trap rock at a 1 to 4 ratio
(f) This pavement was given a surface treatment to densify the top
(g) A 15% solids latex additive was used to construct this pavement
(h) A 20% solids latex additive was used to construct this pavement

All pavements were cured, or preconditioned, before testing. This was done to simulate the time lapse normally provided between completion of pavement construction and cold weather exposure to sand, salt, and studded tires. All tests were run within the subfreezing temperature range of 25 to 30 deg. F. The wheels rolled freely at 35 mph with no externally applied torque. Tires used throughout were E 78-14 snow tires of the same brand and tread design. The studded tires contained 90 studs, with 15 studs in each of six rows. Limiting criteria for stud protrusion during testing were established at 0.020-inch minimum and 0.070-inch maximum. During the early portion of the testing, the upper limit of protrusion occurred after one million tire passes. In subsequent testing, the one million tire passes was the basic criterion for tire replacement. (See Figure 10) The stud type (Figure 11), stud hardness and the procedure for inserting the studs into the tires were held constant. Since the various pavements showed different wear rates, the entire ring pattern of the 12 pavement specimens was adjusted frequently to create a consistently level tire riding surface. The loading on each wheel was maintained at 1000 pounds to simulate a typical passenger car wheel load.

To produce a uniform application of stud contacts across a 7.7-inch-wide wheel path, each wheel was slowly moved radially 1.78 inches while the machine made 11 revolutions. One set of wheels was offset from the other also by 1.78 inches. The resulting path then resembled the center of the approximately 36-inch-wide wheel path on a typical traffic lane.

The amounts of materials and times of application corresponded to typical sanding and salting operations in winter highway operations. The calibrated sanding mechanism is shown in Figure 12. Salt brine was sprayed on the track through the black discharge tube shown in Figure 9.

Tests were continued until each of the wearing courses had experienced four million tire passes or had been worn to a depth of about 1.5 inches. This was considered a sufficient depth to establish long-range wear rates. A typical highway would be unserviceable long before a rut could be worn to a depth of 1.5 inches.

Laboratory Test Results

The first three test series (1, 2 and 3) consisted of tests on bituminous wearing courses and concrete pavements typically used in Minnesota with the exception of Mixes 7 and 8 which were specially formulated to increase strength and wear resistance. Replicate pavement slabs were cast for each of the three series. A discussion of Mix 7 and 8 pavements is included in this section of the report under the subheading, "Trial Pavement Compositions for Improved Durability". Pavement wear tests were conducted in two separate paths on the same pavement segments with studded tires run on the outer path and unstudded tires on the inner path.

The pavement wear rate from studded tires was not uniform across the wheel path. In effect, two channels resulted with a slight ridge between, the outer channel being deeper than the inner channel. Most of the difference can be explained by the fact that the tests were run in a circular path. The wear of each of the three zones (channel-ridge-channel), as well as the average wear, was analyzed separately. Each analysis yielded similar results. In this report, only the average values are used because a good relationship was found with the wear recorded at measuring points on the highway system.

Three average wear rates were determined for each pavement. The upper 0.1 inch of depth wore the most rapidly since it was composed primarily of portland cement mortar or an asphalt-sand mixture. This is referred to as the "initial" rate. The depth from 0.1 to 0.2 inch represented somewhat less rapid wear due to the presence of some coarse aggregate. This is called the "intermediate" rate. Deeper than 0.2 inch, the coarse aggregate had a greater effect on the wear rate, usually resulting in a slower, or "terminal", rate.

The average stud protrusion (the distance the tip of the stud protrudes beyond the surface of the tire) was different for each tire set and, therefore, for each test series. The rate of pavement wear increased significantly with increased stud protrusion, particularily on bituminous pavements. For example, a high-type bituminous pavement (Mix 1) in Test Series 1 abraded at the rate of 0.57 inch per million studded tire passes at an average stud protrusion of 0.030 inch and 0.84 inch at a protrusion of 0.040 inch. Similar figures for a concrete pavement (Mix 6) were 0.43 and 0.53. In order to obtain a consistent set of data, all wear rates were corrected to a common stud protrusion. A protrusion of 0.040 inch was selected since this approximated the average value for the entire laboratory study. Throughout this report, all pavement wear rates reflect this correction.

The wear from unstudded tire tests was very slight. No refined analysis was therefore warranted, and only the average wear values are presented.

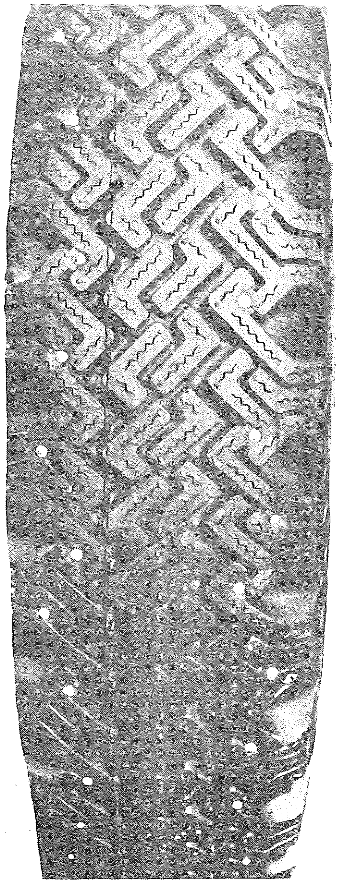


Figure 10. Studded Tire

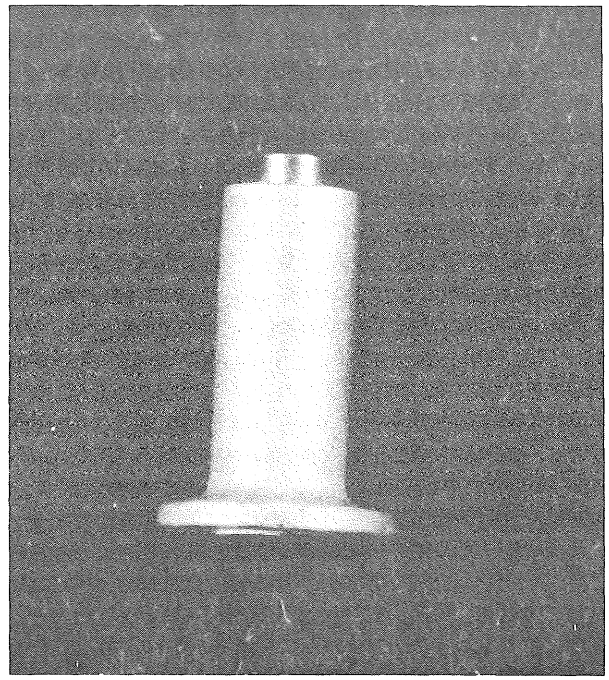


Figure 11. Tungsten Carbide Stud

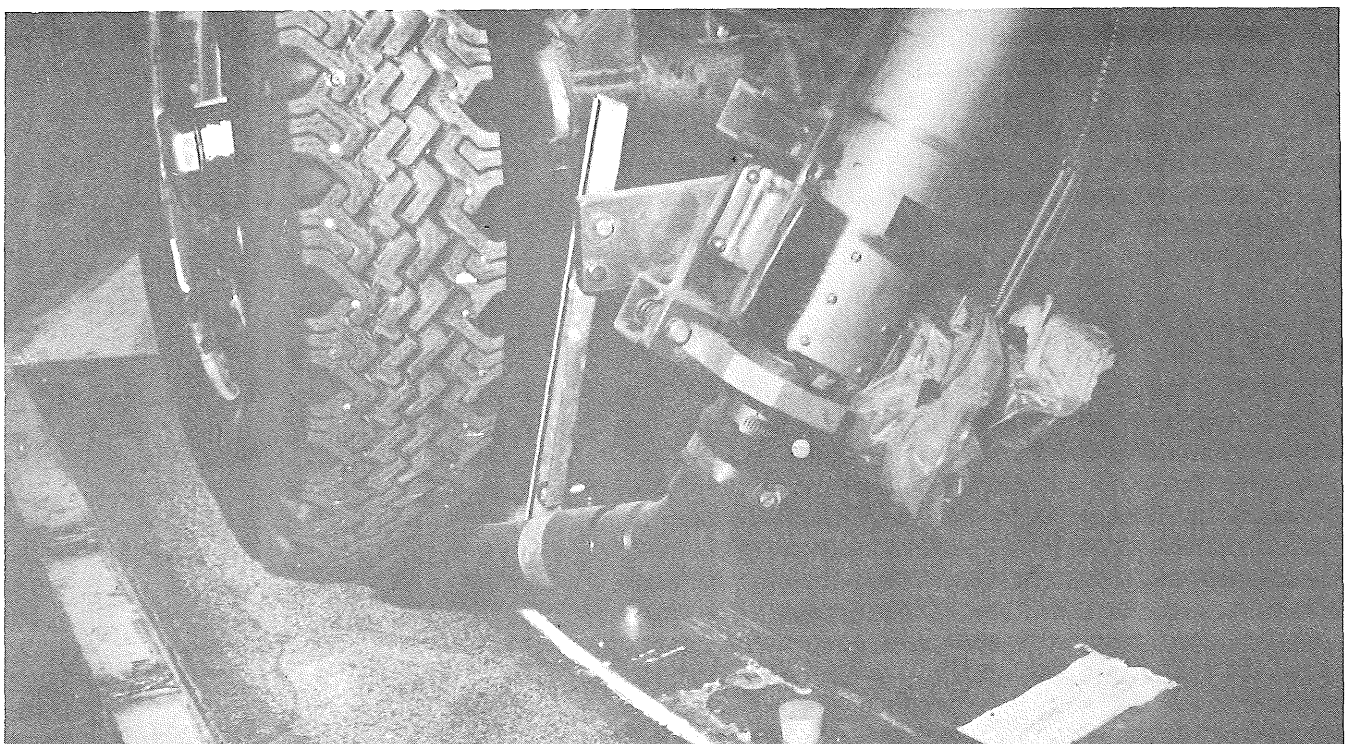


Figure 12. Sand Applicator

Conventional Pavement Mixes

Results from Test Series 1, 2 and 3 disclosed the relative wear resistance of the various pavements and the proportion of total pavement wear separately attributable to studded tires, sand or salt. All three basic wear rates, or stages of wear (initial, intermediate and terminal) contributed to the segregation of the pavements into four groups which relate type of material to relative abrasion resistance. The terminal wear rate, which prevailed for the major portion of each test period and which would represent the predominant wear phase out on the road, was the major influencing factor in determining the group classifications. The four groups are: (1) regular-type bitumionus, (2) high-type bituminous, (3) concrete with limestone coarse aggregate, and (4) concrete with gravel coarse aggregate. The corresponding terminal wear rates in inches per million studded tire passes are 0.91, 0.75, 0.47 and 0.30 respectively. Aggregates from other sources might show somewhat different characteristics from those used for this project. The relationship between depth of wear versus tire passes is shown in Figure 13.

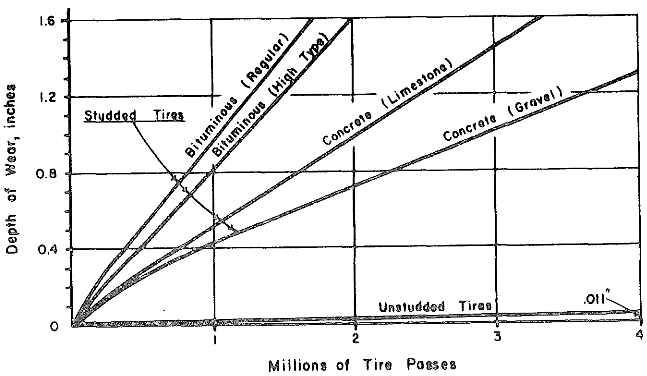


Figure 13. Wear Rates of Pavement Specimens at Test Track

Analysis of the terminal wear rates for the three tests with studded tires indicates that sand and salt had contributed a small amount to the total wear of the pavements. Sand appeared to account for about 12 percent of the total damage to the bituminous pavements and four percent to the concrete. The contribution of salt was more variable, ranging between 0 and 13 percent for the bituminous pavements and 4 to 21 percent for the concrete. For both types of pavements, the contribution of salt seemed to be related to the percentage of limestone in the mix. Salt had no significant effect on igneous materials.

The wear rate for pavements subjected to unstudded tires was negligible compared with the rate for studded tires. There was no difference within either the bituminous or concrete groups or between the two groups. In the presence of sand and salt, the average amount of wear on all the pavements was 0.011 inch from over four million unstudded tire passes, an average rate of 0.0026 inch per million passes. This was less than one percent of the wear rate due to studded tires, even on the best concrete pavements. This means that studded tires produced at least 100 times more abrasion damage than the incremental wear produced by sand and salt with unstudded tires. In the presence of salt only, unstudded tires produced no measurable pavement wear.

Both sand and salt under the influence of studded tires tended to increase the wear on pavement surfaces. Whether the incremental wear from this source is physical or chemical in nature is unknown. It is significant, however, that with unstudded tires the wear from sand and salt was scarcely measurable.

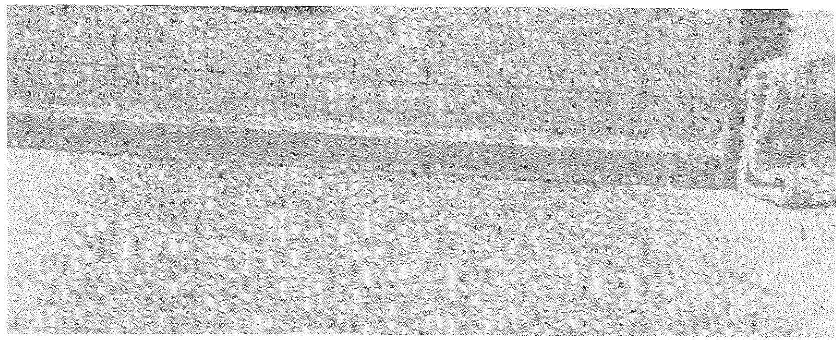
Photographs of a typical concrete pavement with gravel course aggregate at various stages of the testing with studded tires are shown in Figure 14. A similar set of photographs for a typical high-type (Mix 1) asphalt pavement is shown in Figure 15. At the conclusion of Test Series 1, a one-foot-wide section in the middle of each pavement slab was cut out for further observation and display. Photographs of sections removed from the two slabs mentioned above are shown in Figure 16. The right portion of each slab was subjected to four million and three million studded tire passes, respectively, and the left portion to four million unstudded tire passes. Sand and salt were applied to the pavement in both cases.

Trial Pavement Compositions for Improved Durability.

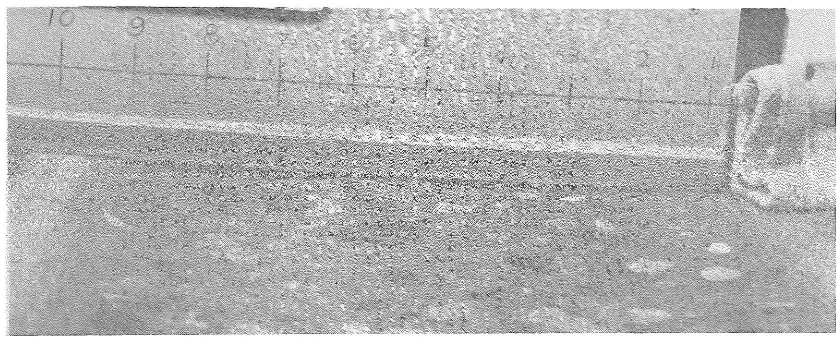
Test Series 4 pavements, though not standard specification pavements in Minnesota, were formulated to meet the Legislature's instructions for exploring more abrasion-resistant materials that might reduce pavement damage from tire studs. Two of the pavements in the first three test series (Mixes 7 and 8) were also included for this purpose. Test Series 4 involved the use of sand and salt as did Test Series 1.

The most wear-resistant surfacing was the epoxy-sand mixture (Mix 17) which showed about 25 percent less wear than the conventional concrete pavements with gravel coarse aggregate (Mixes 4 and 5). This pavement, however, developed a polished, slippery surface which would be unsuitable as a highway wearing course. Also,

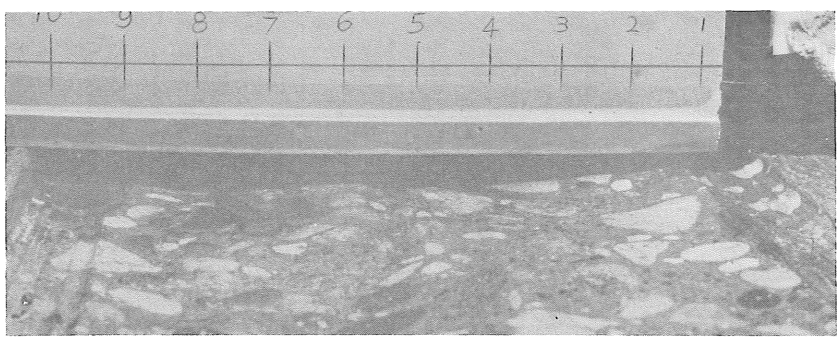
After
Conditioning
Passes



After 250,000
Studded Tire
Passes



After 2,000,000
Studded Tire
Passes



After 4,000,000
Studded Tire
Passes

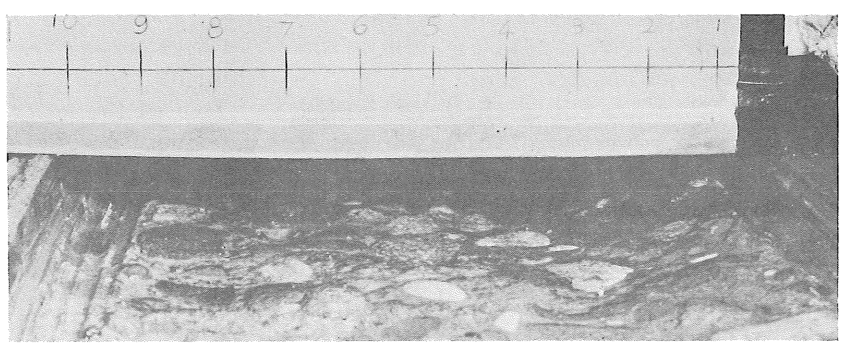
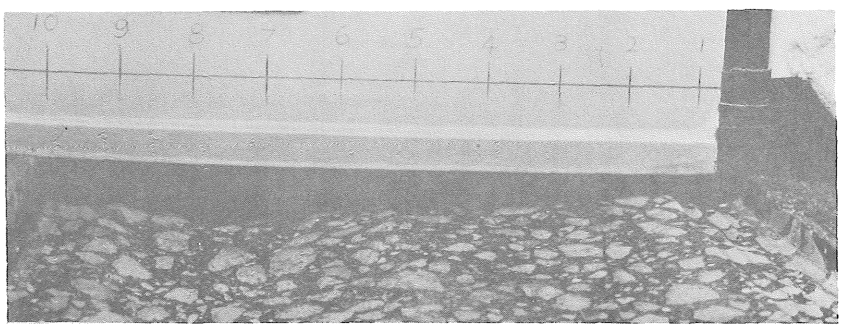


Figure 14. Wear Progression of Concrete Pavement Test Slab

After
Conditioning
Passes

After 250,000
Studded Tire
Passes

After 1,000,000
Studded Tire
Passes



After 3,000,000
Studded Tire
Passes

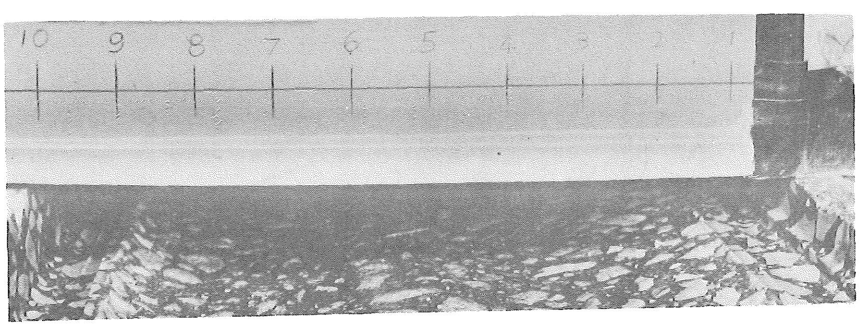
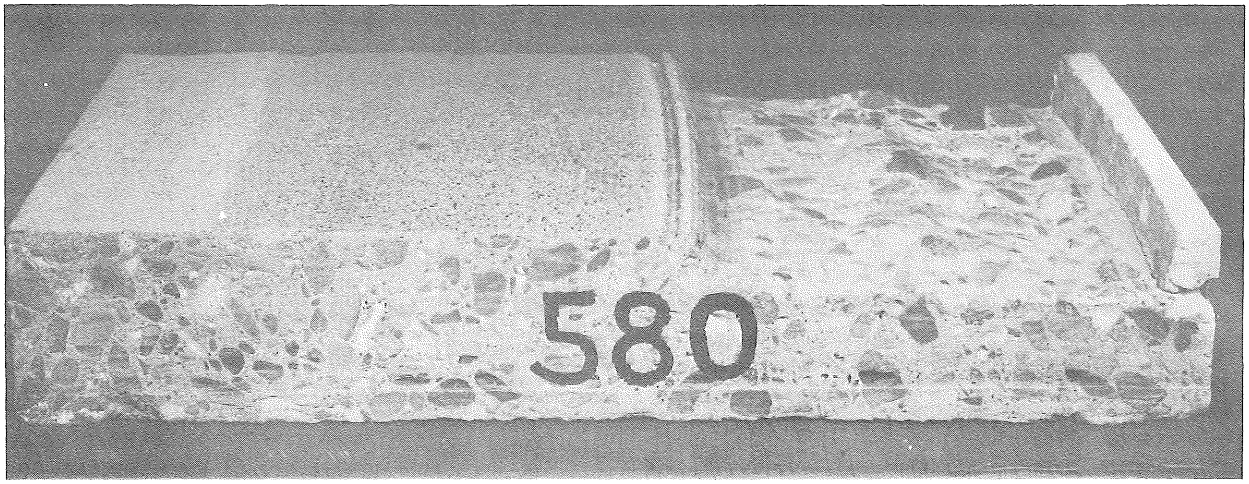


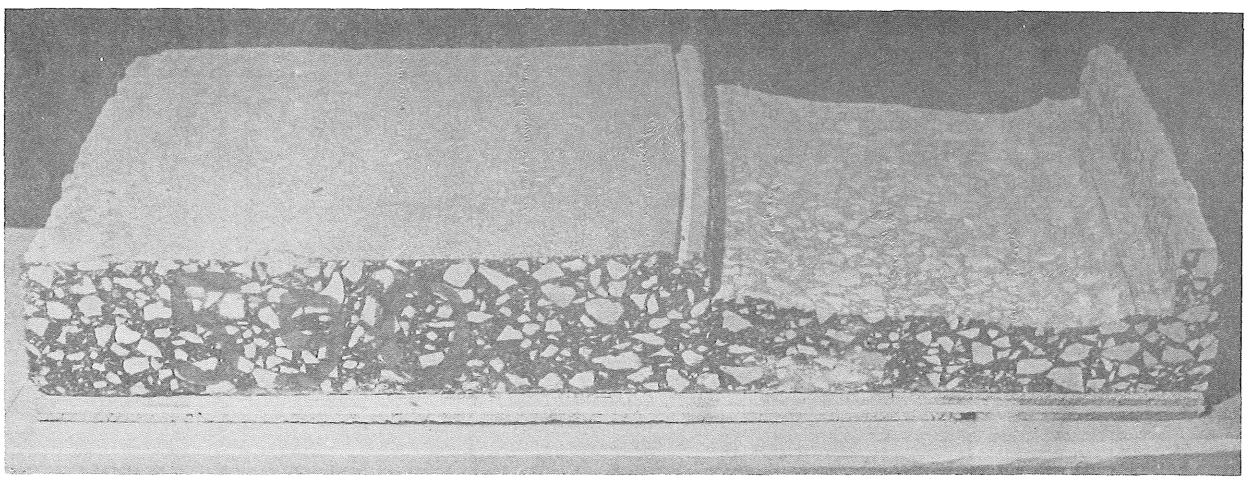
Figure 15. Wear Progression of Asphalt Pavement Test Slab



4,000,000 Unstudded
Tire Passes

4,000,000 Studded
Tire Passes

Concrete Pavement



4,000,000 Unstudded
Tire Passes

3,000,000 Studded
Tire Passes

Bituminous Pavement

Figure 16. Sections of Pavement Removed at Termination of Laboratory Test

the cost of this type of pavement would be three to four times more than conventional concrete pavement. The concrete mix with trap rock and 15 percent extra portland cement (Mix 7) was about 10 percent more wear-resistant than Mixes 4 and 5 but the cost increase would be about 25 percent. The wear resistances of the other concrete pavements (Mixes 8, 18, 19 and 20) were either no better or worse than the conventional pavements.

The use of trap rock as the coarse aggregate in a high-type bituminous pavement (Mix 13) resulted in about 40 percent less wear than the conventional pavement (Mix 1). The increased cost of this improvement was about 20 percent. The addition of rubber and asbestos to high-type bituminous pavements with trap rock coarse aggregate (Mixes 14 and 15) reduced wear an additional 15 percent while increasing costs 20 to 25 percent over the cost of Mix 13. Thus, overall, a maximum improvement in wear-resistance of 50 percent could be achieved at a cost increase of 40 to 45 percent.

Mix 16 was identical to Mix 2 except that rubber and asbestos were added. The additives reduced the wear rate 25 to 30 percent, but increased the cost by the same amount.

Mixes 9 through 12 should be considered separately from the other bituminous pavements since they are designed for thin overlays (5/8 inch thick). The pavement with crushed trap rock (Mix 10) wore almost 20 percent less than the one with crushed granite (Mix 9) with no significant increase in cost. The former was almost as abrasion-resistant as the conventional high-type bituminous pavement. The crushed granite pavements with rubber added (Mix 11) and rubber and asbestos added (Mix 12) were slightly better than the same mixtures without additives but were significantly more costly.

Relationship of Laboratory Wear to Highway Surface Wear

One of the purposes of the laboratory study was to obtain data which could be used to predict long-term wear rates on state highway surfaces. In determining this relationship, emphasis was placed on concrete pavements with gravel coarse aggregate because more extensive field data was available for this type of surface than for any other.

The relationship between laboratory wear and actual highway surface wear was established by plotting the number of studded tire passes producing given depths of wear on the concrete pavement slabs at the test track versus the calculated number of studded tire passes producing the same depth of wear as measured on actual highway concrete surfaces. The resultant relationship is shown in Figure 17. The slope of the straight line portion of this curve is 5.5 to 1, which means that on the average the depth of wear produced by one million studded tire passes on the concrete pavement at the test track would be reproduced by 5.5 million wheel passes on a highway surface of the same type. This ratio, 5.5 to 1, also proved valid for the other types of pavement surfaces. The highway-to-test-track ratio of 5.5 to 1 correlates reasonably well when the width of wheel path on highways is compared with the wheel path width at the test track. Highway wheel path widths are generally about three feet wide. The portion of the wheel path subjected to studs at the test track was 7.7 inches wide. The ratio by this means, then, is 4.7 to 1.

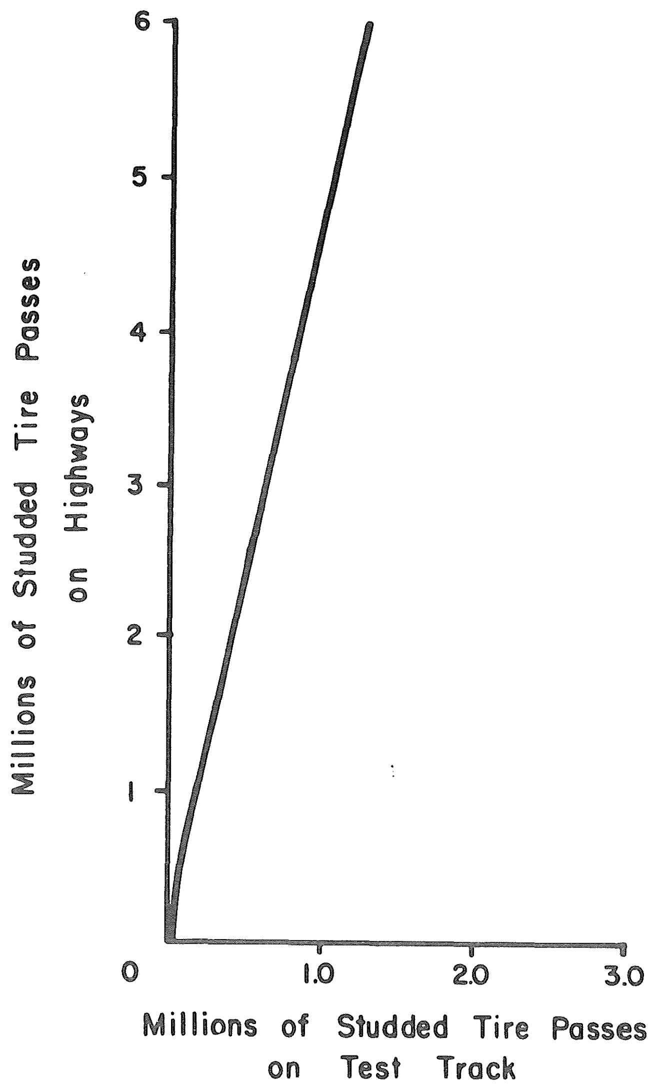


Figure 17. Relationship of Wear Between Test Track and Highway Surfaces

Pavement Damage Costs

The continued use of studded tires would unquestionably cause further detrimental wear to Minnesota highways. The degree to which damage would occur depends on a number of variable factors, not the least of which is the continued relative popularity of studded tires, particularly the extent of any trend to use studded tires on all four wheels. Correlation of the laboratory wear tests, however, with actual wear on roadways in relation to traffic provides a tool whereby, under a given set of criteria, damage can be predicted and costs assessed.

As part of this report, to illustrate the possible magnitude of studded tire damage to roadways and bridge decks, an estimate has been made of potential damage costs in terms of anticipated expenditures for repair. The estimate is necessarily based on certain reasonable assumptions that may or may not prevail for the full estimate period. These assumptions, or criteria, are:

- That studded tires will be legalized indefinitely during each winter season between October 15 and May 1.
- That the mileage and pavement type distribution will conform to the highway system as it will exist in 1973.
- That roadways will require repair when the wear rut in the wheel tracks reaches a depth of three-fourths inch.
- That bridge decks will require repair when the wear rut in the wheel tracks reaches a depth of one-half inch.
- That traffic volumes will increase at the rate of four percent per year through 1980.
- That the percentage of vehicles equipped with studded tires will increase to 60 percent by 1973-74 and remain approximately at that level.
- That the percentage of vehicles equipped with studded tires on all four wheels will approximate three percent by 1975 and increase at the rate of three percent per year thereafter to a maximum of 30 percent.
- That studded tires will necessitate additional expenditures for more wear-resistant materials on new construction.
- That construction costs will increase at an average rate of four percent per year.
- That the cost of resurfacing bridge decks and roadways for reasons other than studded tire damage will be omitted.

Some of the foregoing criteria are self-explanatory, but others require further explanation.

The three-fourths inch wheel rut is based on the expectation that the depth will produce adverse steering characteristics and cause water to either pond or flow within the wheel paths. It is further anticipated at that point of wear exposed stone in the pavements will be more easily dislodged by traffic and weathering. A wear depth of one-half inch was chosen for bridge decks because bridge deck deterioration is closely linked with the amount of cover over the reinforcement steel and the degree of rusting occurring from infiltration of mositure. Most bridges have about 1½ inches of cover over the steel. A half-inch loss is considered critical in reducing protection over the steel and contributing to corrosion and subsequent structural weakness.

Using the highway-to-test-track relationship, the number of studded tire passes to produce three-fourths inch of wear was selected from Figure 8 for the various pavement groups as listed in Table 5. Bridge decks, generally composed of gravel aggregate concrete, would wear to a depth of one-half inch in 6.1 million studded tire passes.

TABLE 5.
PAVEMENT TYPE WEAR RATES

Pavement Group	Millions of Studded Tire Passes to ¾-inch Wear Depth
Concrete (Gravel)	10.1
Concrete (Limestone)	7.4
Bituminous (High Type)	5.1
Bituminous (Regular Type)	3.8

The repair costs for roadways was based on the work required to fill the ruts with a regular bituminous mix and overlay with a 1 ½-inch wearing course of high-type bituminous mixture. Bridge deck repair requires an inlay instead of an overlay. Damaged concrete has to be removed within the affected area and replaced with a concrete patching mixture. The cost of this type of work was estimated on the basis of repairing two three-foot widths, or six feet, in each traffic lane. Since bridge deck deterioration in the wheel tracks can also develop from other causes, a proportional deduction was made in the estimate for that effect. Likewise, bituminous pavements on the average require an overlay after 17.5 years of service while concrete is expected to serve 35 years without major surface rehabilitation. These factors also were considered in the cost analysis.

The assumption that studded tire use would reach 60 percent by 1973 is based on a projection of past growth rates and the progression of use in other areas, particularly Finland and the Scandinavian countries. Ontario has experienced a growth rate similar to that of Minnesota. If studded tires are not discontinued, it is expected that a growing number of vehicles will be equipped with studs on the front as well as the rear. The estimate provides a three percent per year increase after 1975. Data from Finland indicates that in 1967, 70 percent of the vehicles had studded tires on the front. In 1968 Sweden had a corresponding figure of 60 percent. Information from Quebec for 1970 showed that 60 percent of the vehicles had studded tires and 10 percent had studded tires in front.

Using highway inventory data, the various routes were categorized by traffic volume, kind of pavement, and number of traffic lanes. The annual number of studded tire passes was then computed for each highway segment using the traffic data, studded-tire-use percentage, and the length of the studded tire season shortened to adjust for the rising use during the fall and diminishing use in the spring. It was then possible to determine at what point in time a wear rut of three-fourths inch would be reached and an overlay required. Likewise, the time at which bridge decks within each segment would reach a wear depth of one-half inch in the wheel tracks was computed. From this analysis the number of lane miles of roadways needing overlays and the lengths of bridge decks needing inlays was developed for each year.

The continued use of studded tires would focus attention on the need to construct new highway pavements with more expensive but more wear-resistant materials. Using the information obtained from the American Oil Company tests and applying the increased incremental cost to the anticipated highway construction program, the additional cost was taken into account in the estimate under the heading "Additional New Construction Cost".

Based on the described procedure, costs were calculated for repair of pavements when studded-tire wear will have reached the ¾-inch maximum depth criterion within the period 1965 to 1980. No costs were assessed before 1973 when the first pavements are expected to reach the critical wear depth. Estimated expenditures by years as shown in Table 6 will reach a total of $55 million by 1980. The repair costs would be relatively modest the first few years, somewhat more than the 1973 cost of $2.3 million estimated in the progress report of December, 1970 which did not include bridge deck repair and use of more expensive, wear-resistant materials for new construction. During the latter 1970's the annual costs would rise significantly due to the compounding of overlay work on high-volume roadways. Dramatically larger annual increases could be expected after 1980 when wear rates would have progressed to include medium-volume as well as high-volume roadways.

These cost estimates are based on pavement damage estimates for the state highway system only and do not include damage sustained by county roads, municipal streets, commercial and private properties. Not included also are related damaging effects, such as premature loss of pavement markings, abrasion loss of safety grooving used to improve skid resistance at dangerous locations and inconvenience and diversion of traffic for additional surface repairs.

TABLE 6. ESTIMATED ADDITIONAL STATE HIGHWAY EXPENDITURES
For Damage Repair From Studded Tires

Year	Pavement Overlay Cost	Bridge Deck Repair Cost	Additional New Construction Cost	Total
1973	$ 680,000	$ 120,000	$ 2,050,000	$ 2,850,000
1974	160,000	60,000	2,130,000	2,350,000
1975	680,000	580,000	2,210,000	3,470,000
1976	2,720,000	280,000	2,300,000	5,300,000
1977	2,710,000	1,340,000	2,390,000	6,440,000
1978	5,170,000	1,180,000	2,490,000	8,840,000
1979	10,200,000	580,000	2,590,000	13,370,000
1980	7,790,000	2,120,000	2,690,000	12,600,000
Total	$30,110,000	$6,260,000	$ 18,850,000	$55,220,000

The third research task assigned by the legislature was to "evaluate the effects, if any, that discontinuing the use of studded tires will have on highway safety".

Until recently, efforts to evaluate the effectiveness of studded tires as a traffic safety device have generally been directed toward measuring the degree to which they could improve various performance functions of a vehicle when operating on a glare-ice surface. A number of investigations have been conducted to measure the performance of an automobile on ice when equipped with studded tires, i.e. shorter stopping distance, increased traction for faster starts, and better steering maneuverability. Such studies, made by competent researchers, have also investigated the effects that various stud and tire tread configurations and different ice temperatures have upon these performance characteristics. Results of these tests have been widely circulated and used in promoting the use of studded tires. A summary of findings of these studies is presented herein to inform the reader of the performance capabilities and limitations of various tire types under different winter road conditions.

Improvements in vehicle performance on ice have been cited as a means for achieving greater winter driving safety. However, highway safety can benefit from the use of any safety device only if the potential safety improvement is translated ultimately into real reductions in accident severity and occurrence. The Department of Highways has, therefore, sponsored a study by Cornell Aeronautical Laboratory, Inc. of traffic accidents to establish directly the degree of involvement of studded tires. This report describes that study briefly and presents a summary of its findings. Complete documentation of the study may be found in a separate report by Cornell Aeronautical Laboratory, Inc. *(Ref. 10)*

Vehicle Performance on Ice

The three general areas of vehicle performance on ice which can be improved to some extent by use of studded tires are: traction, cornering, and stopping. The Highway Department has not conducted or sponsored any tests of these properties as such, because considerable information is available from other sources, such as the National Safety Council, the NCHRP (National Cooperative Highway Research Program) Report No. 61, and the Canada Safety Council, *(Ref. 1, 6, 7, 8 & 11)*. A brief review of these properties will provide some understanding of their significance in relation to safety.

Traction

Improved traction and acceleration afforded by studded rear tires on icy surfaces are largely convenience benefits. That most users have regarded studded tires primarily as an aid to starting traction is evidenced by the fact that more than 99 percent of all vehicle with studded tires have them only on the rear wheels. If stopping capability were the primary consideration and only two tires were to be studded, better braking would probably be achieved by placing them on the front. *(Ref. 11)*

The safety benefits of starting traction are somewhat similar to those afforded by reserve horsepower for passing, such as the benefit of improved acceleration on ice when entering a busy arterial from a side road. Acceleration tests indicate that studs may reduce by about 30 percent the time of exposure to possible collision as compared with snow treads when crossing a busy road on glare-ice. Hill climbing on ice without hazardous backing down may be possible in some cases. Friction tests indicate that on glare-ice studs should enable climbing of grades of eight percent at constant speed, or about twice as steep as with regular treads.

Cornering

In driving on slippery roads, it is important to be able to maintain the intended direction of travel and the ability to maneuver without loss of control. A limited number of tests of vehicle maneuvers requiring change of direction have been performed on ice. *(Ref. 1, 7, 8 & 11)*. These evaluated the cornering characteristic of the vehicle - its ability to change direction a desired amount and at a controlled rate. Tests have been conducted on glare-ice in a pylon figure eight, a marked serpentine course and a marked passing maneuver.

Various testing authorities agree that studded tires on only the rear wheels did not substantially improve cornering ability. Only the manner in which control of the vehicle is lost is changed. The vehicle with studded rear tires slides ahead without changing direction; the vehicle without studs spins out.

Tests by the National Safety Council indicate that a vehicle with four studded tires can negotiate a 200-foot radius curve (typical cloverleaf) on an icy surface at a greater speed than one with only two studded tires, (an increase of about four miles per hour). Tests sponsored by the Canada Safety Council confirm this. Speeds up to about 70 percent of comfortable dry pavement speeds were reached.

As yet, no tests are known to have been conducted for evaluating advantages offered by studded tires in maintaining straight-line travel. This capability may be enhanced by use of studded tires if the speed is such that maneuvers can be made without loss of control.

Stopping

The most important safety feature of studded tires in winter driving is their improvement of stopping capability on ice. By far the greatest number of vehicle performance tests have been conducted to evaluate this feature.

Typical stopping distances at 20 deg. F. (the average below freezing temperature in Minnesota) and from 20 mph are shown in Table 7 and in Fig. 18. *5, 6 & 7).*

TABLE 7.
STOPPING DISTANCES FOR VARIOUS TIRE CONFIGURATIONS

Tires	Distance (ft.) (Wheels locked)
4 regular treads, glare ice	143
2 regular treads front, studded rear, glare ice	116
4 regular treads, bare pavement	18

The car with studded rear tires was able to stop stop quicker on ice by 27 feet. Nevertheless, the car with studded tires required 6½ times more distance for stopping on ice than the car with regular treads on bare pavement.

On 20 deg. F. glare-ice at 35 mph a regular tread-equipped car requires 382 feet to stop. On dry pavement the same car could stop in the same 382 feet from a speed of about 80 mph. The stopping distance from 35 mph on ice for a vehicle with studded tires on the rear is 325 feet, about the same as the dry pavement stopping distance from 75 mph.

The greatest stopping advantage, percentage-wise, for studded rear tires only compared with regular treads is 19 percent when traveling on 20 deg. F. glare-ice at 20 mph. With four studded tires the greatest advantage over regular treads is 38 percent at 20 mph. The greatest stopping distance advantage is at high speeds, e.g. a 96-foot reduction at 50 mph with studded tires only on the rear, and a 209-foot reduction at 50 mph with four studded tires, on 20 deg. F. glare-ice.

Studded tires provide the greatest degree of improvement in stopping distance on clean, warm, unfrosted glare-ice, a condition that is comparatively rare on road surfaces. A lesser degree of improvement is obtained on other road surface cover conditions that occur more frequently. *(Ref. 1, 14)* Figure 19 depicts the relative effectiveness of various tire configurations for several road cover conditions.

While test data are meager for snowy conditions and lacking for ice temperatures below -5 deg. F., some comparisons can be made. The stopping distances for any tire configuration on snow (loose or packed) are roughly about 1/3 to 2/3 less than those on glare-ice. The stopping distances on cold ice (0 deg. F.) with regular tires are about 3/4 of those on warm ice (30 deg. F.). The degree of stopping improvement through use of studded tires at 0 degree F. is about 1/4 of that at 30 deg. F. The improvement from studded tires may be very small on loose snow or slush where the soft surface provides little grip for the studs, and traction is provided by the snow tread configuration.

Greater improvement in stopping distances when using studded tires might be expected on packed snow. However, some limited test data available indicate that studded tires unexplainably require longer stopping distance on packed snow than unstudded snow tires. *(Ref. 14)* Reliable performance tests on snow are difficult to conduct; therefore, any performance advantage of studded tires on snow is not well established.

Figures 18 and 19 also indicate that sanding reduces the stopping distance on 30 deg. F. glare-ice by over 60 percent as compared to the 19 percent reduction for studded rear tires. Converting icy surfaces to wet surfaces by salt application reduces the stopping distance by 80 to 90 percent.

Worn studded tires are considerably less effective on ice than new studded tires. Tests after 5,000 miles of wear showed loss of 67 to 85 percent of the initial improvement over new unstudded tires. *(Ref. 12).*

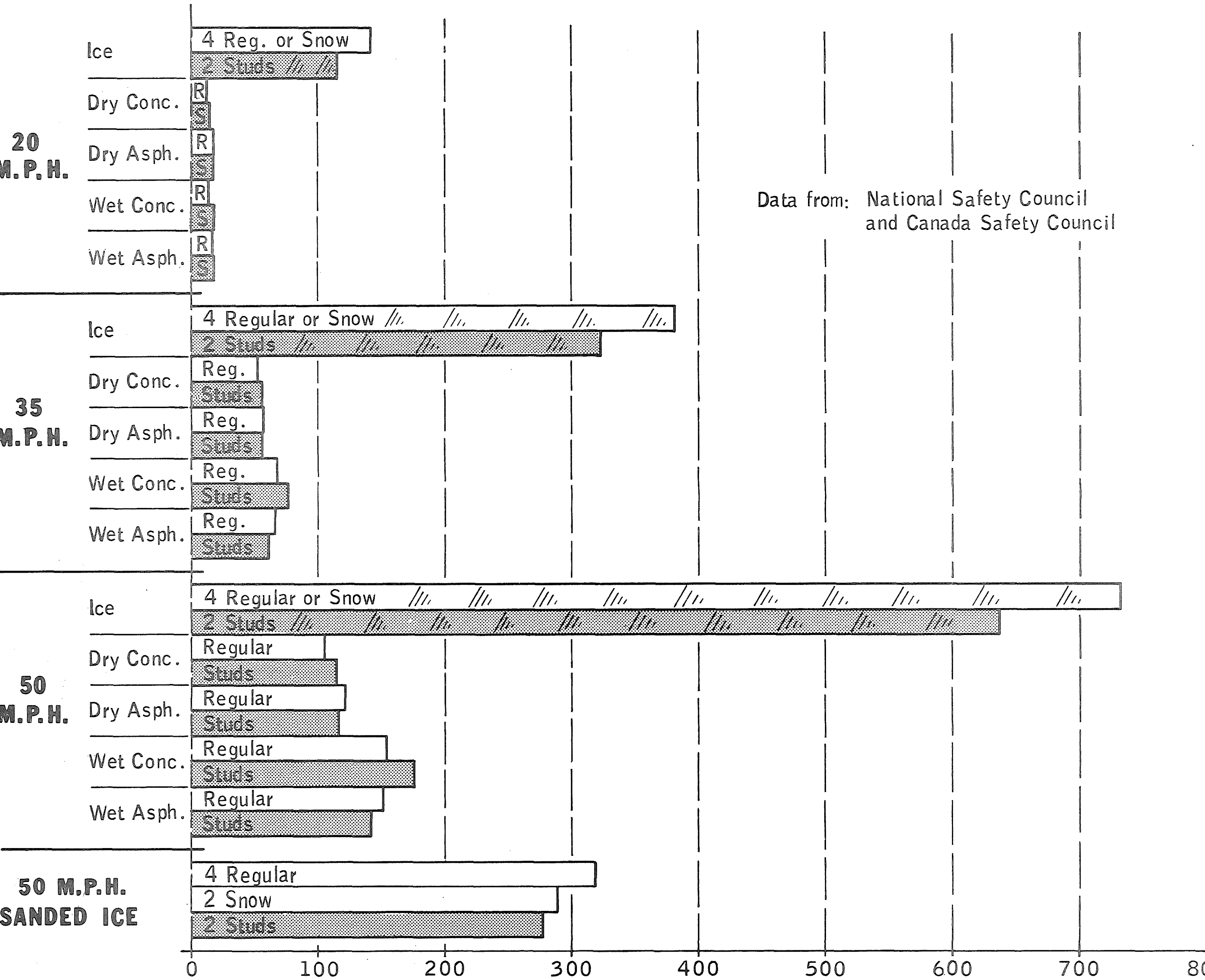


FIG. 18 MEAN STOPPING DISTANCE AT 20° F (FEET) (After Brakes Applied)

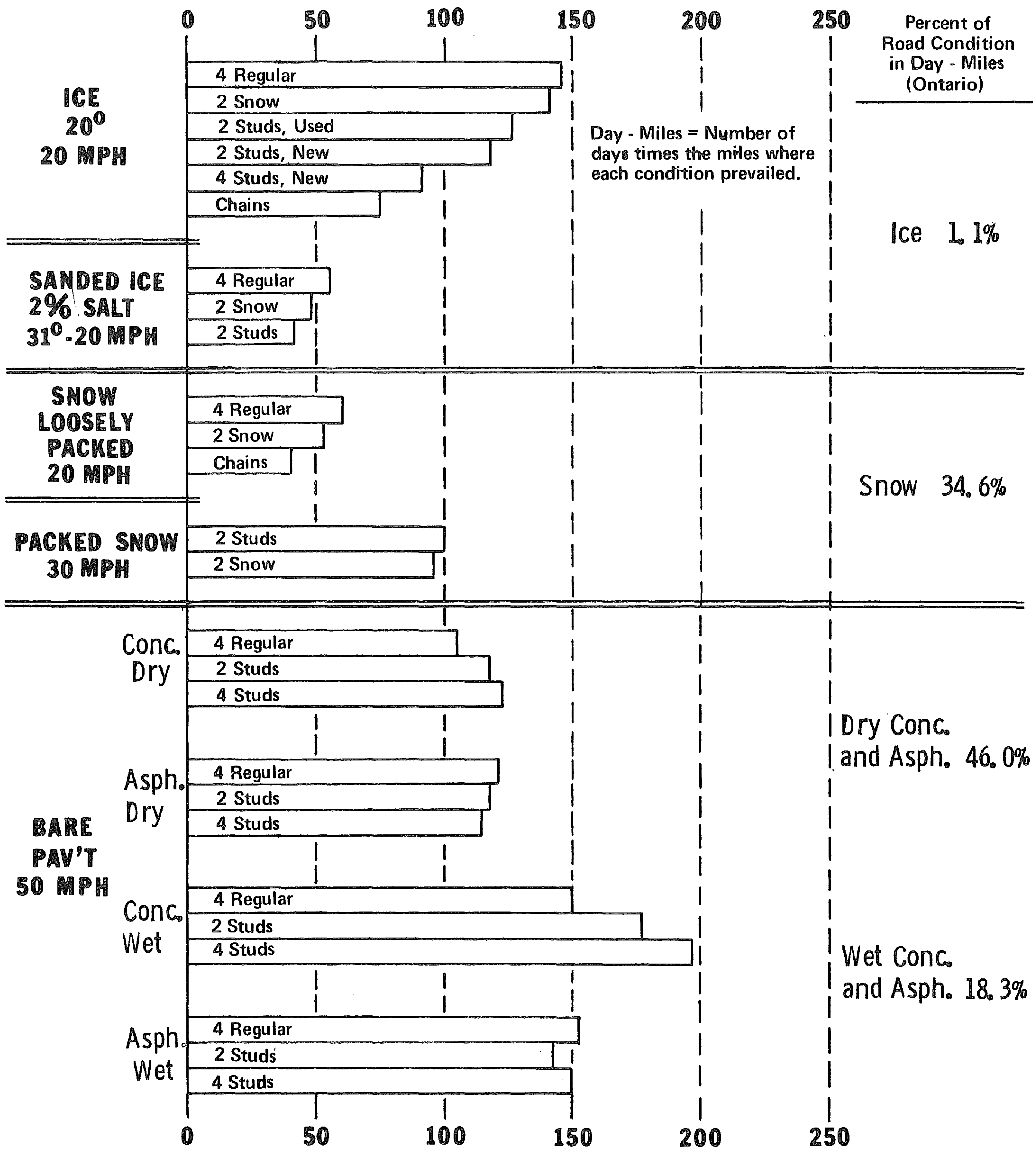


FIG. 19 MEAN STOPPING DISTANCE (FEET)

(For Regular, Snow and Studded Tires and Tires with Chains, After Brakes Applied)

Data from: National Safety Council
Canada Safety Council
and Ontario Dept. of Highways

Winter Driving in Minnesota

In addition to the vehicle performance information previously considered, a review has been made of climatological records, driving condition survey data, official traffic volume reports, and official accident statistics. A summary of this information should help to define the actual severity of the winter driving safety problem in Minnesota including the relative exposure of Minnesota motorists to various winter driving situations.

The number of reported traffic accidents in Minnesota increased from about 60,000 in 1958 to about 80,000 in 1965 and to about 100,000 in 1970. Fig 20 shows the number of accidents for various road conditions since 1958. The accident rates have also increased slightly, averaging about 4.8 per million vehicle miles, *(Ref. 4)*. Fig. 21 shows the number of fatal accidents for various road conditions since 1958. On the average about 12 deaths occur for each 10 fatal accidents. The fatal accident rate also has increased slightly, averaging 4.3 per 100 million vehicle miles.

The rigorous Minnesota winters influence highway safety rather markedly. Over the last 13 years as shown in Fig. 20, the proportion of accidents reported on snowy or icy roads and streets has averaged about 22 percent of all reported accidents, ranging between 16 and 29 percent. The fluctuations are apparently related to the severity of the winter weather. A small upward trend in the percentage of accidents on snowy or icy roads is discernible. On the average, 10 percent of all fatal accidents, 16 percent of all personal-injury accidents, and 26 percent of the property-damage-only accidents occur on snowy or icy roads. Thus, accidents on snowy or icy roads are generally of less than average severity. *(Ref. 21)*.

Average annual snowfall for Minnesota is in the range of 35 to 65 inches, and maximum winters have on the order of 80 to 100 inches or more. On the average in the Twin Cities area, 13 days out of each winter have snowfall of one inch or more.

Average temperature in the state during the legal period for studded tires is about 26 deg. F., with an average below freezing temperature about 19 deg. F.

The proportion of time that various surface conditions prevailed on different types of roads and streets in the winter of 1969-70 was observed on representative thoroughfares in the Twin Cities and surrounding rural area and found to be as shown in Table 8, based on approximately 18,000 observations.

The Ontario Department of Highways reported that on its King's Highways the road condition was bare (wet or dry) 64 percent of the time on the average, snowy or slushy 35 percent, and icy one percent. *(Ref. 14)*

Assignment of relative amounts of travel on the various roadway types yields the approximate proportion of travel for each of the general road conditions for the winter of 1969-70 as shown in Table 9.

Table 9 shows that on the average about 25 percent of all travel in the state during the winter of 1969-70 was on snowy or icy roads. Statewide, winter daily traffic averages about 90 percent of the annual average daily traffic. Total winter travel for the 6½-month studded-tire period (October 15 - May 1) in the winter of 1969-70 amounted to about 48 percent of total annual travel. Therefore, about 12 percent of total annual travel was on icy or snowy roads and about 88 percent was on roads essentially bare. Only about half of that, in turn, was on surfaces that could be classed as icy (where studded tires are potentially useful).

The approximate ratios of accident rates on snowy or icy roads to annual rates under all conditions are as shown in Table 10.

Thus, it appears that accidents are more likely to occur on snowy or icy roads, but these are generally of less than average severity. If studded tires are significantly helpful on icy and snowy roads, benefits should most likely appear in property damage and personal injury accidents, in that order. These data indicate that studded tires could be potentially helpful for about 10 to 15 percent of winter travel to some degree (i.e. about 5 - 7 percent of annual travel).

Adverse Safety Effects of Studded Tires

Stopping on Bare Pavement

Stopping distances when using studded tires on bare pavement have been shown to increase with the number of studs. If more than 70 to 100 studs per tire are used, stopping distances on bare pavement will generally exceed that required by regular unstudded tires Most studded tires sold have more than 80 studs. While the degree of increase is not large, the exposure to bare pavements is great on most Minnesota roads. Furthermore, since speeds are much higher on bare roads, the severity of accidents precipitated by extended stopping distance may be aggravated. *(Ref. 11)*

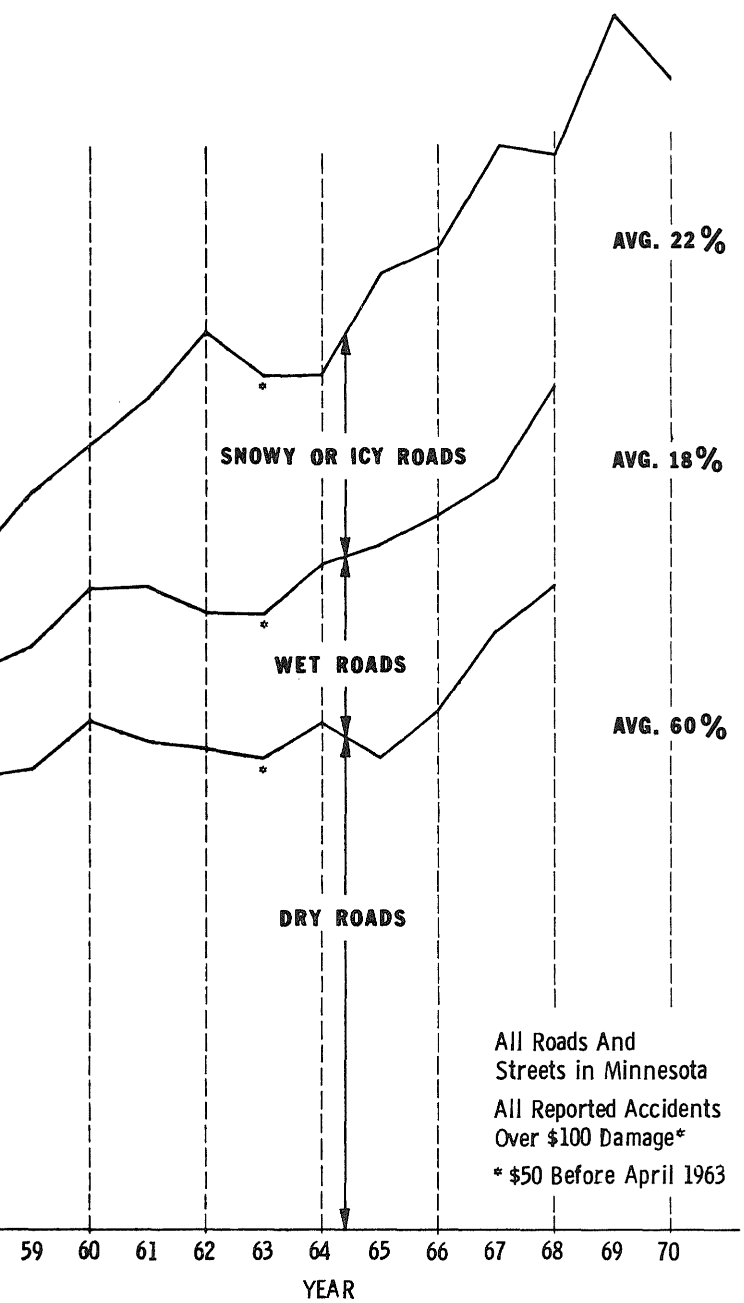


FIG. 20 TOTAL ANNUAL ACCIDENTS
EFFECT OF ROAD CONDITIONS

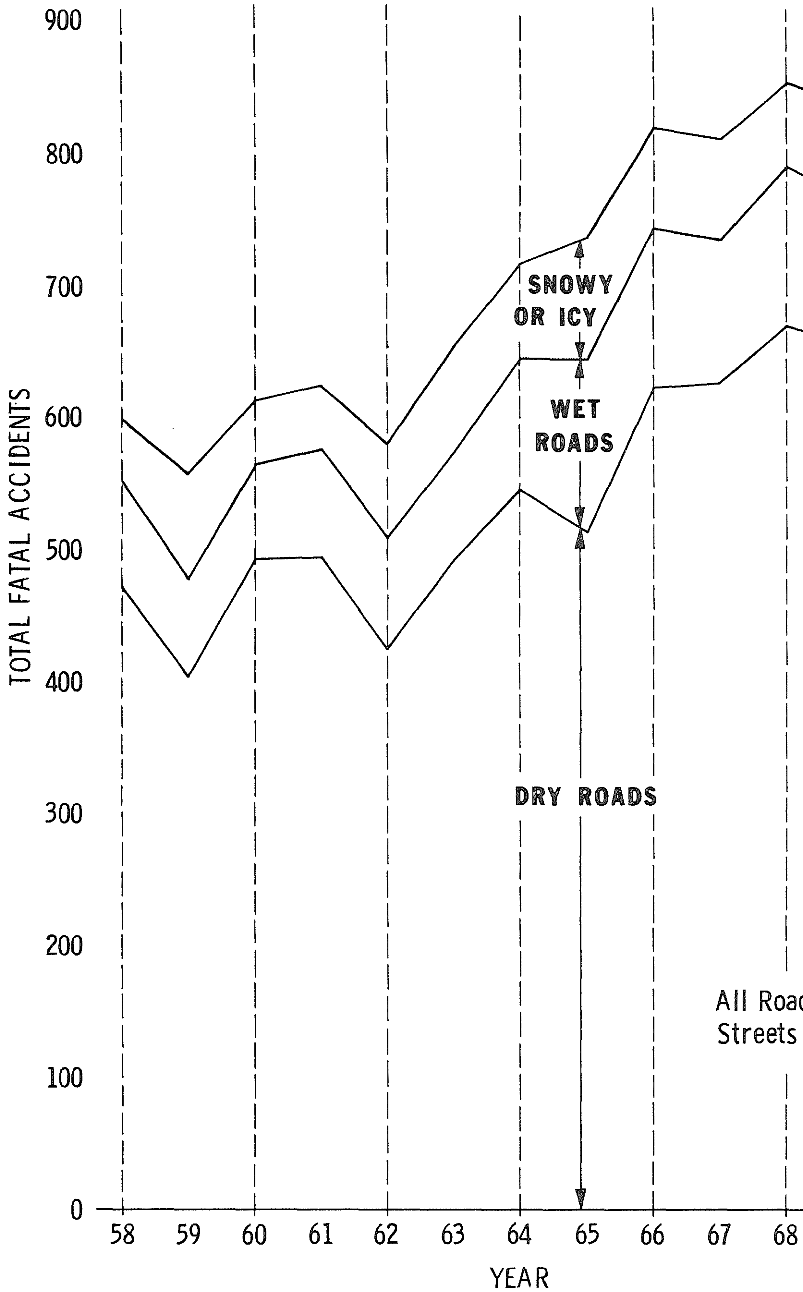


FIG. 21 TOTAL ANNUAL FATAL ACCIDENTS
EFFECT OF ROAD CONDITIONS

TABLE 8. WINTER ROAD CONDITIONS FOR DIFFERENT ROAD TYPES
PERCENT OF TIME - (OCT. 15, 1969 - MAY 1, 1970)

Type of Road	Bare (Wet or Dry)	Icy or Packed Snow	Other Loose Snow, Slush, Etc.
Freeways, urban (lower speed)	96	2	2
Freeways, rural	97	1	2
State highways, rural	90	4	6
Main Streets	82	7	11
County roads	74	11	15
Secondary Streets	74	7	19
Residential roads	47	29	24

TABLE 9. PROPORTION OF WINTER TRAVEL (1969-70)
FOR DIFFERENT ROAD, CONDITIONS, PERCENT

Type of Road	Total All Conditions	Bare (Wet or Dry)	Icy or Hard Snow	Other – Loose Snow, Slush, Etc.
Freeways	11	10.6	0.2	0.2
State Highways and Main Streets	37	33	2	2
County roads, Residential Streets, Township roads	52	31	11	10
Total All Roads	100	75	13	12

TABLE 10. RATIO OF ACCIDENT RATES ON ICY OR SNOWY ROADS
TO TOTAL ACCIDENT RATES

All Types	Fatal	Personal Injury	Property Damage
1.8	0.8	1.4	2.2

Tests by the Tennessee Highway Research Program on bare bituminous pavements at speeds between 20 and 40 mph, generally indicate small increases in stopping distance for studded tires up to five percent more than for unstudded tires. These represent increases on the order of one to six feet. Canada Safety Council tests on wet concrete in 1970 showed up to a 27 percent increase, representing 24 feet. The average increase was 12 feet, or 18 percent, with test speeds ranging between 20 mph and 50 mph. For dry concrete pavements the average increase was five feet, or 10 percent. *(Ref. 1)* Dr. Gerhard Zichner of West Germany states that stopping distances on bare pavements are increased up to 40 percent by use of studded tires. *(Ref. 17)*

Recent Ontario Provincial Police tests on various pavement types and road surface conditions at speeds of 30 mph and 50 mph showed that, on the average, studded tires required longer stopping distances (ranging between four and 22 percent) on all surfaces tested. *(Ref. 14)*

Indications are that the performance advantages of studded tires on ice may be largely offset by disadvantages on bare pavement when the relative amounts of exposure are taken into account. Approximately 75 percent of all winter travel in 1969-70 was on bare roads. Studded tires could, therefore, have a net disadvantage in stopping distance on roads kept bare most of the time by high level winter maintenance practices.

Effects Related to Pavement Wear

Studded tires have been credited, justifiably or unjustifiably, for a number of other effects detrimental to traffic safety. Most of these are based on a consensus of value judgments made either from actual observations or driving experiences. Only a limited number are supported by research study, but all bear a valid relationship to the traffic safety aspect of studded tires. The miscellaneous effects are:

- Premature loss of paint striping to delineate pavement lane lines and center lines.
- Loss of pavement grooving where provided for skid prevention.
- Loss of skid resistance in pavement wheel-track ruts.
- Reduction in driving visibility due to splash and spray from water accumulating in worn pavement wheel troughs.
- Hydroplaning from accumulated water in wheel troughs.
- Adverse vehicle handling behavior caused by wheel troughs during lane-changing or passing maneuvers.
- Increased noise produced both inside and outside the vehicle from tires riding on roughened pavement.
- Danger from loosened stones and flying studs.

The premature loss of paint striping and pavement grooving from abrasion caused by studded tires is an observed fact. What is not known is to what degree these two factors have made driving more hazardous. Because lane lines cannot be repainted during the winter with any degree of success, premature loss of lane markings implies a more hazardous condition. Likewise, a loss of skid resistance produced by the abrasion of pavement grooving in critical locations, such as on curves, is an evident safety detriment.

There is little evidence to prove that studded tires reduce the normal skid resistance of pavement surfaces. Limited skid resistance tests by the Department of Highways on wet pavements both within and outside the worn wheel tracks indicate little measurable difference. The small differences observed did show a slight trend toward less skid resistance in the troughs. Water, however, accumulating in the wheel troughs does contribute to increased splash and spray that adversely affect visibility and can contribute to hydroplaning (loss of vehicle control due to tires riding on a layer of water). However, the frequency and consequences of hydroplaning over water in worn wheel troughs have not been established.

Any deeply rutted road surface will require extra driver effort in controlling a vehicle, especially during lane-changing or passing maneuvers. Adverse effects on vehicle handling due to studded tire wear have not yet become pronounced in Minnesota. Roughened driving surfaces, however, are a present fact and increased noise produced by tire-surface interaction (particularly with studded tires) is disconcerting both inside and outside the car. Lateral displacement of vehicle position in a driving lane because of either water or noise causes crowding of the vehciles in adjacent or oncoming lanes with increased accident potential normally associated with narrow lanes. Lane widths presently used on highways have been established as a result of research indicating an increase in accidents with narrowing clearance between vehicles. Vehicle positioning shifts associated with ruts tend to negate the benefits of the lane widths provided on modern highways.

Instances of loose stones and studs being thrown up from wheels in traffic and causing damage have been reported by vehicle owners on returns of questionnaires designed for this study.

Cornell (CAL) Accident Study

Although the intent of many of the investigations previously discussed has been to demonstrate and attempt to evaluate the safety benefits of studded tires, these have been indirect measures aimed only at certain individual vehicle performance characteristics. The real measure of highway safety effectiveness is in the prevention of accidents and the reduction of accident severity. The direct approach to the problem (i.e., what effects, if any, will the discontinuance of use of studded tires have on highway safety) includes the investigation and analysis of automobile accidents during the winter months to determine whether studded tires are producing any differences in accident frequency or severity. Since there was a complete lack of information on research of this nature, the Department of Highways initiated with Cornell Aeronautical Laboratory, Inc. the safety study hereafter described.

Objective

The ultimate objective of this study was to determine whether the performance advantages of studded tires do, in fact, provide greater safety on the highways and streets in mixed traffic under all winter conditions. The study was done by comparing studded tires to other tire types in terms of:

- The amount and type of usage.
- The effect upon accident precipitation.
- The effect upon accident characteristics, including damage costs, severity, and injury.

Data Collection

In order to isolate studded tires from other factors that may influence accidents, a large amount of information was included in the study, and relationships of many variables were considered in the analysis. There were two principal sources of information: (1) data on the driving population collected through questionnaires sent to randomly-selected automobile owners; (2) data on accident characteristics collected on police accident report forms used by participating police agencies. Additional information from state accident records was furnished to Cornell Aeronautical Laboratory (CAL) in the hope that statewide conclusions could be developed.

Questionnaires were sent to a statistically selected random sample of Minnesota registered automobile owners who were asked to supply information about themselves, the automobile they drove most frequently, and the driving conditions on a particular driving day. Specifically, the respondent was asked to describe his vehicle and his driving as experienced the day before filling out the questionnaire. Typical data obtained from the questionnaires included such information as age, sex, driving experience, and attitude toward studded tires; vehicle characteristics, such as make, age, power assists, brake type, tire type and age, and total mileage driven; road conditions and driving exposure time on the day being reported. Equal numbers of the questionnaires were mailed twice weekly in order to sample all days throughout the data-collection period. A cover letter signed by Governor LeVander requesting the respondent's cooperation accompanied each questionnaire.

Accident reports, augmented by a supplementary informational form designed by CAL, were received for each investigaged and reported accident from the Minnesota Highway Patrol and a number of municipal police departments. The cities in the Twin Cities metropolitan area that participated were Minneapolis, St. Paul, Brooklyn Center, Edina, Richfield and Roseville. Out-state, the cities of Duluth, Grand Rapids, Mankato, Rochester and St. Cloud participated. The Minnesota Highway Patrol furnished statewide coverage of most state highway accidents in rural and smaller urban areas. The cities furnished coverage of most accidents on city streets, except that in Minneapolis the police normally investigate only injury and fatal accidents.

Typical data obtained from the supplemental police accident forms, in addition to accident data normally reported, included such information as tire type, road conditions, accident severity, officer's opinion of cause, driver characteristics and vehicle characteristics. The use of these data is carefully restricted to research purposes only in order to protect the rights of all parties involved.

The Department of Highways began collection of data for this study in February, 1970 and continued until May 1, 1970, the end of the legal studded-tire period. The second data collection period resumed the following fall on October 15, 1970, and continued until January 4, 1971, when it was terminated for this study. Data analysis and preparation of a final report by CAL have followed. Data collection activities as summarized in Table 11 indicate the scope of the study.

TABLE 11. DATA COLLECTION - CORNELL STUDY.

Recording Periods	Feb. to Apr., 1970	Oct. 15, 1970 to Jan. 4, 1971	Total
Questionnaires			
Mailed	48,100 (3,848 per week)	36,000 (3,000 per week)	84,100
Returned	22,500	16,800	39,300
% Return	47	47	47
Police Accident Reports	1,890	2,930	4,820
Minn. Highway Patrol	1,330	1,725	3,055
City Reports	560	1,205	1,765
Cities Reporting	4 (2 mo.) 11 (1 mo.)	10	

As the questionnaires and accident reports were received by the Department of Highways, they were transmitted to CAL where the data were coded, checked and stored for subsequent computer processing. Concurrently, procedures and computer programs for analysis of the data were developed and tested by CAL.

Preliminary analyses of the information data collected through February, March and April 1970 were conducted by CAL in November and the findings reported in the Department of Highways Progress Report . These were simple statistical summaries of information obtained from questionnaires and accident reports. The information has been used to determine the general characteristics of the collected data so that detailed analytical procedures could be formulated.

The questionnaire returns and accident report data as analyzed by CAL have not been regarded by them to be strictly statistically representative of all drivers or all accidents. Therefore, rigorous statistical analyses were not fully consummated. The results are, nevertheless, considered to be indicators which do reflect strongly the parameters involved in this study.

Questionnaire Responses

Some general characteristics of the winter driving population and road conditions in Minnesota have been ascertained from the questionnaire survey. Use of different tire types varied widely throughout the state by region, locale, owner differences and vehicle characteristics. Statewide, about 38 percent of the driving during the study period was with studded tires, about 23 percent with snow tires, and about 38 percent with regular tires. Less than one-half of one percent of the respondents used studded tires on all four wheels. Percentagewise, more female owners than males used studded tires. Owners over 60 years of age used more snow tires and less studded tires. The proportion of studded tires tended to decrease with lower annual mileage. More sedans and convertibles had studded tires proportionately than did station wagons. Usage was greater for vehicles equipped with power brakes or power steering. Studded-tire use increased with later model vehicles up to 1969-70 when a decline was noted.

Six percent of all driving occurred on roads described as completely covered with ice, snow, slush, or frost. Another six percent occurred on mostly covered roads, and 18 percent on roads with scattered cover. Thus, 70 percent of all driving in Minnesota during the 6½ month winter period when studded tires are legal was on roads essentially bare. This figure checks well with independent estimates by the Department of Highways (Table 9). Only three-tenths of one percent of the respondents did not drive because of snowy or icy roads.

The reported incidence of skidding of any kind was slightly less for vehicles using studded tires than for vehicles using either snow tires or regular tires.

The majority of respondents expressed the opinion that studded tires allow one to drive closer to the speed limit on slippery roads. This opinion was held most frequently by studded-tire owners. This view suggests that the studded-tire driver may utilize his traction advantage to drive at higher speeds on slippery surfaces, perhaps thereby diminishing safety benefits. This contrasts, however, with the lower driver accident propensity associated with users of studded tires as found in the accident analysis of the CAL survey.

Analysis of 2,580 unsolicited comments appended to the questionnaire by respondents indicated 40 percent favored continued use of studded tires, 29 percent favored banning studded tires, and 31 percent expressed no opinion or were undecided. Respondents from the Twin City metropolitan area tended to favor banning studded tires, while respondents from other parts of the state tended to favor continued use.

Accident Reports

A usable sample of approximately 4,500 reported automobile accidents was collected during two winter periods totaling 5½ months. By comparison, in 1970 about 60 percent of the 99,400 accidents and about 44 percent of the 987 traffic deaths in Minnesota occurred in the 6½ months during the two periods when studded tires were legal.

The study has suffered somewhat from an insufficient number of accident reports. Reports on at least ten thousand accident vehicles were desired to provide a data base large enough to permit analyses that could more completely exclude many extraneous influences. Several factors reduced the size of the collected accident sample below that anticipated when the study was initiated. The chief cause was the fact that several of the participating cities were unable, for one reason or another, to provide the degree of police investigation needed to report on all accident occurrences.

In attempting to isolate tire effects, the accident reports required close scrutiny to determine how each vehicle was involved - whether it triggered the accident and whether it was involved due to sliding. These two variables along with road cover and tire configuration are basic to most of the analyses.

For each accident, where possible, one accident-precipitating vehicle, called the trigger vehicle, was identified. A vehicle was said to be a trigger vehicle if it clearly violated another's right of way or was the last vehicle to convert a situation into an accident by changing speed or direction. Hence, all vehicles in single-car accidents and those which initiated an accident by striking a stopped vehicle or fixed object or by leaving the road, were also trigger vehicles. In most cases blame was irrelevant. Rather, the object was to determine which vehicle was most active in precipitating the accident, irrespective of the reason for such behavior. Where no vehicle could be clearly specified as a trigger vehicle, the issue was not forced and the trigger vehicle was coded as unknown.

In addition to assigning one trigger vehicle per accident, each accident vehicle that was involved due to sliding was identified whenever a sound decision could be made. For instance, a vehicle was said to have been involved due to sliding if it would not have been involved in the accident had its path been free of ice, snow, slush, and frost. It should be noted that the assignment of a trigger vehicle and the determination of whether a vehicle was involved due to sliding were independent; i.e., a trigger vehicle might or might not have been involved due to sliding, and a vehicle involved due to sliding might or might not have been a trigger vehicle.

Trigger vehicles are of particular interest in attempting to isolate tire effects since they participate most actively in precipitating the accident. Therefore, trigger vehicles are most likely to make extraordinary demands on tire traction. Sliding vehicles are of importance because vehicle performance tests already cited indicate that any potential traffic safety effects of various tire types would involve the mechanism of sliding.

The study sample included just over 4,000 accidents to which a trigger vehicle would be assigned. These 4,000 accidents included about 7,150 automobiles, 114 deaths, and 2,562 injuries. Vehicles other than automobiles were not included in the study.

Influence of Winter on Traffic Accidents

Twenty-one percent of the 4,000 accidents to which a trigger vehicle could be assigned were said to have been triggered by automobiles sliding on ice, snow, slush or frost. Nineteen percent of the 7,150 accident vehicles were involved in accidents triggered by sliding. Of all single-vehicle accidents in the study 30 percent were said to have been triggered by sliding. Considering all accident vehicles, only 14 percent were involved due to their own sliding. (This figure is low because the group of all accident vehicles includes those which were stopped or were suddenly imposed upon.) Thus, accidents precipitated by sliding are more apt to be single-car accidents.

Almost 80 percent of all vehicles that triggered accidents on snowy or icy roads were involved due to sliding. About 90 percent of all vehicles triggering accidents on roads specifically reported as icy or frosty were involved due to sliding. As road conditions changed from little or no cover to completely covered, the indicated probability of triggering an accident for any reason more than doubled, regardless of tire type. Independent studies by the Department of Highways substantiate this finding (Table 10).

The proportion of accidents triggered by sliding varied considerably through the winter months rising to a peak in the midwinter months and tapering off toward spring in a manner consistent with weather and road conditions. Assuming the CAL study to be representative of winter traffic safety in 1970, the results infer that about 13 percent of all 1970 traffic accidents in Minnesota could have been triggered by sliding on ice, snow, slush, or frost.

Accidents triggered by sliding were of considerably lower severity than accidents triggered by other causes. In the study the incidence of deaths and injuries was generally less for accidents triggered by sliding than for accidents triggered for other reasons. Although 21 percent of all accidents in the sample were triggered by sliding, an average of only 12 percent of the deaths and 15 percent of the injuries occurred in such accidents. More specifically, the accidents precipitated by sliding accounted for 13 percent of the A-level injuries, 15 percent of the B-level and 17 percent of the C-level injuries.*

Thus, the more severe injuries occurred less frequently than the less severe injuries. On the other hand, 32 percent of accidents causing only property damage were triggered by sliding. However, the average estimated property damage per accident for sliding accidents was on the order of ten percent less than that for all accidents. Again assuming the CAL study to be representative of winter traffic safety in 1970, the results infer that about six percent of all 1970 traffic deaths could have occurred in accidents triggered by sliding on ice, snow, slush, or frost.

In general, these findings corroborate official Minnesota accident records, which indicate that accidents are less severe on snowy and icy roads, and show specifically that accidents on snowy and icy roads are less severe when triggered by sliding. The reduced severity is consistent and clear in all severity classes and may be attributed to increased driver caution and lower speeds when roads are slippery.

Influences of Tire Type on Accident Rates

In the sample about 14 percent of all vehicles involved in accidents were equipped with studded tires, 27 percent with snow tires, and 59 percent with regular tires. From the questionnaire survey during the winter periods when studded tires were legal, about 38 percent of all driving involved vehicles equipped with studded tires, 23 percent with snow tires, and 38 percent with regular tires. For each road surface condition reported, the proportion of vehicles equipped with studded tires and involved in accidents was considerably less than the proportion of driving with studded tires. The indicated accident rate on bare roads for autos equipped with studded tires was lower than the rate for autos. With other tires, this is incompatible with the fact that on bare roads vehicle performance tests have shown little or no advantages - and some disadvantages - for studded tires. Thus, a "bias" (extraneous influence in the data) favoring studded tires is indicated.

The most reasonable explanation for this apparent paradox is that many motorists who have equipped their vehicles with studded tires are more safety-oriented by nature and tend to have fewer accidents than the average motorist. Possible

These levels are criteria used by Minnesota law enforcement officers to describe degrees of personal injury as judged from visual indivations.
A - level injuries include bleeding wounds, cuts, distorted member, or any condition that required the victim to be carried from the scene.
B - level injuries include other visible injuries such as bruises, abrasions, swelling, limping, or other painful movement.
C - level injuries include non-visible injuries such as complaint of pain and momentary unconsciousness.
Note that C-level injuries, while often minor, also could be sumptoms of very serious internal injury while A-level and B-level injuries, while often serious, also could be only superficial.

explanations for this decreased accident propensity could be a greater safety consciousness, a general attitude of caution and responsibility, or some other personal trait associated with the motorist's decision to purchase studded tires. At any rate, the implied driver effects complicate the accident-analysis phase of the study. Another possible explanation for the bias influence might be inaccurate reporting. A considerable degree of inaccurate police accident reporting of tire type was detected in two separate accident studies conducted in Canada by the Ontario Department of Highways and the City of Quebec *(Ref. 14 & 9)*. However, for the CAL study, because the officer was asked to inspect each tire on each accident vehicle and measure the depth of its remaining tread, the accuracy of the reported data regarding tire type is considered good.

The increase in accident rate attributable to roads becoming snowy and icy is obtained by computing the ratio of accident rates on snowy and icy roads to the accident rate on bare roads. These ratios were computed for the entire study period and for each month, tire type and amount of road cover for all accidents triggered on snowy and icy roads regardless of cause. Results for the study period taken as a whole showed little difference between the indicated rate increases for studded tires and snow tires, both of which increased considerably less than the rate increase for regular tires. However, results for the midwinter months of December, February and March (January not studied) showed that when roads became snowy and icy, increases in indicated accident rates were smaller for vehicles with studded tires than for vehicles with snow tires. Similar comparisons indicate that snow tires were beneficial in accident reduction when comparied to regular tires on snowy and icy roads. On the other hand, results for the early and late winter months of October (last half), November, and April showed smaller increases in indicated accident rates for snow tires than for studded tires, which, in turn, showed smaller increases than regular tires. The reason for the difference is not clear. It may be due to inconsistencies in data obtained during the transitional periods at the beginning and end of the studded tire season, both in terms of changing tire use and the variable nature of road cover conditions.

Because ratios are used, primary differences due to driver accident propensities associated with tire type tend to cancel out. To the extent that the relative driver accident propensities associated with tire type do not change with amount or type of winter road cover, studded tires appear to be beneficial in reducing accidents on snowy and icy roads in the four midwinter months in Minnesota.

The analysis just discussed included all accidents in the study triggered on snowy and icy roads without regard to the triggering influence. Vehicle performance tests already cited have indicated that potential safety benefits from the use of studded tires and snow tires on snowy and icy roads would be derived through the mechanism of reduced sliding. Therefore, indices of the probabilities of triggering an accident by sliding or a given condition of road cover and for a given tire type were computed from the data. These results have also been corrected using procedures intended to remove effects of driver accident propensity associated with tire type. Once again, to the extent that the relative driver accident propensities associated with tire type do not change with amount or type of winter road cover, studded tires appear to be more beneficial during the four midwinter months than unstudded snow tires in reducing the probability of triggering an accident by sliding on snowy and icy roads in Minnesota. Snow tires are similarly beneficial over regular tires.

A small sub-sample of accidents was obtained from reports in which officers specifically noted ice or frost road cover. Similar analysis of these data indicated a greater benefit in accident reduction by studded tires on ice or frost than on roads reported as snowy and icy.

The data itself and the procedures used to make corrections for bias are not sufficiently precise to permit a quantitative estimate of the actual increase in accidents that might have occurred if studded tires had been replaced by snow tires during the study period. The uncorrected "face value" findings simply say that the inherent lower accident propensity for the motorists presently using studded tires combined with the actual influence of studded tires apparently have a small but beneficial effect upon traffic safety in Minnesota. Because of the extent of driver influence upon accident precipitation, the degree of increase in traffic accidents on snowy and icy roads that could be attributed to replacement of studded tires by snow tires would be slight when compared to the total number of accidents occurring in Minnesota.

Influence of Tire Type on Accident Severity

Examination of four indicators of accident severity yielded mixed results. Impact speed, preimpact rotation, impact-deformation and driver injury were analyzed for vehicles that triggered accidents due to sliding. In many cases the number of reported occurrences, when separated by tire type and amount of road cover, were insufficient to yield reliable indications. For the most part only roads with speed zones above 50 mph had enough reported accidents to support definition of trends. Differences in driver accident propensities could not be eliminated from any of the severity indicators analyzed. Thus, any results indicating severity reductions from studded tires are probably influenced to an unknown degree by the characteristics of the motorists who use studded tires. Since drivers of vehicles equipped with studded tires have been shown to be less accident prone, any skills or attitudes which reduce their accident propensity may also operate to reduce the severity of accidents in which they become involved.

Analysis of impact speeds shows that for accidents triggered due to sliding, vehicles with studded tires tend to have lower impact speeds than vehicles with snow tires, which in turn often have lower impact speeds than regular tires. The apparent differences in impact speed associated with tire type usually were small - less than 5-mph reduction on roads zoned above 50 mph. Vehicles in single-vehicle accidents tended to have higher impact speeds than trigger vehicles in multivehicle accidents.

Reported preimpact rotation on dry roads was least for regular tires and greatest for studded tires, while on wet roads both studded tires and snow tires performed slightly better than regular tires in this respect. In accidents triggered due to sliding on snowy and icy roads, vehicles with studded tires tended to have somewhat less incidence of preimpact rotation than did snow tires. When preimpact rotation did occur, the incidence of severe rotation (90 degrees or more) was somewhat less for vehicles with studded tires than for snow tires. Similarly, vehicles with snow tires often had less preimpact rotation than those with regular tires. On roads reported as completely covered with ice or frost, studded tires performed better than snow tires and snow tires somewhat better than regular tires with respect to preimpact rotation.

These findings regarding impact speed and preimpact rotation suggest that in emergency sliding conditions on snowy and icy roads some drivers may be able to retain better control with studded tires, at least in rural or high-speed situations. On the other hand, in emergency conditions on dry roads some drivers may be less able to retain control with studded tires.

Examination of the incidence of vehicle impact-deformation greater than six inches yielded results which are inconsistent with the lower impact speeds observed for vehicles equipped with studded tires. That a majority of accident vehicles had more than six-inch impact-deformation testifies to the fragile construction of automobiles. No consistent or systematic reduction in incidence of deformation greater than six inches, however, could be detected for any one of the tire types.

The proportion of drivers for vehicles which triggered an accident by sliding was determined for each tire type, excepting roll-over and side-swipe accidents. Comparing drivers injured, the proportion was somewhat smaller for vehicles with studded tires than with snow tires. In turn, drivers with snow tires had consistently lower injury rates than drivers with regular tires. In a small sample of single-car accidents none of the 23 drivers with studded tires was injured. Because of the small number of occurrences in the sample this finding could be due to chance; the data, nevertheless, indicate a clear tendency for reduced driver injury in single-car accidents involving vehicles equipped with studded tires.

The results relating to preimpact behavior and accident severity appear to ascribe some benefit to the use of studded tires, but the extraneous effects of driver safety characteristics associated with tire type could produce part or all of the observed effect. The degree of potential increase in severity, therefore, that might occur if studded tires were replaced by snow tires, cannot be reliably reported. The findings that accidents on snowy and icy roads are historically less severe than other accidents in Minnesota tends to lessen the chances for further reductions in accident severity through use of studded tires or other devices.

General Summary of CAL Study

The factors and interactions causing traffic accidents and affecting severity are so complex that the identification and quantification of the effect of any single factor, such as tire type, are extremely difficult. On the other hand, because of complex interaction by many causative factors in the overall traffic accident problem the probability of any one factor having a pronounced effect on overall traffic safety is small. The results of the CAL study do not demonstrate outstanding advantages for studded tires in terms of accident precipitation or severity. The findings are confined mostly to the effects of tire type on snowy and icy roads. Little data was obtained relative to effects of tire type on bare roads, and the scope of the study did not include effects of road surface wear upon traffic safety.

Accident Studies by Others

Other accident studies have been conducted in Canada. The province of Ontario conducted a study of 2,790 accident vehicles in February 1970. This study *concluded that "the estimated* percentage of studded-tire-equipped vehicles involved in icy-road accidents is not markedly less than the percentage involved in non-icy-road accidents, which is contrary to expectations if studded tires afford a significant contribution to safety. In fact, the estimated percentage involvement in icy-road accidents is greater than in non-icy-road accidents, although the difference is not statistically significant". *(Ref. 14)*

The percentage of vehicles with studs involved in accidents on both icy and non-icy roads was only about two-thirds the percentage of vehicles so equipped driving in the province. However, differences in driver skills, concern for safety, and differential exposure may account for this indication. All of the icy-road accidents were rated by a panel of four as to the usefulness of studded tires in preventing the accident or reducing its severity. Ratings showed studded tires probably would have helped in 21 percent of accidents on icy roads and probably, or definitely, would not have helped in 41 percent of the accidents. No decision was possible for 38 percent of the accidents.

A study of accidents in the City of Quebec, Canada, was conducted by the Quebec Department of Roads covering 2,235 accidents, of which about 45 percent involved skidding. The study concludes *(Ref. 9)* that "in the Quebec area, the use of studded tires has not brought about any major improvement in winter accident statistics. In fact the data taken at its face value indicated virtually no improvement".

APPENDIX

TABLE A-1. DESIGN GRADATION OF BITUMINOUS PAVEMENTS

Mix No.	% Passing Sieve Size ¾"	5/8"	½"	3/8"	No. 4	No. 10	No. 40	No. 80	No.200	Specific Gravity Mixture	Abrasion Loss Los Angeles Rattler (a)
1	100	99	86	72	54	46	28	16	5.3	2.390	21
2		100	92	86	71	62	24	8	2.6	2.323	17
3		100	93	84	69	55	21	7	3.8	2.336	17
9					100	75	30	15	6.9	2.375	--
10					100	73	27	16	10.1	2.472	--
11					100	75	30	15	6.9	2.375	--
12					100	75	30	15	6.9	2.384	--
13	100	99	92	78	56	46	27	14	4.7	2.474	9
14	100	100	92	78	55	45	26	12	3.1	2.484	9
15	100	100	92	78	56	46	27	14	4.7	2.483	9
16	100	97	87	80	70	55	17	6	3.0	2.370	17

(a) Los Angeles Rattler Tests are run only on Coarse Aggregates.

TABLE A-2. DESIGN GRADATION OF RIGID PAVEMENTS

% Passing Sieve Size															Abrasion Loss Los Angeles
2"	1½"	1¼"	1"	¾"	5/8"	½"	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Rattler (
		100	93	71	58	49	42	33	29	23	15	5	1	0.4	18, 3
	100	97	85	64		52	45	34	30	24	16	5	1	0.4	20, 1
100	91	80	70	61	58	55	42	33	30	25	16	5	1	0.4	32
100	97	93	87	80	75	66	55	39	28	19	10	7	5	1.1	9
		100	93	71	58	49	42	33	29	23	15	5	1	0.4	18, 3
								10	79	47	29	20	14	9.7	9 (b
		100	93	71	58	49	42	33	29	23	15	5	1	0.4	18, 3
			100	100	95	86	76	61	54	44	29	10	2	0.8	31
			100	100	95	86	76	61	54	44	29	10	2	0.8	31

Los Angeles Rattler Tests are run only on Coarse Aggregates. Where 2 results are given values are for +¾" and -¾". A single value fo
concrete is the ave. for +¾" and -¾".

This value is for parent rock.

TABLE A-3. DENSITY AND ASPHALT CONTENT OF BITUMINOUS PAVEMENTS

Test Series No.	Mix No.	Pavement No.	Specification Lbs./Cu. Ft.	End Block Lbs./Cu. Ft.	Actual Pavement Lbs./Cu. Ft.	% Asphalt Design	% Asphalt Actual
1	1	590	144.5 to 147.5	147.6	146.5	5.2	5.2
	1	591	144.5 to 147.5	146.8	145.6	5.2	5.0
	2	587	140.5 to 143.4	138.7	139.2	7.0	6.8
	3	588	139.7 to 142.7	137.6	140.8	6.0	6.1
	3	589	139.7 to 142.7	139.4	142.2	6.0	5.8
2	1	601	144.5 to 147.5	148.1	146.6	5.2	5.0
	2	602	140.5 to 143.4	137.7	139.9	7.0	6.5
	2	603	140.5 to 143.4	140.0	140.7	7.0	7.1
	3	604	139.7 to 142.7	139.6	139.0	6.0	5.7
	3	605	139.7 to 142.7	140.0	141.1	6.0	5.7
3	1	613	144.5 to 147.5	148.0	144.8	5.2	5.5
	1	614	144.5 to 147.5	147.0	146.0	5.2	5.3
	2	616	140.5 to 143.4	141.0	137.9	7.0	6.6
	2	617	140.5 to 143.4	139.0	140.6	7.0	6.3
	3	615	139.7 to 142.7	141.0	140.8	6.0	5.9
4	9	623	143.5 to 146.5	140.9	144.0	7.5	7.9
	10	624	149.5 to 152.5	145.3	148.6	8.0	8.4
	11	625	143.5 to 146.5	140.2	139.0	7.5	7.8
	12	626	143.5 to 146.5	136.8	140.0	8.5	8.9
	13	622	150.1 to 153.3	153.5	152.0	6.0	6.4
	14	627	150.1 to 153.3	150.1	146.5	7.0	7.6
	15	628	150.1 to 153.3	153.1	150.4	7.0	7.3
	16	629	143.4 to 146.3	144.7	148.3	7.0	7.4

TABLE A-4. MARSHALL STABILITY MIX DESIGN DATA FOR BITUMINOUS PAVEMENTS.

Mix No.	Voids	Stability, lbs.	Flow, in	Mix No.	Voids	Stability, lbs.	Flow, in.
1	3.0	2527	.094	11	4.0	1832	.136
2	3.6	1376	.086	12	4.0	1832	.136
3	5.6	1152	.073	13	3.0	1574	.083
9	4.0	1832	.136	14	1.5	1659	.203
10	5.0	1820	.139	15	1.8	1395	.240
				16	2.3	1249	.179

TABLE A-5. ASPHALT EXTRACTION TEST DATA

	Aggregate Gradation - % Passing Sieve Size										
Pavement No.	¾″	5/8″	½″	3/8″	No. 4	No. 10	No. 20	No. 40	No. 80	No. 100	No. 200
590	100	97	82	70	52	44	35	25	14	12	5.7
591	100	95	85	69	52	44	35	26	15	12	5.4
587		100	93	82	67	58	39	23	8	7	3.8
588	100	99	96	89	72	58	42	22	8	7	4.2
589	100	99	95	85	69	55	39	20	7	6	4.1
601	100	96	85	70	51	43	34	25	14	12	5.1
602		100	94	83	71	61	40	23	8	6	3.1
603		100	94	84	71	61	41	23	8	7	3.2
604	100	99	94	85	69	56	40	22	7	6	3.6
605	100	98	92	82	67	54	38	20	6	5	3.2
613	100	94	88	75	55	46	37	27	15	13	5.3
614	100	99	88	75	55	46	37	27	15	13	5.3
616		100	94	82	70	59	38	21	7	6	2.8
617		100	94	84	68	56	37	21	8	6	2.9
615	100	100	92	85	70	57	42	23	8	7	4.0
622		100	95	81	58	45	35	24	11	9	4.1
623				100	99	65	38	25	14	12	7.8
624					100	76	44	29	18	16	11.4
625				100	99	67	40	27	15	12	7.8
626					100	70	42	27	15	12	7.7
627		100	93	82	59	45	34	22	9	7	3.0
628	100	97	92	79	58	45	35	25	11	9	4.5
629	100	97	89	84	70	53	30	15	6	5	3.1

TABLE A-6. PROPERTIES OF RIGID PAVEMENTS

Test Series No.	Mix No.	Pavement No.	Mix Slump, Inches		Mix Air Content, %	
			Design	Actual	Design	Actual
1	4	580	1 to 2	1-½	4 to 7	5.9
	4	583	"	1-¾	"	5.4
	5	581	"	2-¼	"	5.9
	6	582	"	1	"	4.2
	6	585	"	1-½	"	4.9
	7	584	"	1-¾	"	4.5
	8	586	"	1-¼	"	4.9
2	4	594	"	1-¼	"	4.8
	5	595	"	2	"	5.9
	5	596	"	1-¾	"	5.2
	6	598	"	1-¾	"	5.9
	6	599	"	1	"	4.7
	7	600	"	1-¼	"	4.2
	8	597	"	1	"	4.6
3	4	606	"	1-½	"	5.4
	4	607	"	1-¾	"	5.2
	5	608	"	2	"	4.6
	5	609	"	1	"	4.7
	6	610	"	1	"	4.8
	7	611	"	1	"	4.9
	8	612	"	1	"	4.7
4	18	620	"	3-½	"	5.1
	19	619	"	1-½	"	6.0
	20	618	"	2	"	5.9

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