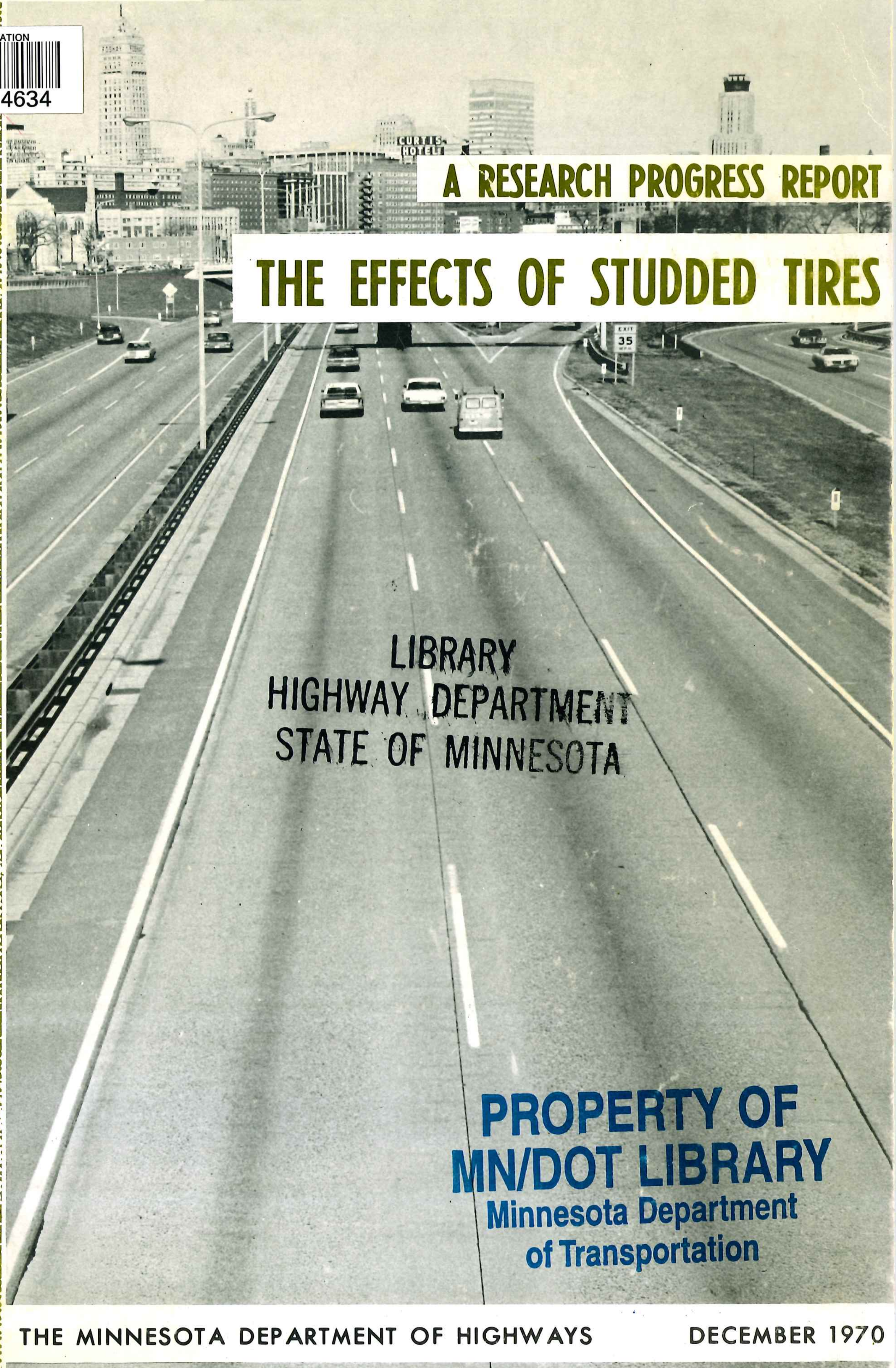
R THE MINNESOTA LEGISLATURE



A RESEARCH PROGRESS REPORT

THE EFFECTS OF STUDDED TIRES

THE MINNESOTA DEPARTMENT OF HIGHWAYS DECEMBER 1970

A Research Progress 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

December, 1970

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 is a report on the progress of that study and is prepared for preliminary use by the Legislature when it convenes in January, 1971. The final report is expected to be available by April 1, 1971. The findings in this report, therefore, must be considered tentative pending completion of the study.

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 and findings 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.

TABLE OF CONTENTS

SUMMARY OF TENTATIVE FINDINGS

Pavement Wear Effects

1. During the 1969-70 winter 40 percent of the passenger vehicles in Minnesota were equipped with studded tires, nearly all of them on the rear wheels only. By 1973-74, this figure is expected to reach 60 percent.

2. Pavement wear measurements show that pronounced wheel path wear was virtually non-existent on high-type roadway surfaces 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 bituminous wearing courses ranged from 0.54 to 0.74 inch per million studded tire passes. For the concrete wearing courses this range was 0.25 to 0.43 inch per million studded tire passes.

5. The abrasive effect of studded tires is related to the distance the studs protrude beyond the tire surface.

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. (The concrete pavement test specimens were formulated using an air-entraining agent, a standard ingredient used in Minnesota concrete pavements for over 20 years and a known inhibitor of surface deterioration from salt.)

7. Studded tires abrade roadway surfaces approximately 100 times as rapidly as unstudded tires with surface applications of sand and salt.

8. From the tests designed to find more wear-resistant surfacings, only nominal improvements were found. One exception was an epoxy-sand mixture which displayed superior wear resistance. Throughout the testing this material had a polished, slippery surface. The estimated construction cost of this treatment is $250,000 per two-lane mile. For the best of the other materials, a small improvement in wear resistance was achieved only through the use of substantially more expensive construction materials.

9. A wear-rate relationship of 5 to 1 was established between the test track wear rate and the measured rate of wear on highway surfaces. This relationship is the same for all materials studied. It is further validated by comparing the width of a typical highway wheel track about (36 inches) with the width of the studded tire path (7.7 inches) at the test track, a ratio of approximately 5 to 1.

10. If the use of studded tires should continue at the present rate, the surface life of high-traffic-volume roadways would be reduced sufficiently to require extensive repair of surface damage during the normal service life of the pavement.

11. Under the influence of studded tire traffic, by 1973 the cost to repair prematurely worn surfaces will be 2.3 million dollars annually on the trunk highway system alone. If the use of studded tires on the front wheels also becomes popular, the figure could increase to 6 to 7 million dollars annually.

Safety Effects

1. Accidents are almost twice as likely to occur when roads are snowy or icy but they are generally less severe.

2. Fatal accident rates on snowy and icy roads have been less than the fatal accident rates for all road conditions.

3. Vehicle performance on ice is significantly enhanced by the use of studded tires but does not approach the performance on bare pavements.

   - Vehicle stopping performance on glare-ice is 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 of 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.

4. Vehicle performance when aided by use of studded tires, is most improved on warm, clean glare-ice. A significantly lesser improvement is obtained on other than glare-ice surfaces.

5. Use of studded tires is generally detrimental to vehicle performance on bare pavements where stopping distances have been increased, in some instances, up to 27 percent (24 feet) by use of studded tires.

6. Winter travel (exposure) on bare pavement averages about six times more than on icy roads. Exposure to icy and snowy roads depends on the type of road and regional location. (Bare road travel occurs over 95 percent of the winter on freeways and less than 50 percent of the winter on township roads).

7. There is, as yet, no proof or evidence of consistent reduction in accident occurrence or severity on snowy or icy roads attributable to the increased use of studded tires in Minnesota. (Data from the Cornell study are insufficient at this time to define any trend.)

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, improved driving stability and shorter braking distances. Associated with the use of studded tires is observed pavement wear which can be severe particularly on high-speed, heavy-traffic 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 following biennium by 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. During the 1969 legislative session the Commissioner of Highways expressed deep concern over the pavement wear damage being observed at various locations on the trunk 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 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 progress report on that investigation. It is expected that the studies will be completed and a final report filed with the legislature by April 1, 1971.

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

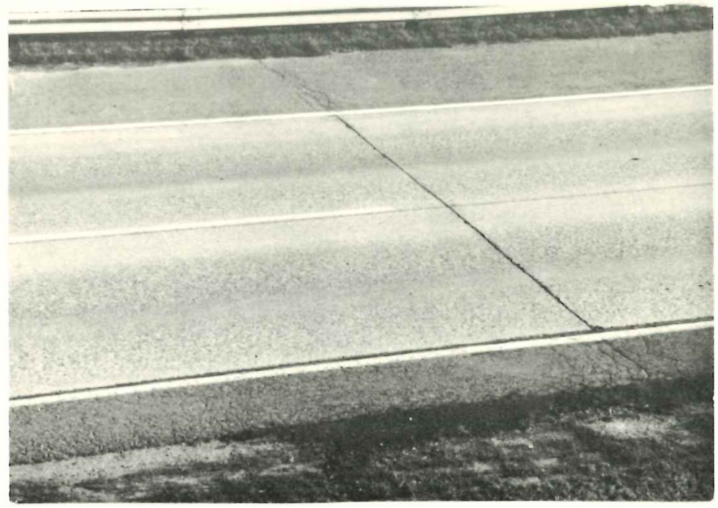
The study assigned by the legislature involved essentially three tasks: (1) a determination of the relative damage, if any, caused to pavement surfaces by studded tires, de-icing chemicals and other materials, (2) an evaluation of pavement compositions that might resist damage to the surfaces by studded 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 trunk 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.

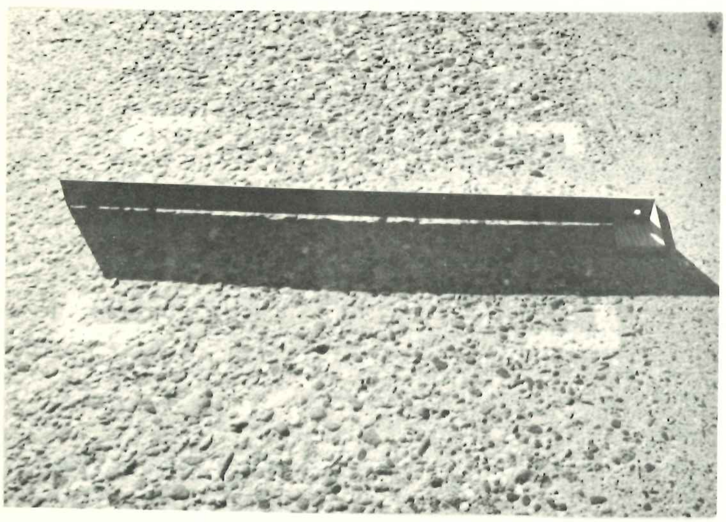
Literature Review

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 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

Wheel Path
Abrasion





Wear Depth
in
Wheel Path

Aggregate
Severely
Exposed

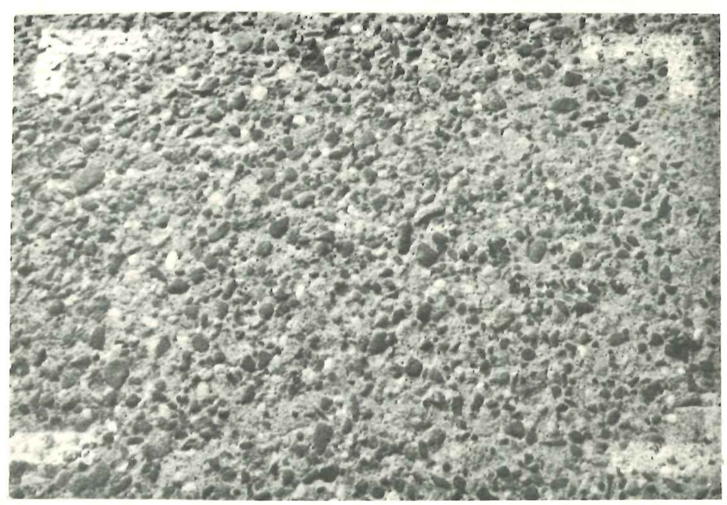
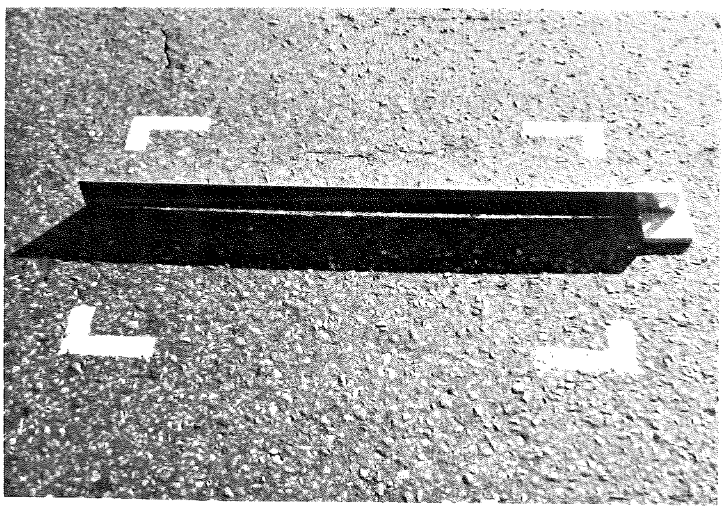


Figure 1. Concrete Pavement Wear.

Wheel Path
Abrasion



Wear Depth
in
Wheel Path

Aggregate
Severely
Exposed

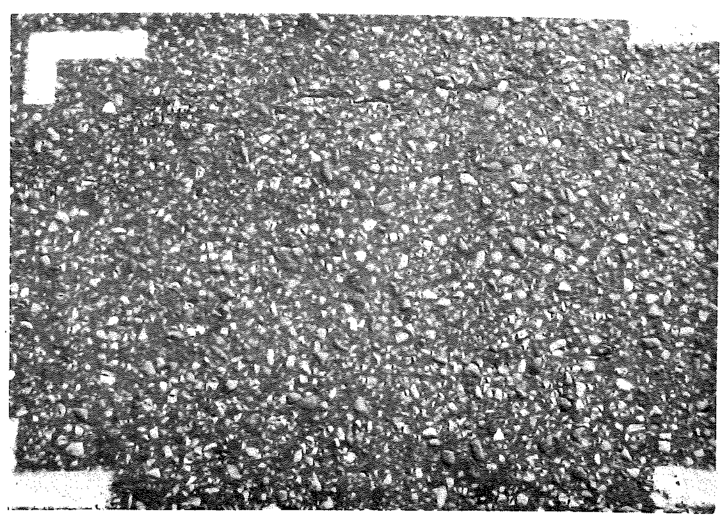


Figure 2. Bituminous Pavement Wear.

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 first 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 frozen lake 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, because of the very limited scope of all these tests the results were considered 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 Cooperative 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 by consulting engineers for the Canada Safety Council in March and April, 1970. 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.

The first task, together with all necessary liaison with the contract research agencies and others, 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.

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	$100,000*
American Oil Company	244,700
Cornell Aeronautical Laboratory	62,140
University of Minnesota	15,000
Total estimated project costs	$421,840

**Costs chargeable to project and estimated administrative overhead.*

Participation by Other States

When the costs of the program became apparent to those in the Department responsible for management functions, 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

Status of Project

As of this writing (November,1970), the laboratory pavement wear tests are expected to be completed in mid-December. The Department will continue its surveys of studded-tire use and measurements of highway pavement wear during the winter. All of these data will be analyzed and correlated for the final report. Data-gathering for the safety effectiveness studies will be discontinued for the project on January 4, 1971. The ensuing three months are needed for data analyses and report writing. The final report should be submitted to the legislature by April 1, 1971.

PAVEMENT WEAR ASPECTS

Studded Tire Usage

Since studded tires were first legalized in 1965, periodic 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. Occasional observations indicated that the number of passenger cars equipped with studded tires on the front was negligible. Also, the number of trucks equipped with studded tires was negligible.

Surveys were conducted annually in the Minneapolis-St. Paul metropolitan area. Those in the outstate districts were taken less frequently. Results of the surveys are shown in Table 1. The rate of growth of the use of studded tires in the metropolitan area only is shown in Figure 3. State-wide figures are similar. The results for 1969-70 indicate that the state could be divided into four general studded-tire-use areas as shown in Figure 4.

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. Combining this information with the results of the studded-tire surveys, it is estimated that by the winter of 1973-74, 60 percent of the passenger cars in Minnesota will be equipped with studded tires.

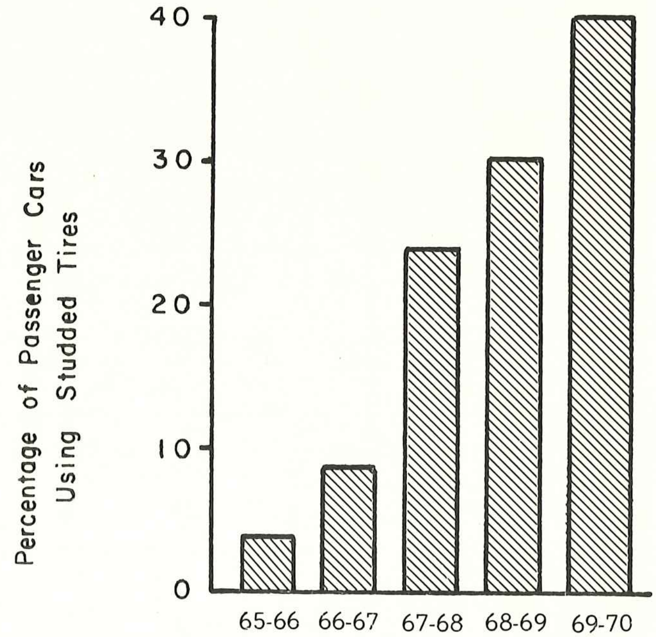


Figure 3. Studded Tire Useage Minneapolis - St. Paul Metro Area.

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

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

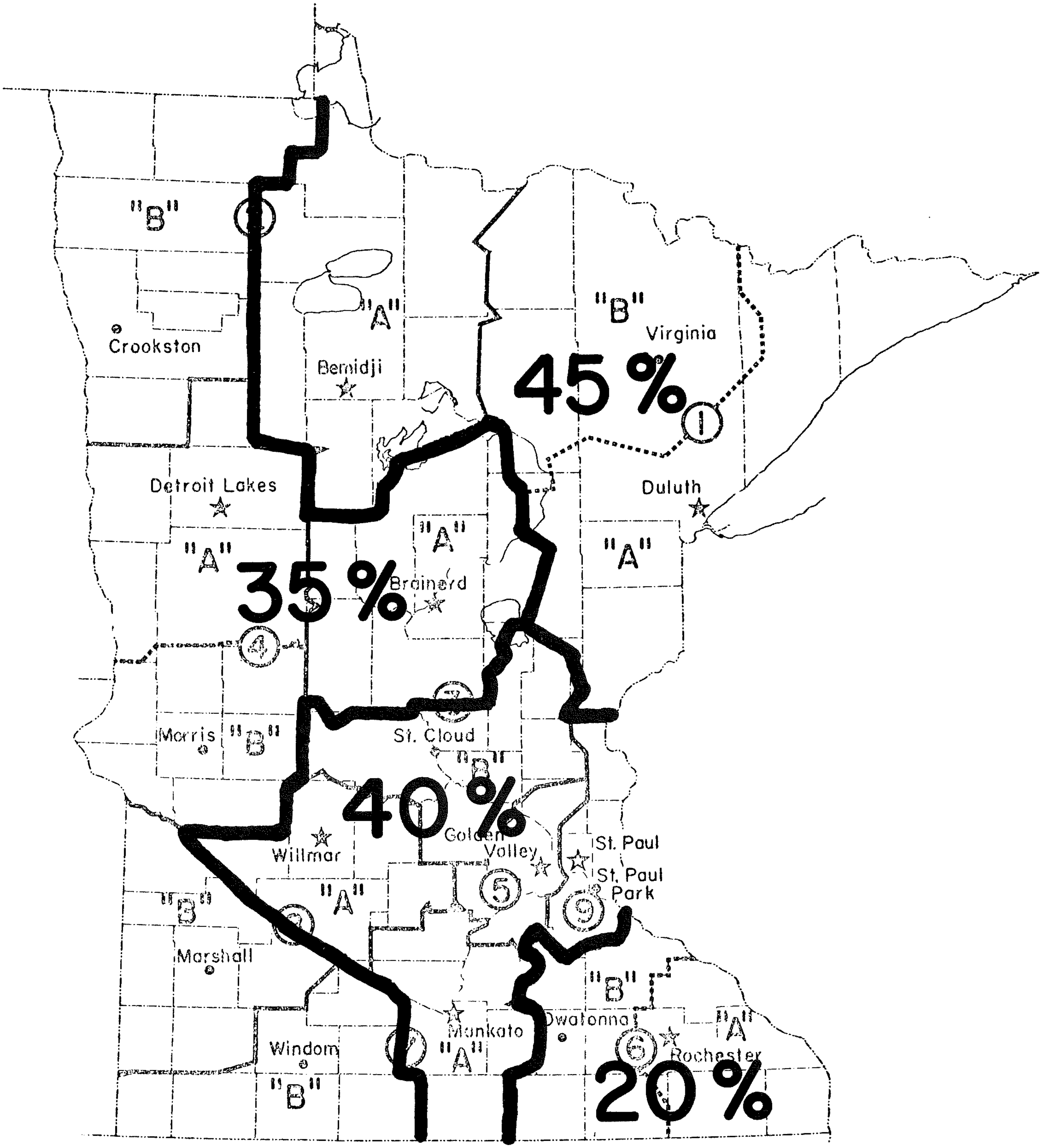


Figure 4. State-Wide Studded Tire Use by Zones.

Field Measurements

A program was developed for measuring the rate of wear on trunk highway surfaces. Test sites were chosen to include variables such as surface type, aggregate type, pavement age, traffic volume and geography. Initially, only six sites were established beginning in the winter of 1966-67, but others were added annually as apparent wear due to studded tires became more serious. A total of 86 sites was selected. The distribution is shown in Figure 5.

Detailed cross-sections were taken periodically with the device shown in Figure 6. The frame is placed on center-punched plugs set below the pavement surface. This assures that the frame is in the same location, both horizontally and vertically, each time measurements are made. Dial gage readings are taken at one-inch intervals across a 21-inch portion of the wheel track. The amount of incremental wear occurring between measurements is simply the difference between the readings. The analysis includes both the amount of wear at individual gage points and the average wear.

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 is placed on the recessed plugs at the measuring point. The camera box is then placed on the pavement over the wire. A flash unit is located above and to one side of the wire. This device projects a shadow of the wire onto the pavement surface. A series of five photographs is taken along the wire across the wheel track. The amount of pavement surface wear between periodic photographs is proportional to the increased distance between the image of the wire and the image of its shadow. *(Ref. 13)*

The Department had not noted detrimental abrasion damage on modern wearing courses prior to the introduction of studded tires even though sanding and salting was initiated long before studs became legal. Therefore, in order to analyze the wear measurements in a meaningful manner, these measurements were related to the accumulation of studded tire traffic. This is considered valid since many studies by the Department and many other agencies during the late 1940's and the 1950's showed conclusively that the air-entrained concrete used in the pavements of Minnesota since the early 1950's was substantially free from attack by de-icing salts. *(Ref. 4, 10)* Construction and materials inspection procedures along with construction methods employed by the Department give assurance that this type of concrete is used in pavements. Air-entrained concrete should not be confused with non-air-entrained concrete such as commonly used for much private work. Non-air-entrained concrete is attacked by de-icing chemicals.

The Traffic Analysis Section of the Department calculated the total number of vehicles passing over the test site during each studded-tire season. The traffic data, coupled with the studded tire usage survey results, provided an estimate of the number of studded tire passes to which each test site had been subjected. For each test site the relationship between depth of wear and number of studded tire passes was then established. 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 which has actually occurred at the test sites. The dashed line portion indicates predicted wear based on the laboratory pavement wear study which is described later in this report.

Laboratory Pavement Wear Tests

This portion of the research was conducted by The American Oil Company 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 was used for the test program and 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 from 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?

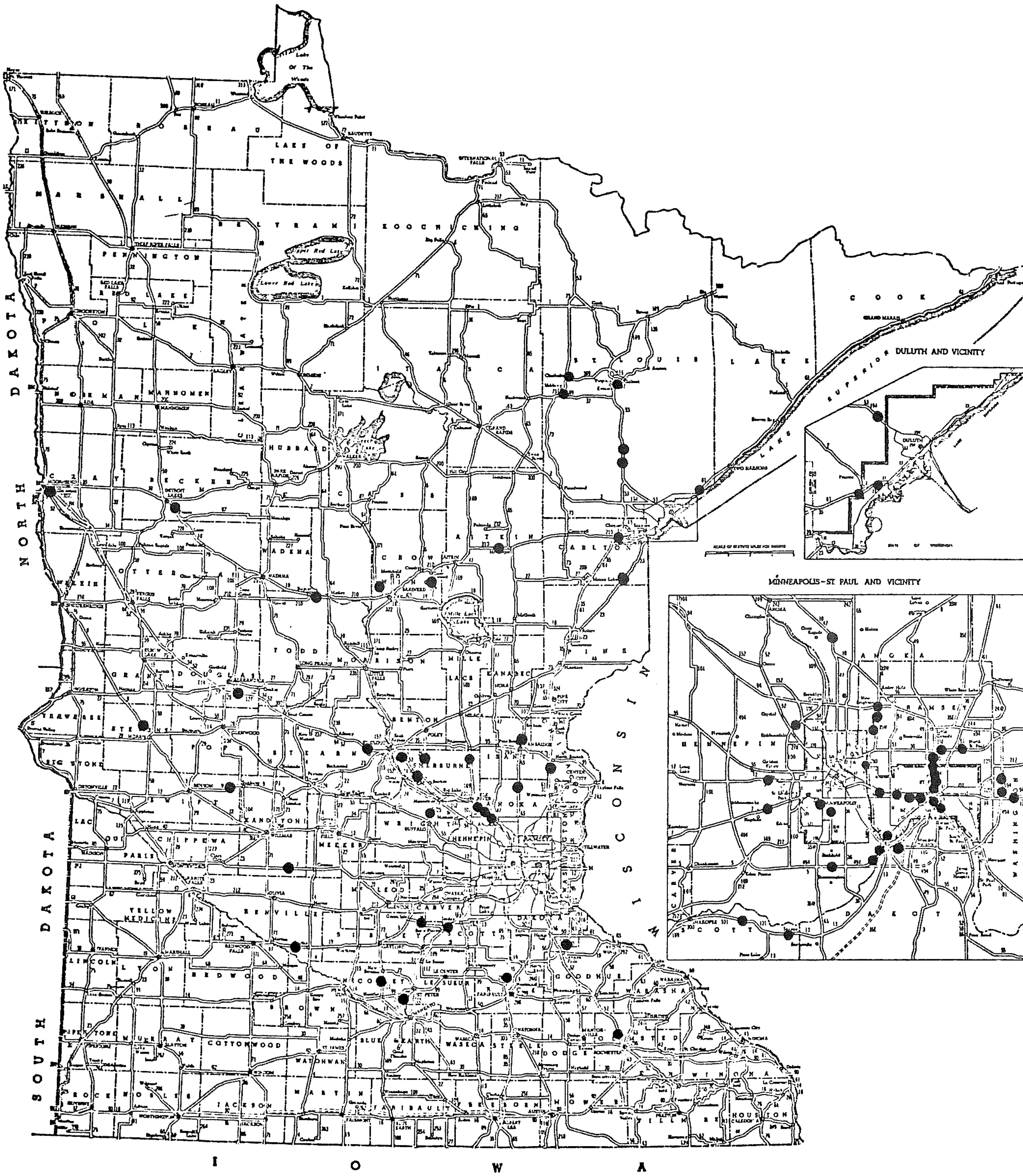


Figure 5. Location of Pavement Wear Sites.

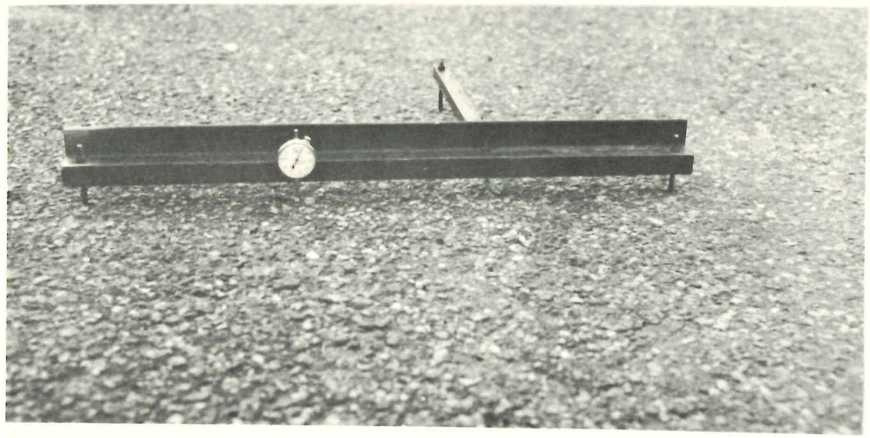


Figure 6. Dial Gage Measuring Device.

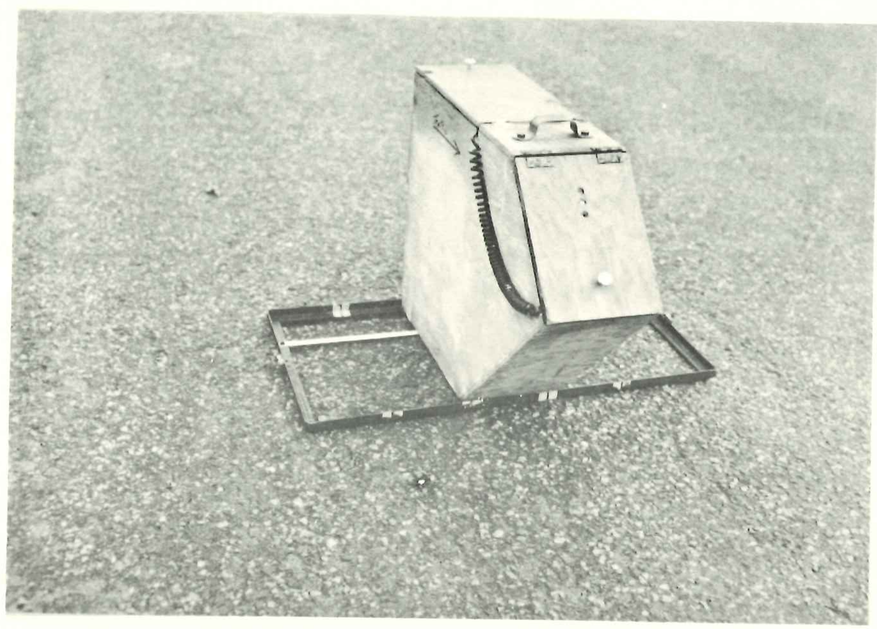


Figure 7. Camera Box Measuring Device.

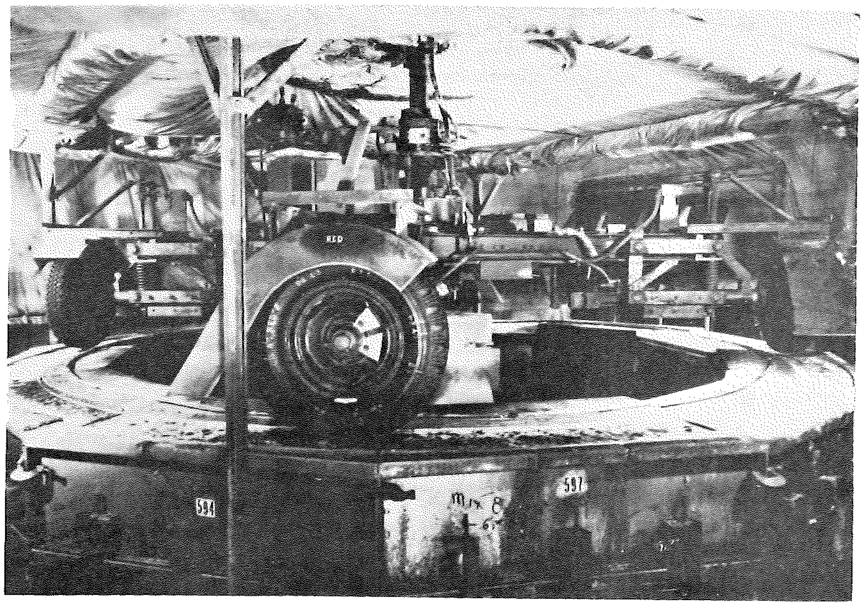


Figure 9. Traffic Simulator

Figure 10.
Studded Tire.

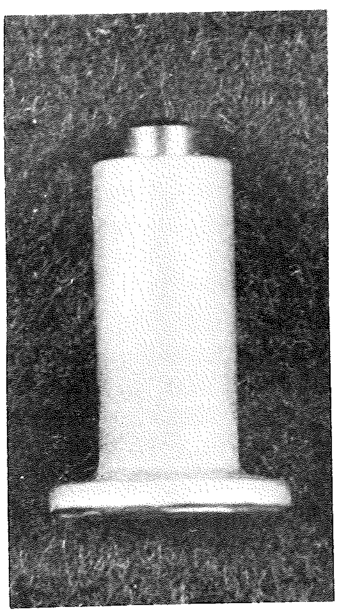


Figure 11. Tungsten
Carbide Stud.

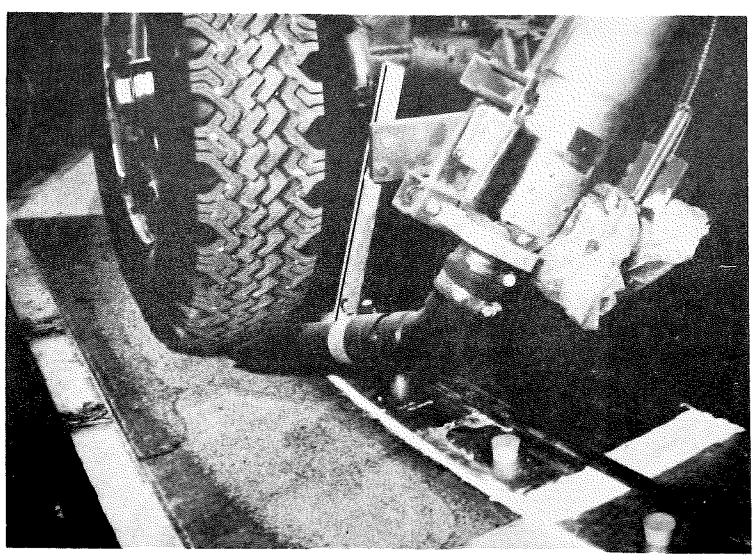


Figure 12. Sand Applicator.

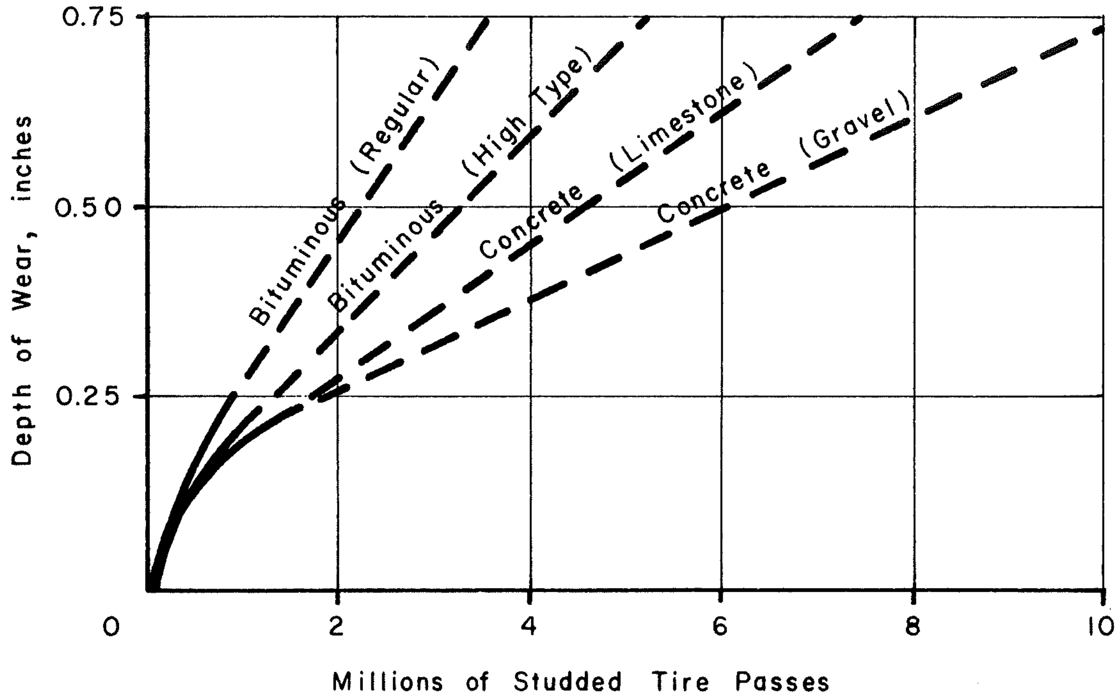


Figure 8. Wear Rates on Typical Minnesota Pavements.

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

Four series of tests, each series consisting of two tests, were undertaken, to answer the questions. The following table describes the test variables.

Test Series 1, 2 and 3 were conducted on the various bituminous and concrete pavement types used in Minnesota. A description of these pavements and the ingredients used is provided in Tables 2 through 5. Series 4 tests were conducted on specially formulated wearing courses to determine abrasion-resistant qualities. Descriptions of these are also shown in Tables 2 through 5.

TEST SERIES	TEST NO.	TIRE TYPE	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 outer wheel path	No	No
	3B*	Unstudded tires on inner wheel path	No	No
4	4A	Studded tires on outer wheel path	Yes	Yes

*Not run

TABLE 2. COMPOSITION OF FLEXIBLE PAVEMENTS

DESIGN GRADATIONS

Mix No.	Aggregates - Type & Source	% Passing Sieve Size 3/4"	5/8"	1/2"	3/8"	#4	#10	#40	#80	#200	Specific Gravity Mixture	Abrasion Loss Los Angeles % (e)
1	Coarse Aggregate - Crushed Limestone. Fine Aggregate - Natural Sand. Filler - Limestone Dust.	100	99	86	72	54	46	28	16	5.3	2.390	21
2	Coarse Aggregate - Crushed Gravel. Fine Aggregate - Natural Sand & Crushed Granite		100	92	86	71	62	24	8	2.6	2.323	17
3	Coarse Aggregate - Natural Gravel. Fine Aggregate - Natural Sand.		100	93	84	69	55	21	7	3.8	2.336	17
9	Crushed Granite					100	75	30	15	6.9	2.375	--
10	Crushed Trap Rock					100	73	27	16	10.1	2.472	--
11	Crushed Granite (a)					100	75	30	15	6.9	2.375	
12	Crushed Granite (a) (b)					100	75	30	15	6.9	2.384	--
13	Coarse Aggregate - Crushed Trap Rock. Fine Aggregate - Natural Sand. Filler - Limestone Dust	100	99	92	78	56	46	27	14	4.7	2.474	9
14	Coarse Aggregate - Crushed Trap Rock. Fine Aggregate - Natural Sand. Filler - Limestone Dust. (a) (b) (c)	100	100	92	78	55	45	26	12	3.1	2.484	9
15	Coarse Aggregate - Crushed Trap Rock. Fine Aggregate - Natural Sand Filler - Limestone Dust (a) (b) (d)	100	100	92	78	56	46	27	14	4.7	2.483	9
16	Coarse Aggregate - Crushed Gravel. Fine Aggregate - Natural Sand & Crushed Granite. (a) (b)	100	97	87	80	70	55	17	6	3.0	2.370	17

(a) Asphalt contains 3% rubber latex
(b) Aggregate contains 2% asbestos fibers
(c) Aggregate contains 2% mineral filler
(d) Aggregate contains 4% mineral filler
(e) Los Angeles Rattler Tests are run only on Coarse Aggregates

TABLE 3. COMPOSITION OF RIGID PAVEMENTS
DESIGN GRADATIONS

Mix No.	Aggregates - Type Source	% Passing Sieve Size 2"	1-1/2"	1-1/4"	1"	3/4"	5/8"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200	Abrasion Loss Los Angeles %
4	Coarse Aggregate - Gravel, (Garland.) Fine Aggregate - Natural Sand.			100	93	72	58	49	42	33	29	23	15	5	1	0.4	18, 31 (e)
5	Coarse Aggregate - Gravel, (Shiely Grey Cloud.) Fine Aggregate - Natural Sand (Garland)		100	97	85	64		52	45	34	30	24	16	5	1	0.4	20, 18 (e)
6	Coarse Aggregate - Crushed Limestone. Fine Aggregate - Natural Sand.	100	91	80	70	61	58	55	42	33	30	25	16	5	1	0.4	32 (e)
7	Coarse Aggregate - Crushed Trap Rock. Fine Aggregate - Crushed Trap Rock.	100	97	93	87	80	75	66	55	39	28	19	10	7	5	1.1	9 (e)
8	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand.			100	93	71	58	49	42	33	29	23	15	5	1	0.4	18, 31 (e)
17	Fine Aggregate - Crushed Trap Rock Epoxy (a)									10	79	47	29	20	14	9.7	9 (f)
18	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand (b).			100	93	71	58	49	42	33	29	23	15	5	1	0.4	18, 31 (e)
19	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand (c).				100	100	95	86	76	61	54	44	29	10	2	0.8	31 (e)
20	Coarse Aggregate - Gravel (Garland). Fine Aggregate - Natural Sand (d).				100	100	95	86	76	61	54	44	29	10	2	0.8	31 (e)

(a) A two component epoxy resin & trap rock at a 1 to 4 ratio
(b) This pavement was given a surface treatment to densify the top
(c) A 15% solids latex additive was used to construct this pavement
(d) A 20% solids latex additive was used to construct this pavement
(e) Los Angeles Rattler Tests are run only on Coarse Aggregates. Where 2 results are given values are for +3/4" and -3/4". A single value for concrete is the ave. for +3/4" and -3/4".
(f) This value is for parent rock

TABLE 4. PROPERTIES OF FLEXIBLE PAVEMENTS

Test Series No.	Mix No.	Pavement No.	Specification Lbs/Cu Ft	Actual 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	
	10	624	149.5 to 152.5	145.3	148.6	8.0	
	11	625	143.5 to 146.5	140.2	139.0	7.5	
	12	626	143.5 to 146.5	136.8	140.0	8.5	
	13	622	150.1 to 153.3	153.5	152.0	6.0	
	14	627	150.1 to 153.3	150.1	146.5	7.0	
	15	628	150.1 to 153.3	153.1	150.4	7.0	
	16	629	143.4 to 146.3	144.7	148.3	7.0	

ASPHALT EXTRACTION TEST DATA

Pavement No.	Aggregate Gradation - % Passing Sieve Size: 1"	3/4"	5/8"	1/2"	3/8"	# 4	#10	# 20	#40	#80	#100	#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

(TABLE 4 CONTINUED)

MARSHALL STABILITY MIX DESIGN DATA

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 5. 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	1-1/2	4 to 7	5.9
	4	583	"	1-3/4	"	5.4
	5	581	"	2-1/4	"	5.9
	6	582	"	1	"	4.2
	6	585	"	1-1/2	"	4.9
	7	584	"	1-7/8	"	4.5
	8	586	"	1-1/4	"	4.9
2	4	594	"	1-1/4	"	4.8
	5	595	"	2	"	5.9
	5	596	"	1-3/4	"	5.2
	6	598	"	1-3/4	"	5.9
	6	599	"	1	"	4.7
	7	600	"	1-1/4	"	4.2
	8	597	"	1	"	4.6
3	4	606	"	1-1/2	"	5.4
	4	607	"	1-3/4	"	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	"	3-1/2	"	5.1
	19	619	"	1-1/2	"	6.0
	20	618	"	2	"	5.9

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. All tires rolled freely at 35 mph with no externally applied torque. All testing was conducted using 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 became 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 leveled frequently to create a consistently smooth tire riding surface. The loading on each wheel was maintained at 1000 pounds to simulate a typical passenger car wheel load.

In order to simulate a typical highway wheel path, the four tires on the test track machine were offset from each other radially, and each tire was moved in and out very slowly on its axle to produce a uniform application of stud contacts across a 7.7-inch-wide wheel path. 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 correspond to typical sanding and salting operations in winter highway operations. The calibrated sanding mechanism is shown in Figure 12. Salt was sprayed on the track through a discharge tube barely visible on 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

Each pavement series (1, 2 and 3) consisted of tests on bituminous and concrete wearing courses typically used in Minnesota. Identical pavement types were cast for each of these three series. 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.

Three average wear rates were determined for each pavement. The upper 0.1 inch of depth wore the most rapidly since it is 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. Below 0.2 inch the coarse aggregate had a greater effect on the wear rate, usually resulting in a slower, or "terminal", rate.

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

Test Series 1 - Sand and Salt.

No significant difference in initial wear rates was found between the individual specimens of the portland cement concrete pavement group nor between individual specimens of the asphalt pavement group, although there was a significant difference between the concrete and asphalt pavements. The average initial rate of wear of the seven concrete pavements and the five asphalt pavements was 1.08 and 1.80 inch respectively per million wheel passes.

The intermediate wear rate divided the concrete pavements into two groups. The conventionally designed pavements wore at the rate of 0.48 - 0.50 inch per million wheel passes for both gravel and limestone aggregate pavements. When 15 percent extra portland cement was added, the wear rate was reduced to 0.31 inch, a reduction of about 37 percent. The pavement with all trap rock aggregate and 15 percent extra cement wore at the rate of 0.35 inch per million passes. These data indicated that, in the intermediate zone, the wear rate from studded tires was affected by cement content but not by the properties of the coarse aggregate. Regarding the rate of wear on the asphalt pavements, there was little difference among the three mixes, the average being 0.71 inch per million passes.

The most important wear rate is the terminal (that below 0.2 inch) since this represents the highway surface during most of its service life. The terminal rate basically divided the concrete pavements into two groups - those with limestone coarse aggregate, and all others. For each pavement the wear rate varied for the four tire sets due to differences in stud protrusion. Also, the studs used in the fourth tire set were different from those used throughout most of the study, flat-tipped studs having been used by mistake rather than oval-tipped studs. Using average values for the entire test series, the rate of wear for the limestone concrete pavements was 0.43 inch per million wheel passes. For the other concrete pavements, this figure ranged from 0.25 to 0.29 inch, the mixes with Garland gravel being at the upper end of this range and the others being at the lower. These data indicate some relationship between rate of wear and aggregate type, particularly the inferiority of limestone to resist wear. The use of additional portland cement seems to have some merit. The terminal rate for the asphalt pavements indicated lowest wear rates (average of 0.54 inch) for Mix 1 pavements. There appeared to be no difference in wear rates between Mix 2 and Mix 3 pavements. These averaged 0.74 inch per million passes.

The wear rate for specimen pavements when subjected to unstudded tires was virtually negligible when compared to the rate for studded tires. No difference was found within either the concrete or asphalt pavement groups or between the two groups. The average wear of all pavements was 0.011 inch total for the four million plus passes, or an average rate of 0.0027 inch per million wheel passes. Therefore, the primary finding of Test Series 1 is that studded tires produce 100 times more abrasion damage than that produced by combined sand and salt.

The rates of wear of the various types of pavements are shown in Figure 13. Photographs of a typical concrete pavement with gravel coarse aggregate at various stages of the testing with studded tires is 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 and shipped to Department headquarters in St. Paul. 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 studded tire passes and the left portion to four million unstudded tire passes. Sand and salt were applied to the pavements in both cases.

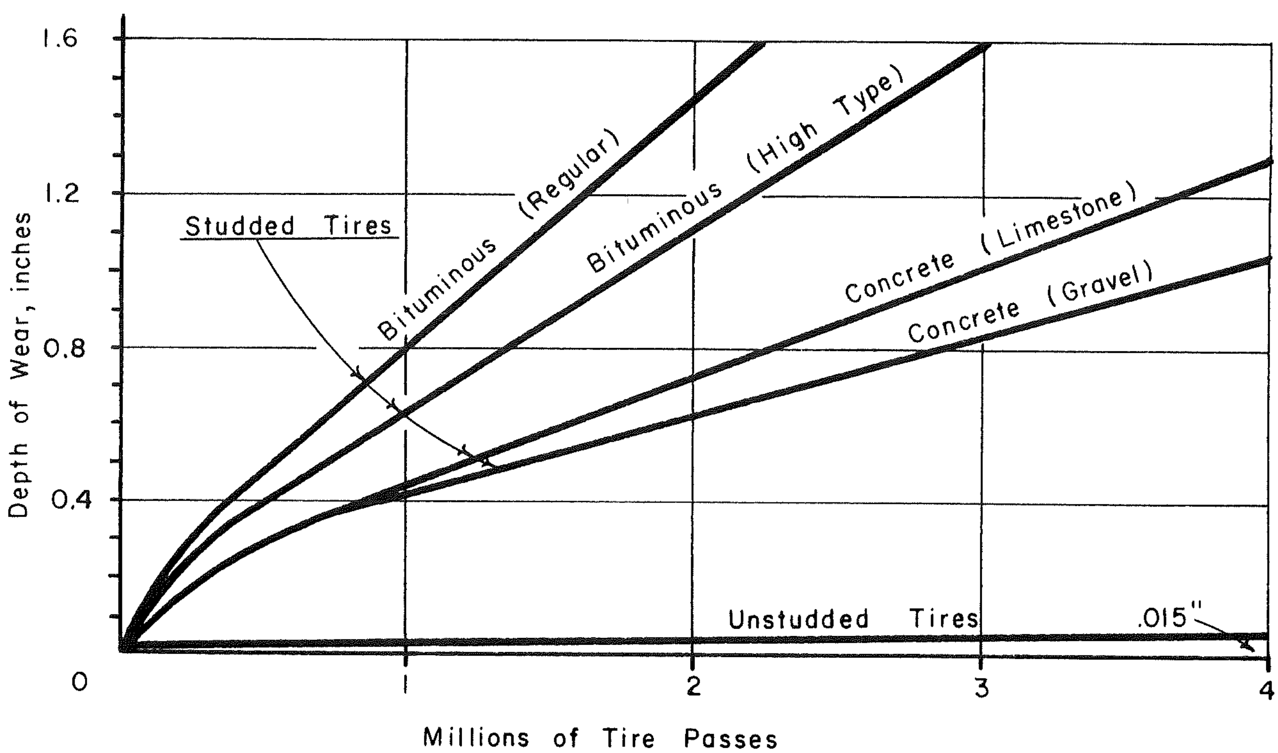
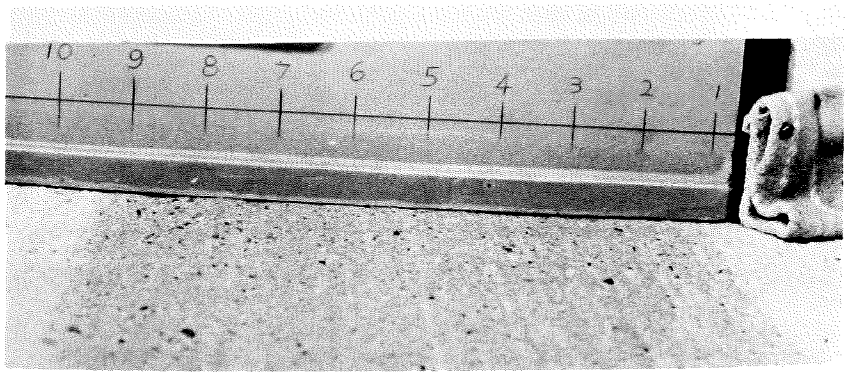
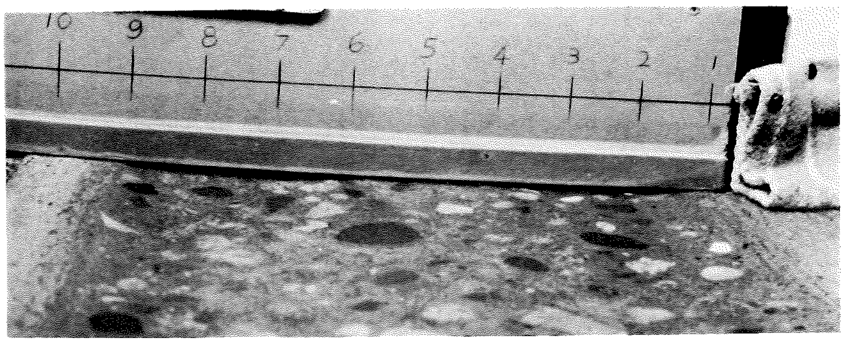


Figure 13. Wear Rates of Pavement Specimens at Test Track

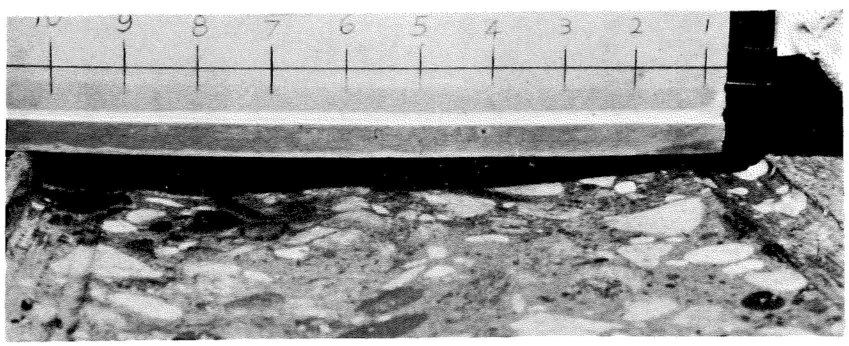
After
Conditioning
Passes



After 250,000
Studded Tire
Passes



After 2,000,000
Studded Tire
Passes



After
4,000,000
Studded Tire
Passes

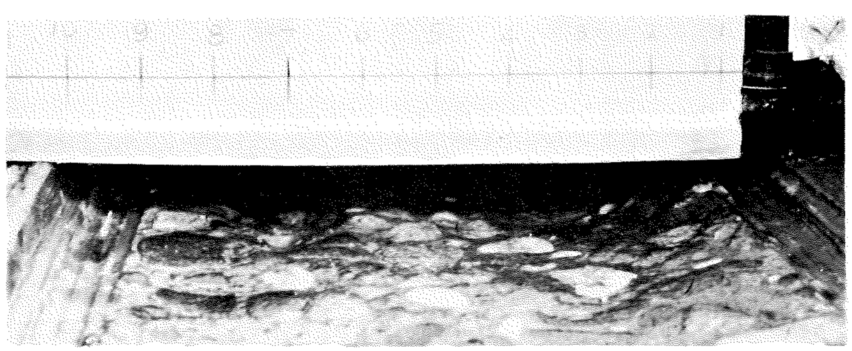


Figure 14. Wear Progression of Concrete Pavement Slab.

After
Conditioning
Passes

After 250,000
Studded Tire
Passes

After 1,000,000
Studded Tire
Passes

After 3,000,000
Studded Tire
Passes

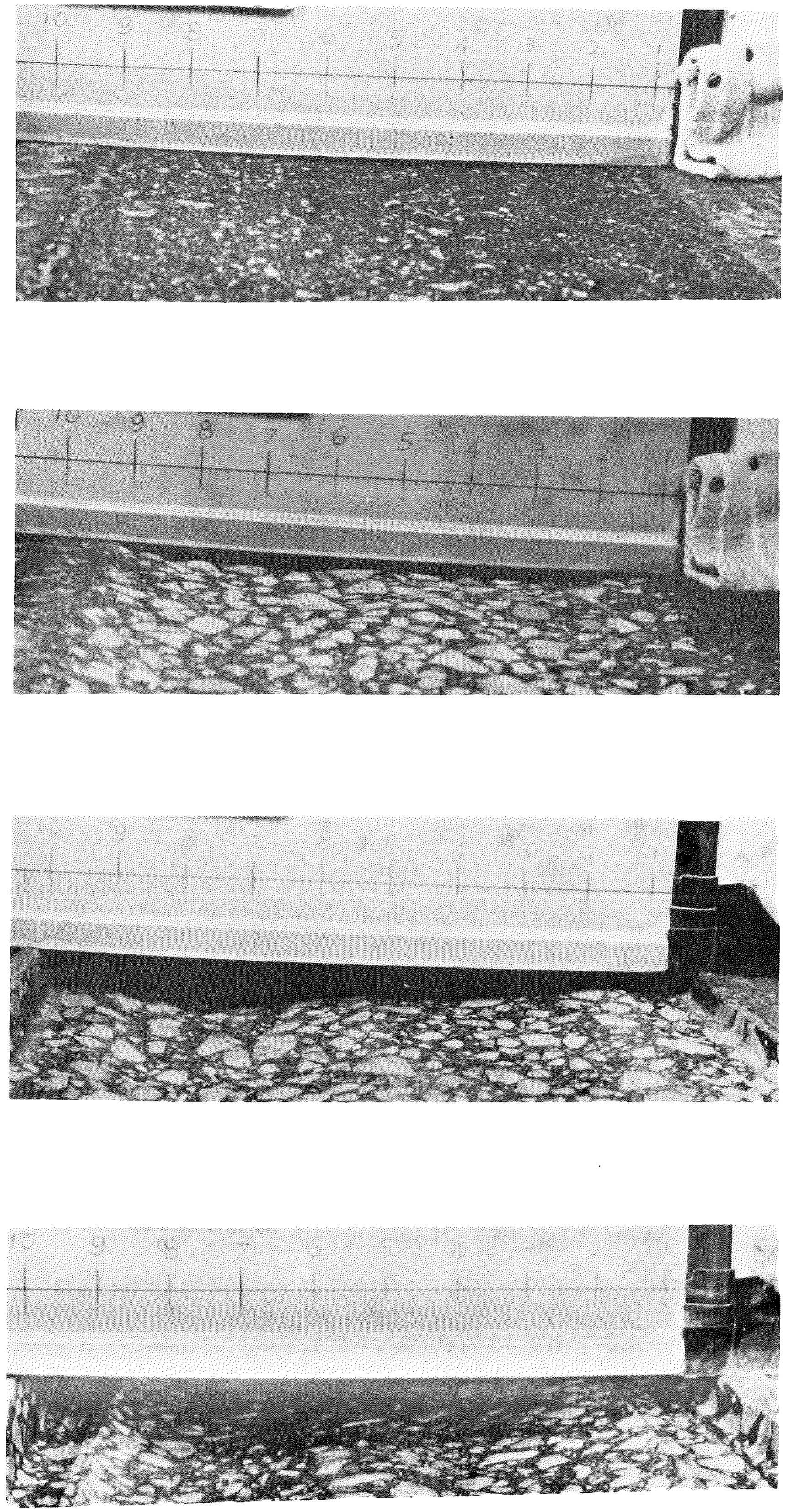
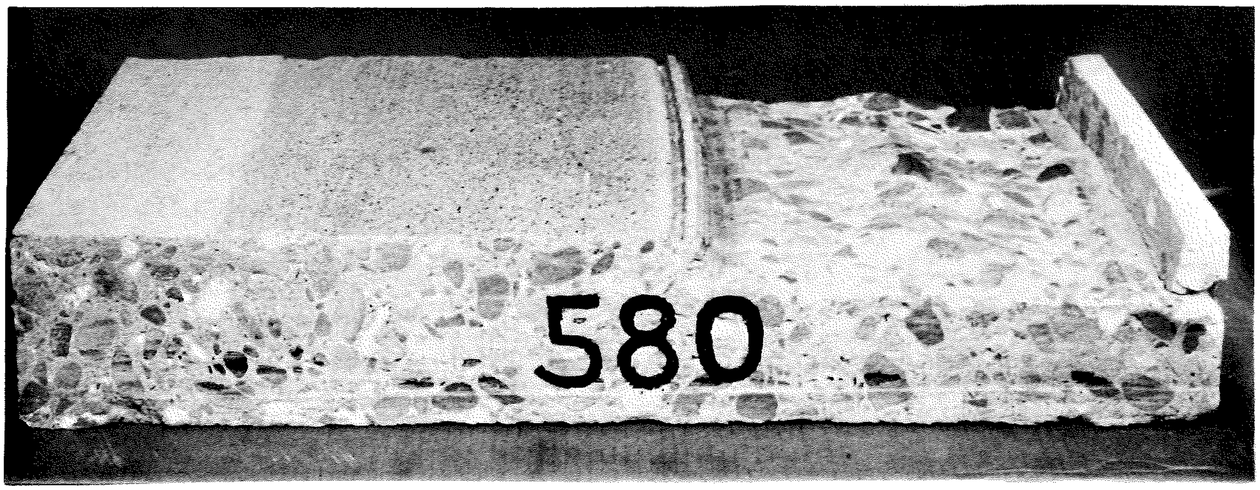


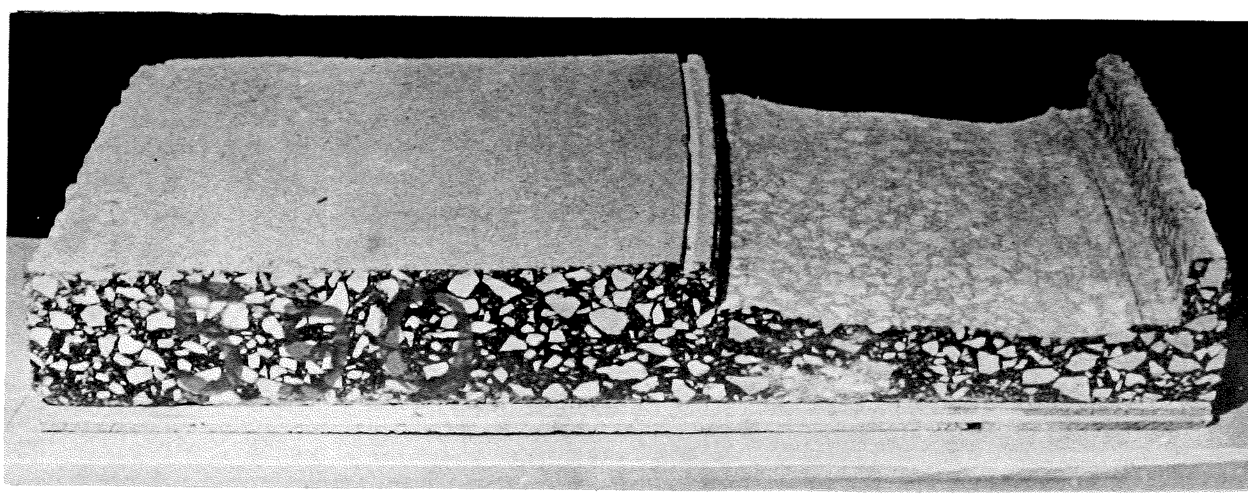
Figure 15. Wear Progression of Asphalt Pavement Slab.



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 Test.

Test Series 2 - Salt Only

The first two tire sets used in Test Series 2-A inadvertently contained the flat-tipped studs mentioned previously. Each set was used for only one-half million passes because the stud protrusion became excessive. These studded tires caused the pavements to wear at a much faster rate than the oval-tipped studs. It was not until the first one million passes had been run that the discovery was made concerning the wrong studs. The correct studs were used during the remaining portions of the study. Test Series 2-A was terminated at approximately three million wheel passes. At this point, the pavements had about the same depth of wear as the Test Series 1-A pavements when terminated at four million wheel passes.

This study was designed in such a manner that a comparison between Test Series 1-A and 2-A would measure directly the contribution of sand to the total wear picture. However, the variation in stud type and the variation in stud protrusion within each type precludes a valid conclusion at the present time. A statistical analysis of the data which could well indicate the effect of sand will be performed prior to preparation of the final report.

The relative wear on the pavements in Test Series 2-A generally reveals the same findings as Test Series 1-A. The one difference is that the performance of the concrete pavements with gravel plus extra cement, and trap rock plus extra cement, were no better than the conventional concrete pavements with gravel.

Test Series 2-B (unstudded tires with salt) has been run but the data are not available as of the writing of this report. Since negligible wear was noted in Test Series 1-B where both sand and salt were used with the unstudded tires, negligible wear is again expected.

Test Series 3 - No Foreign Material.

Test Series 3-A in which studded tires were used was designed to measure the wear contribution of salt by comparing its results to those from Test Series 2-A. The wear rates seem to be quite similar to those in Test Series 1-A, thereby showing an insignificant contribution by salt. However, the data still have to be analyzed to take into account the stud variation.

Test Series 3-B has been eliminated from the study. Because of the almost non-existent wear in Test Series 1-B, it appeared unwarranted to run three separate tests for unstudded tires.

Test Series 4 - New Pavement Mixes.

Four rigid (concrete type) and eight flexible (bituminous type) pavements, specially designed, were subjected to studded tire traffic. Of the rigid types, only the epoxy-sand mixture wore less rapidly than the standard concrete pavements in Test Series 1, 2 and 3. The test specimen, however, developed a polished, slippery surface and, therefore, would probably not be suitable for highway wearing courses. It is also a very expensive treatment.

Some tentative conclusions can be drawn regarding the flexible pavements. Final conclusions must await a complete analysis of the effect of stud protrusion. The wear rates of the four thin-overlay pavements (Mixes 9 through 12) were as high as those of the lower type bituminous pavements tested previously. The thin-overlay type with trap rock basalt aggregate was superior to the one with granite. The rubber and asbestos additives in this type of mix reduced wear only slightly and would not be worth the additional cost as a surface treatment.

The substitution of trap rock basalt for Bryan red rock limestone in the high-type bituminous pavement appears to provide some benefits in reducing wear. At the present time it is difficult to determine how significant this reduction is. The use of rubber and asbestos additives resulted in a significant reduction in wear (about 20%) on this type of pavement. However, the increase in the cost of these mixes may be greater than the benefits derived from the reduction in wear. No difference was noted between the mix with the normal four percent limestone filler and the one with two percent filler.

The use of rubber and asbestos additives in the pavement with 40 percent crushed fines (Mix 16) appears to provide some benefits in reducing wear, but further analysis will be necessary to determine if use of such additives is actually worth-while.

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 trunk 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 which produced given depths of wear on the concrete pavements at the test track versus the calculated number of studded tire passes which produced the corresponding depth of wear on trunk highway concrete surfaces. This is shown in Figure 17. The slope of the straight line portion of this curve is 5.2 to 1, which means that the depth of wear produced by one million studded tire passes on the concrete pavement at the test track would be produced by 5.2 million wheel passes on a highway surface of the same type. This ratio (5.2 to 1) also appeared to be appropriate for the other types of pavement surfaces. The trunk highway to test-track ratio of 5.2 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.

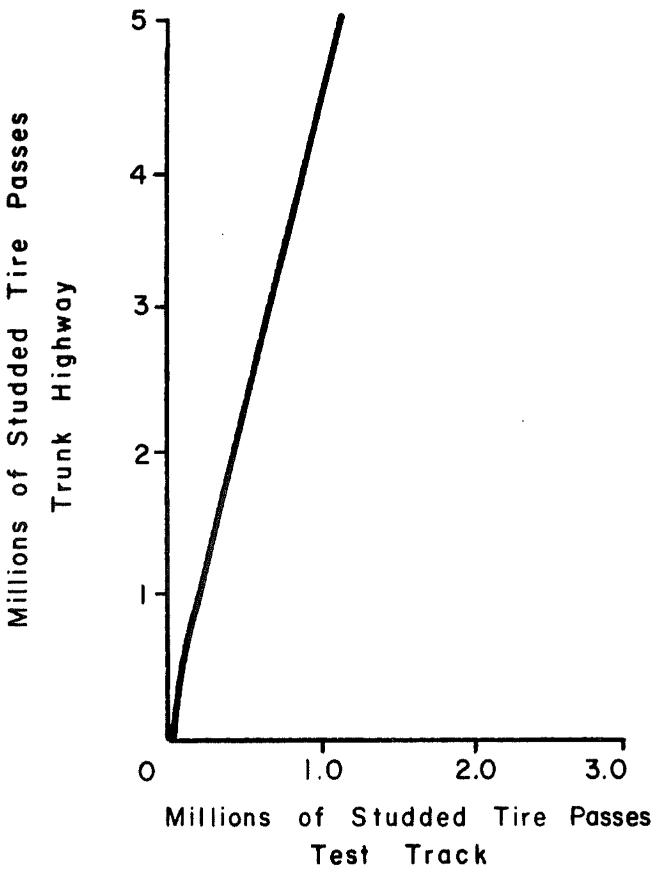


Figure 17. Relationship of Wear Between Test Track and Trunk Highway Surfaces.

Pavement Damage Costs

The test data and field observations indicate definitely that continued use of studded tires will cause pavement damage, resulting in need for premature rehabilitation of these surfaces. The time at which rehabilitation will be needed is a function of two factors: the number of studded tire passes, and surface type. A wear rut of 3/4-inch has been selected as the maximum tolerable limit before the surface must be repaired. Ruts deeper than this would be traffic hazards, since they would create steering difficulties and act as channels for holding water.

From the test track data and its subsequent correlation with field measurements, a prediction can be made as to the time when individual roads will need resurfacing due to studded tire wear. Data indicate that individual roads can be divided into four basic pavement types as listed in the table below. The second column indicates the number of studded tire passes which will produce a 3/4-inch wear rut. The third column, normal pavement life, indicates the average number of years of service that can be expected from the two major types of pavements subject to normal traffic. A concrete road normally will need a new surface after 35 years, while a bituminous road will need an overlay on the average after 17-1/2 years.

The number of studded tire passes over a given point on a highway is based on the percentage of vehicles equipped with studded tires, the average number of days that these vehicles are equipped with studded tires, and the average daily traffic per lane. For purposes of estimating surface damage and its associated costs, the year 1973 was used as the base year. It was estimated that by this date the statewide use of studded tires would reach a peak and level off at 60 percent. The average length of time a vehicle is equipped with studded tires each year is 135 days. Thus, the average number of studded tire passes per year is determined by multiplying 60 percent of the average daily traffic per lane by 135 days.

The total mileage of the state trunk highway system, 12,048 miles, was classified by surface type and the 1973 traffic volumes projected on a per-lane basis. A determination was then made of the number of years that the surface would withstand less than 3/4-inch of wear under the calculated application rate of studded tires.

PAVEMENT	MILLIONS OF STUDDED TIRE PASSES TO 3/4-INCH WEAR DEPTH	NORMAL PAVEMENT LIFE
Concrete (Gravel)	10.1	35 years
Concrete (Limestone)	7.4	35 years
Bituminous (High Type)	5.1	17-1/2 years
Bituminous (Regular)	3.8	17-1/2 years

Assuming each bituminous overlay would survive 5.1 million studded tire passes, as indicated in the preceding table, it then is possible to determine the number of overlays each highway section would need during the design period of 35 years and 17-1/2 years for concrete and bituminous pavements, respectively. Some examples of reduction in roadway surface life are shown in the following table. The last column indicates the reduction of surface life at a number of locations due to the use of studded tires expressed as a percentage of normal pavement surface life.

SURFACE TYPE	LOCATION	AVERAGE DAILY TRAFFIC (ADT) (ESTIMATED 1973)	NO. LANES	PERCENT REDUCTION IN SURFACE LIFE
Concrete (Gravel Agg.)				
	T.H. 5 near Minneapolis - St. Paul International Airport	90,000	4	84%
	T.H. 694 - East of T.H. 61	30,000	4	72%
	T.H. 35 in Duluth	23,000	4	45%
Concrete (Limestone Agg.)				
	T.H. 52 No. of Rochester	20,400	4	60%
	T.H. 35W So. of Lake St. in Minneapolis	100,000	8	78%
Bituminous (High Type)				
	T.H. 53 W. Limits of Duluth	13,200	4	26%
	T.H. 35E Maryland Ave. in St. Paul	60,000	6	66%
	T.H. 10 Coon Rapids	25,000	4	45%
Bituminous (Regular)				
	T.H. 75 No. of I-94 in Moorhead	14,400	4	29%
	T.H. 36 in Maplewood	16,000	4	37%
	T.H. 169 in Eden Prairie	10,000	2	49%

The damage cost estimate is based on overlaying with a bituminous leveling course to fill in the ruts plus a 1-1/2-inch wearing course of high-quality asphalt pavement. Based on the results at the test track, this appears to be the most economical method of repairing worn surfaces. After the total costs of the required number of overlays was calculated, the result was divided by the normal service life (17-1/2 or 35 years) to obtain an expression in terms of annual cost. Costs were also included for overlaying the highway shoulders as needed to maintain a satisfactory cross-section and for rebuilding curbs and adjusting drainage facilities.

In arriving at the cost estimate, four basic assumptions were made:

1. Traffic volumes are based on those predicted for 1973.

2. The percentage of passenger vehicles equipped with studded tires on the rear wheels only will reach a peak and level off at 60 percent of the total number of vehicles.

3. The percentage of vehicles with studded tires on the front wheels will remain negligible.

4. The trunk highway system will remain in total mileage and surface type as anticipated for 1973.

On this basis the amount of damage done to the trunk highway system in Minnesota in terms of the cost of repairing worn surfaces would be 2.3 million dollars annually based on predicted 1973 cost figures. If the addition of studded tires on the front wheels should become more popular in Minnesota, this figure could increase to 6 to 7 million dollars due to the increase in wheel passes and the greater mileage of highways affected. Both of these figures would also increase with increasing traffic volumes and construction costs.

These cost estimates are based on pavement repair costs for the state trunk highway system only and do not include damage sustained by county roads and municipal streets. Not included also, are related damaging effects, such as premature loss of pavement markings, abrasion loss of pavement grooving to improve skid resistance at dangerous locations, inconvenience and diversion of traffic for surface repairs, and reduction of skid resistance through abrasion of rigid pavement surface texture. Other intangibles are roughness, vehicle vibration, noise and steering effects.

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". An interpretation of this statement is that studded tires may have provided some benefit to general highway safety. The investigation should, therefore, determine factually whether elimination of studded tires might result in loss of any such benefits.

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 tempartures have upon these performance characteristics. Results of these tests have been widely circulated and used in promoting the use of studded tires.

Improvements in vehicle performance have been cited as the solution to the problem of how to achieve greater highway 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 Highway Department is, therefore, conducting a study of highway accidents to establish directly the degree of involvement of studded tires. This report describes this study briefly and presents some preliminary findings.

In order to form a basic understanding of the role of studded tires in highway safety, the following elements must be recognized and evaluated:

1. How effective are studded tires under various conditions?

2. How often do these conditions occur?

3. How and to what degree do these conditions contribute to accidents?

These three elements are examined and discussed first.

Vehicle Performance on Ice

Obviously, any safety benefits from studded tires cannot exceed the maximum improvement in vehicle performance that would be attainable through their use. 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, 5, 6, 7 & 9)*. A brief review of these properties will provide some understanding of their significance in relation to safety.

Traction

Improved traction and acceleration afforded by rear studded tires on icy surfaces is primarily a convenience benefit. Studded tires seem to furnish the greatest improvement in starting traction because vehicle speed is not a consideration. The fact that the public has regarded studs largely as an aid to starting-traction is evidenced by the fact that only about one percent of all vehicles with studded tires have them on both front and rear wheels. On the other hand, 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. 9)*

The safety benefits of starting-traction are somewhat similar to those afforded by reserve horsepower for passing. They allow improved acceleration such as needed 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 standard 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 enable climbing of grades of eight percent at constant speed, or about twice as steep as with standard 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, 6, 7 & 9).* 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) 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 to evaluate advantages offered by studded tires in maintaining straight line travel. However, this capability is enhanced 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 on ice. By far the greatest number of vehicle performance tests have been conducted to evaluate this feature. Acceleration and stopping friction afforded by studded tires are roughly of the same magnitude.

The average motorist's tendency is to misjudge stopping distance on ice for even a slowly moving car. Although getting free from a stuck situation through the use of studded tires may seem spectacular to the driver, only a small amount of useful work is actually performed to move a car a few feet at a creep speed (e.g. two mph). About 100 times as much work is required to stop the same car from 20 mph.

Typical stopping distances at 20 deg. F. (the average below freezing temperature in Minnesota) and from 20 mph are shown in the following table and in Fig. 18. *(Ref. 1, 5, 6 & 7).*

Tire Configuration	Stopping Distance (ft.) (Wheels locked)
4 standard treads, glare ice	143
2 standard treads front, studded rear, glare ice	116
4 standard treads, bare pavement	18

By comparison, the car with studded tires on the rear required 6½ times as much distance in which to stop on ice as the car on bare pavement, either wet or dry.

It is important to note that a regular tread-equipped car requires 382 feet to stop from 35 mph on glare ice. 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 about the same as the dry pavement stopping distance of 325 feet from 75 mph.

The greatest stopping advantage percentagewise for rear-studded tires only as against 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. 96 feet at 50 mph with studded tires only on the rear, and 209 feet at 50 mph with four studded tires, on 20 deg. F. glare ice.

In Fig. 19 are shown the relative stopping values for several combinations of tire configurations, pavement cover and speeds. Studded tires show the greatest improvement in stopping distances on clean, warm, unfrosted glare ice, a condition that is rare on road surfaces. A lesser degree of improvement is available on other road surface cover conditions more frequently encountered. *(Ref. 1, 11)* 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)* The comparisons of stopping distances referred to above and as shown on the charts should assist the reader in placing the stopping capability of studded tires in the proper perspective.

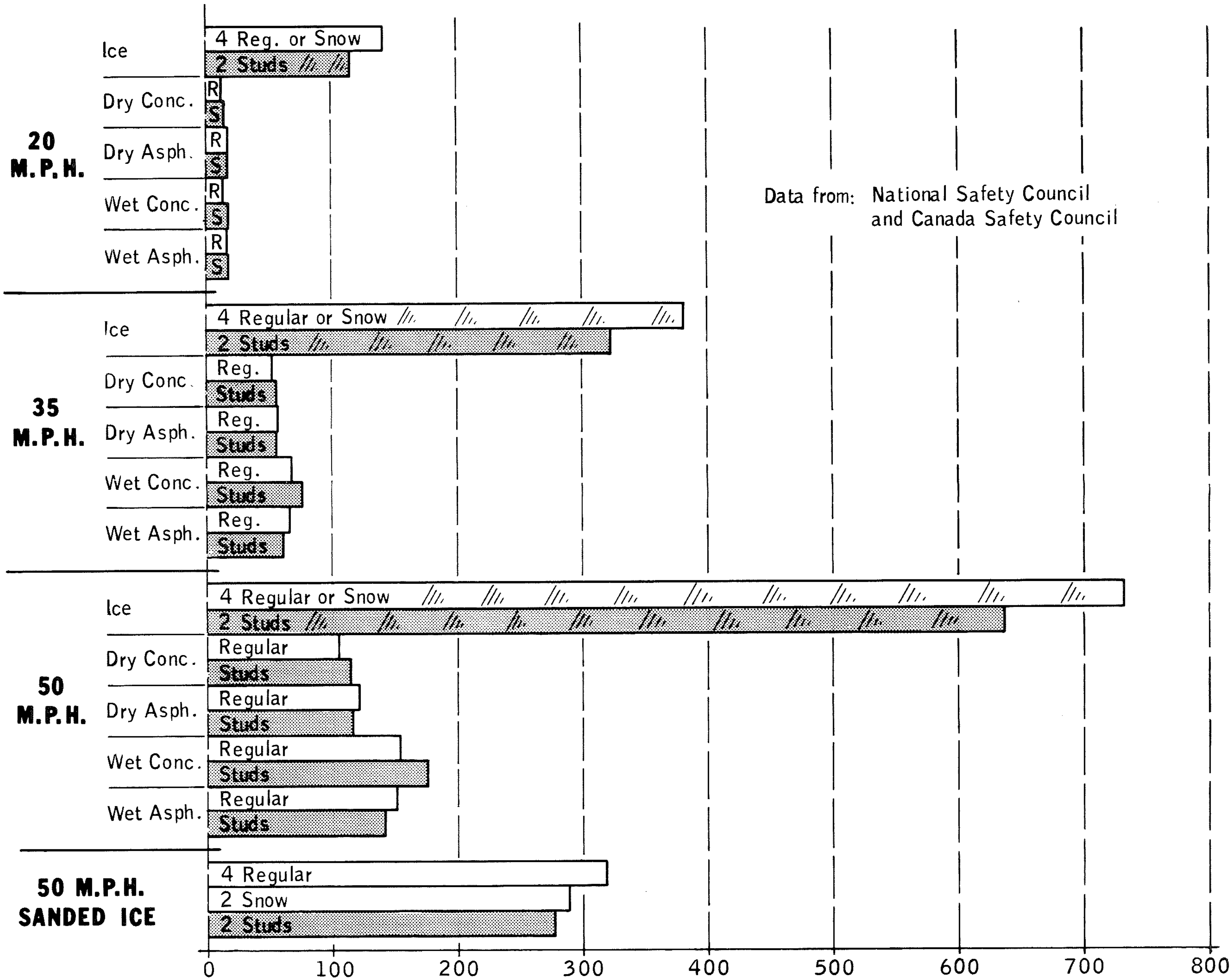


Fig. 18 **MEAN STOPPING DISTANCE AT 20° F (FEET)** (After Brakes Applied)

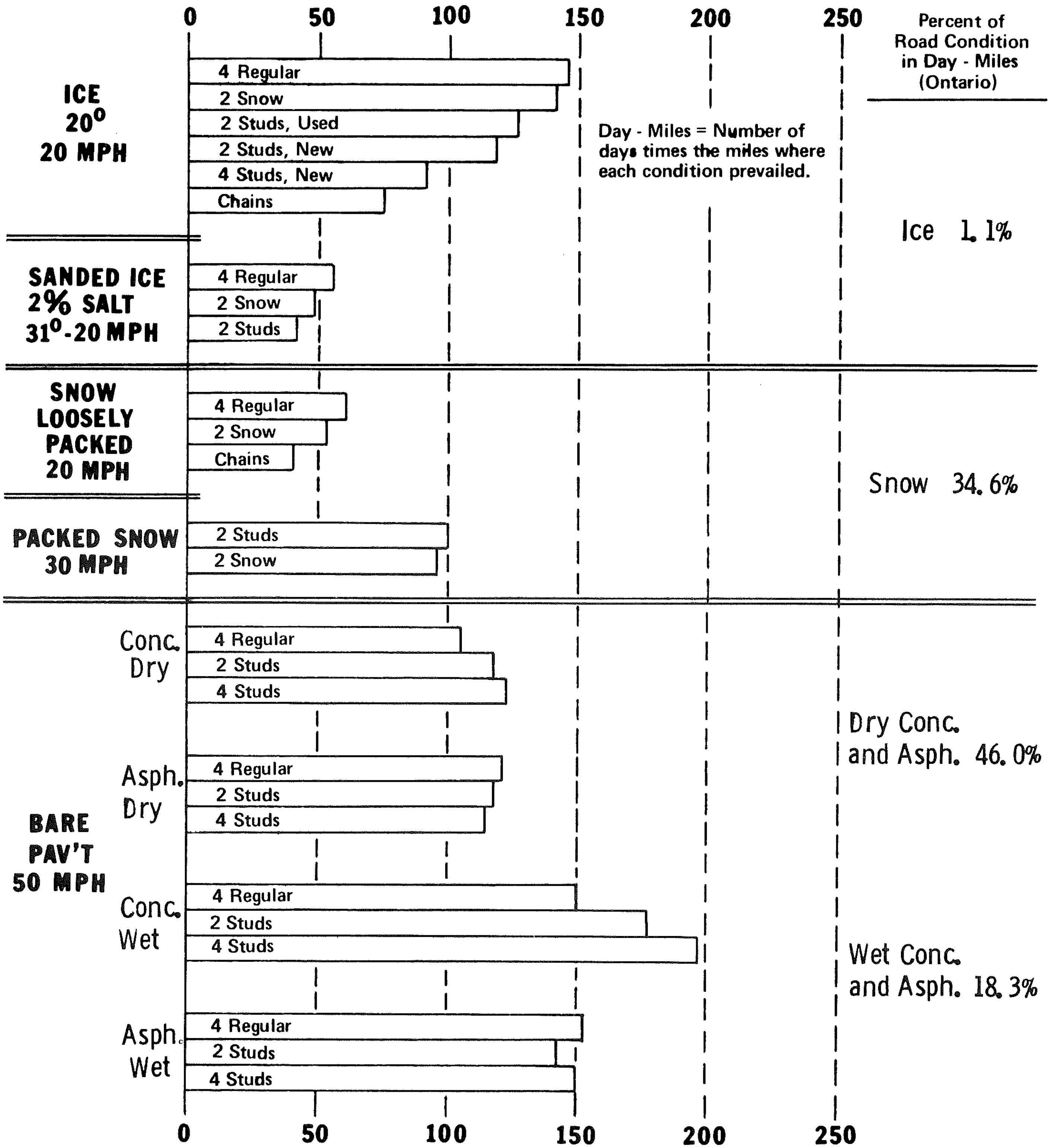


Fig. 19 **MEAN STOPPING DISTANCE (FEET)**

(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 Weather Influence On Traffic Safety

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 1969. The accident rates per 100 million vehicle miles have also increased slightly. *(Ref. 3)*

The rigorous Minnesota winters influence highway safety rather markedly. Over the last 10 years the proportion of accidents reported on snowy or icy roads and streets has ranged between 16 and 29 percent, averaging about 22 percent of all reported accidents. The fluctuations are apparently related to the severity of the winter weather. A small upward trend 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 accidents occur on snowy or icy roads. Therefore, accidents on snowy or icy roads are generally of less than average severity.

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 City area, 13 days out of each winter have a 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 the following table, based on 18,000 observations:

Road Condition - Percent of Time
(Oct. 15, 1969 - May 1, 1970)

Type of Road	Bare (Wet or Dry)	Icy or Hard Packed Snow	Other Loose Snow, etc.
Freeways, urban (lower speed)	96	2	2
Freeways, rural	97	1	2
Trunk highways, rural	90	4	6
Main streets	82	7	11
County roads	74	11	15
Secondary Streets	74	7	19
Residential streets	60	30	10
Township roads	47	29	24

Assignment of relative amounts of travel on the various roadway types yields the following approximation of travel for each of the general road conditions for the winter of 1969-70:

(The Ontario Highway Department reported, based on its trunk highway road condition data, that travel averaged 64 percent on bare pavements [wet or dry], 35 percent on snow or slush, and one percent on ice during the winter. [Ref. 11])

Proportion of 1969 - 70 Winter Travel
For Different Road Conditions, Percent

Type of Road	Total All Conditions	Bare, Wet or Dry	Icy	Snowy
Freeways	11	10.6	0.2	0.2
Trunk 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

This table 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 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. Only half of that, in turn, was on surfaces that could be classed as icy.

The approximate ratios of accident rates on snowy or icy roads to annual rates under all conditions are:

Therefore, accidents are more likely to occur on snowy or icy roads but are generally of less than average severity. If studded tires were significantly helpful on icy and snowy roads, benefits would most likely appear in property damage and personal injury accidents, in that order. Potentially they could be helpful to some degree between 10 and 20 percent of the winter (i.e., between 5 and 10 percent of the year).

ALL REPORTED ACCIDENTS

	All Types	Fatal	Personal Injury	Property Damage
Ratio of Accident Rates on Icy or Snowy Roads to Total Accident Rates	1.8	0.8	1.4	2.2

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 will generally exceed that required by standard unstudded tires. *(Ref. 9)* Most studded tires sold have more than 80 studs. While the degree of increase is not large, the exposure to such conditions is great, since all pavements are bare in Minnesota 75 percent of the legal studded tire period. Furthermore, since speeds are much higher on bare roads, the severity of accidents precipitated by extended stopping distance may be aggravated.

Tests by the Tennessee Highway Research Program indicate an increase in stopping distance for studded tires up to five percent more than for unstudded tires on dry bituminous pavements at speeds between 20 and 40 mph. These represent stopping differences on the order of one to six feet. Canada Safety Council tests in 1970 showed up to a 27 percent increase, representing 24 feet on wet concrete. Speeds ranged between 20 mph and 50 mph. The average increase for dry concrete pavements was five feet (10 percent) and 12 feet (18 percent) for wet pavements. *(Ref. 1)*

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 a longer stopping distance on all surfaces tested. *(Ref. 11)*

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 characteristics produced 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. 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, but whether such accumulated water contributes to hydroplaning (loss of vehicle control due to tires riding on a thin film of water) has not been established.

Assuming that wheel troughs are worn deep enough to require extra driver effort in controlling a vehicle during lane-changing or passing maneuvers, the effect on handling characteristics might conceivably influence some hazardous movement of a vehicle. The described effect is conjectural and not supported by documentation. Roughened driving surfaces, however, are established facts and increased noise produced by tire-surface interaction (particularly with stud-equipped tires) is disconcerting both inside and outside the car. Instances of loose stones and studs being kicked up from wheels in traffic and causing damage have been reported by vehicle owners on returns of questionnaires designed for this study.

Cornell 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) involves 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 Highway Department initiated with Cornell Aeronautical Laboratory the safety study hereafter described.

Objective

The ultimate objective of this study is 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 conditions. This is being 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.

The number of accidents involving each tire type is being determined. The estimated number of accidents that would have occurred had studded tires not been in use is then being determined and compared with the number of accidents that have occurred. Similarly, the frequency of injury-producing accidents, the number of fatalities and the total repair costs are being explored. All of these comparisons are relevant to determining the degree to which any reductions in accident frequencies and severity might offset increased road repair costs.

In addition to establishing effects on accident frequencies, an effort is being made to compute and test accident rate ratios to determine if studded tires and snow tires have different accident rates. Differences in degree of exposure, if any, are also being examined. These results should reflect differences in tire equipment safety which are pertinent to the motorists' choice of winter driving equipment. However, this information is not essential to a legislative decision as it does not indicate the degree of impact of such differences upon highway safety.

Procedure

In order to isolate studded tires from other factors that may influence accidents, a large amount of information is being included in the study, and relationships of many variables are being considered in the analysis. There are 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 is being furnished to Cornell so that statewide conclusions may be developed.

Questionnaires are sent to a statistically selected random sample of Minnesota registered automobile owners who were asked to supply information about themselves, the automobile they drive 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 include: driver characteristics such 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 have been 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 Cornell, were received for each investigated and reported accident from the Minnesota Highway Patrol and a number of municipal police departments. The cities participating in the Twin City metropolitan area 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 trunk 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, include 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 reseach purposes only in order to protect the rights of all parties involved.

Collection of data for this study was started in February, 1970 and continued until May 1, 1970, the end of the legal studded tire period. The second data collection period resumed this fall on October 15 and will continue until January 4, 1971 when it is to be terminated under the contract agreement. Data analysis and preparation of a final report by Cornell will follow. Data collection activities have in general proceeded satisfactorily, as summarized below, to indicate the scope of the study:

Recording periods	Feb. to Apr., 1970	Oct. 15 to Jan. 4, 1971
Questionnaire		
Mailed	48,100 (3,848 per week)	21,000* (3,000 per week)
Returned	22,500	7,600*
% Return	47	40+*
Police Accident Reports	1,890	1,150*
Minn. Highway Patrol	1,330	620*
City Reports	557	530*
Cities reporting	4 (2 mo.) 11 (1 mo.)	10

*As of Dec. 1, 1970

Preliminary Results

Because of the preliminary nature of currently available findings results presented herein must be viewed as tentative only. These results are based only upon limited information obtained in the first data-collection period, February to April, 1970. After completion of the second data collection, the amount of data will be approximately doubled. Thus, upon more detailed analysis apparent findings may require revision.

The results tentatively presented represent simple statistical summaries of information obtained from questionnaires and accident reports. There has not yet been opportunity to critically analyze the statistical data. At this point the questionnaire and accident samples cannot be assumed to be representative of all vehicles nor of all accidents in the state. The questionnaire information, in particular, may include biased responses. Therefore, at the present time, these tentative results are best viewed as reflecting only unverified indications from limited sampling and analysis. Statistical analyses to measure changes in accident rates and to determine the effect of discontinuing studded tires are quite complex and will not be available until the final report is prepared, after completion of all data collection.

The questionnaire and accident report summaries are treated separately, following in sequence. The results given are primarily concerned with the relationships between tire type and user and vehicle characteristics, exposure, accident characteristics and accident effects.

First Questionnaire Survey (February, March and early April, 1970)

1. Forty-three percent of the automobiles in the survey had studded tires; 26 percent used standard tires, and 28 percent snow tires. The percentage of studded tires corresponds quite well with the 40 percent figure determined by the Minnesota Highway Department field survey.

2. The proportion of autos with studded tires decreased from 47 percent in February to 44 percent in March, to 34 percent in early April. The proportion of snow tires also declined in these periods, but at a much slower rate.

3. The proportion of autos with studded tires was highest in rural areas, followed by urban areas, then suburban areas. The differences were small.

4. Usage of studded tires varied with vehicle owner characteristics. Usage by female owners was greater than by males. Owners over 65 years of age used more snow tires and less studded tires. The proportion of studded tires tended to increase with annual mileage of the owner.

5. Usage of studded tires varied with vehicle characteristics. More sedans and convertibles had studded tires than did station wagons. Usage was greater for vehicles equipped with power brakes or power steering. Usage of studded tires increased with newer vehicle model year up to the 1969-70 models, where a decline was noted.

6. Studded tires accounted for 47 percent of all driving time in the period studied. Although this percentage was higher for roads completely covered with ice, snow, or slush, such conditions prevailed for only one to eight percent of all driving time in the period studied. Sixty-eight to 87 percent of all driving time in the period studied, occurred on roads with little or no road cover. (These latter percentages compare reasonably well with the ranges previously noted for the entire winter).

7. Driving in the northern counties was more likely to occur on roads covered with ice, snow, or slush than was driving in the southern counties.

8. The reported incidence of skidding of any kind ranged between about one-fourth and one-half of the vehicles traveling on other than bare roads. The reported frequency of skidding increased as the degree of road cover increased. Skidding was reported least frequently with studded tires; most frequently with standard tread tires. Generally the reported skidding experience with snow tires was more similar to that with studded tires than to that with standard tires. The reported non-skidding superiority of studded tires increased as the degree of road cover increased.

9. The majority of repondents 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 opinion may suggest that the studded tire driver may utilize his traction advantage to drive at higher speeds on slippery surfaces, perhaps diminishing safety benefits.)

10. Only four-tenths of one percent of the respondents did not drive because of snowy or icy roads.

11. Analysis of 972 unsolicited comments appended to the questionnaires by respondents indicated 50 percent favored continued use of studded tires, 37 percent favored banning studded tires, and 13 percent expressed no opinion or were undecided. As the questionnaires were returned the percent favoring continuation remained about constant through the period but the percent for banning increased, indicating increased polarization in attitudes.

First Accident Report Analyses (February, March & early April 1970)

1. The accident sample studied consisted of 2,756 automobiles in 1,810 accidents with 1,422 injuries of which 57 were fatal injuries.

2. Twenty-five percent of the accidents reported in the study period occurred on roads described as having at least a scattered cover of snow, ice or frost. Sixty-one percent were on dry roads with little or no cover. Twelve percent were on wet roads. Only three percent of the accidents occurred on roads where sand or cinders had been spread.

3. In the sample, for all road surface conditions, the proportion of vehicles equipped with studded tires and involved in accidents was less than the proportion of travel by vehicles with studded tires. This implies, for the sample only, an accident rate for autos equipped with studded tires that is lower than the rate for all autos; but this implication is incompatible with the finding that 75 percent of the accidents in the sample occurred on bare roads. The apparent paradox hopefully will be resolved by more data and analyses.

4. For each tire type, there was no marked difference in the proportion of accidents on roads with at least some scattered snow or ice cover and the proportion of accidents on bare pavements.

5. Studded-tire-equipped vehicles showed some performance advantage in reduced involvement in accidents in which slippery roads were reported to be a contributing factor and in reduced incidence of uncontrolled vehicle rotation before the collision impact.

6. Reported impact speeds were sparsely distributed and showed no advantage to any of the tire types in reducing the impact speed of collision.

7. There was no consistent advantage for any tire type in terms of personal injury and vehicle damage.

Accident Studies by Others

Other accident studies have been conducted in Canada. The province of Ontario conducted a study of 2790 accident vehicles in February 1970. This study *(Ref. 11)* 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".

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 2235 accidents, of which about 45 percent involved skidding. The study concludes *(Ref. 8)* 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".

REFERENCES

1. "Effectiveness of Studded Tires," CANADA SAFETY COUNCIL. *A Report on Research Conducted by DAMAS AND SMITH LTD., CONSULTING ENGINEERS & PLANNERS, 1970.*

2. "Climatological Data," U.S. DEPARTMENT OF COMMERCE, ESSA, *Annual Summary, 1967 & 1968.*

3. "Highlights of Minnesota Motor Vehicle Traffic Accidents," MINNESOTA DEPARTMENT OF HIGHWAYS, SAFETY DIVISION, *Report Years 1958-1968.*

4. "Concrete Bridge Deck Durability," NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM, *Synthesis of Highway Practice, Report 4, 1970.*

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

6. "Winter Test Report," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Stevens Point, Wisconsin, 1967.

7. "Winter Test Report," COMMITTEE ON WINTER DRIVING HAZARDS, NATIONAL SAFETY COUNCIL, Stevens Point, Wisconsin, 1968.

8. NORMAND, JEAN, " The Influence of Studded Tires on Winter Driving Safety In Quebec City," Department of Roads, Quebec. *(Draft of a report for presentation at the Annual Meeting, Highway Research Board, January, 1971).*

9. ROSENTHAL, P., HASELTON, F. R., BIRD, K. D., JOSEPH, P. J., "Evaluation of Studded Tires," Cornell Aeronautical Laboratory, Inc. *National Cooperative Highway Research Program, Report 61, 1969.*

10. SNYDER, JACK M., "Protective Coatings to Prevent Deterioration of Concrete By Deicing Chemicals." *National Cooperative Highway Research Program, Report 16, 1965.*

11. SMITH, P. AND SCHONFELD, R., "Studies of Studded Tire Damage and Performance In Ontario--Winter 1969-70." Department of Highways, Ontario, *Report No. RR165, August, 1970.*

12. WHITEHURST, E. A. AND EASTON, E. H., "An Evaluation of Studded Tire Performance." *Highway Research Record, Number 171, 1967.*

13. SCHONFELD, R. AND SMITH, P., "Present and Predicted Pavement Wear in Ontario Due to Studded Tires." Department of Highways, Ontario, 1969.