HIGHWAY RESEARCH RECORD

Number 477 | Winter Driving Traction Aids

10 reports prepared for the 52nd Annual Meeting

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HIGHWAY RESEARCH BOARD

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FOREWORD

The papers in this RECORD deal with the state of the art of winter driving traction aids. The aids discussed are vehicle-mounted and are thus under the purview of the Highway Research Board Committee on Winter Driving Traction Aids, whose scope reads: "This Committee is concerned with the effectiveness of vehicle-mounted winter driving traction aids and their effects on pavements and bridge deck surfaces." The first five papers are concerned with studded tires from two standpoints: their effects on pavements and their relation to safety. These papers, as does the great majority of the literature on studded tires, report that extensive pavement damage results from the use of studded tires. Also reported is the inability to determine safety effects resulting from the use of studded tires. The second group of papers deals with winter driving traction aids other than studded tires, including braking devices, tread design, rubber compounds, and limited-slip differentials. Each of these aids can contribute to safer driving under winter conditions, but their cumulative effect is not known. For this reason a National Cooperative Highway Research Program research project was formulated with the following objectives:

1. Select methods and develop criteria to be used as a standardized procedure for effectively evaluating winter driving traction aids for passenger cars, multipurpose passenger vehicles, and light trucks with regard to vehicle performance (traction, braking, and control), pavement surface characteristics (physical properties of ice and snow), and bare pavement wear;
2. Conduct an experimental program to evaluate the performance of available winter driving traction aids on ice and snow, using the standardized procedure for evaluating vehicle performance;
3. Provide a limited evaluation of any possible adverse effects of these aids on vehicle performance on other than snow- and ice-covered pavements; and
4. Prepare an overall cost-benefit type of ranking for winter driving traction aids, singularly and in combination where appropriate, considering such factors as performance on snow and ice, pavement wear, economics, user convenience, practicality, durability, and reliability.

It is anticipated that this project will provide information and recommendations that will contribute to safer winter driving. In the meantime, highway departments are faced with a dilemma as to how to convince their legislators to ban studded tires in the face of pressure from those who wish to have studded tires remain legal.

The Committee on Winter Driving Traction Aids, which sponsored these state-of-the-art papers and supports the NCHRP project on winter driving traction aids, is also contemplating the preparation of an educational document for individual states to use in providing information to their legislators and citizens.

—David C. Mahone

USE OF STUDDED TIRES IN THE UNITED STATES

Stephen E. Roberts, Iowa State Highway Commission, Ames

About 30,000 studded tires were sold in the United States in the winter of 1963-64. Sales are expected to reach about 6,000,000 during the 1972-73 winter months. Estimates from 30 states indicate that 6 to 61 percent of passenger cars in those states are equipped with studded tires. The weighted average for these same states is 20 percent.

•STUDDED tires were little more than a novelty in the United States 10 years ago. Today, they are standard wintertime equipment on millions of highway vehicles in this country. Many highway administrators and engineers have questions about the safety of studded tires under some operating conditions, and most of them recognize that studded tires are either an actual or a potential cause of serious pavement damage. For these reasons, professionals in the highway field should know where, and to what extent, studded tires are being used.

STUDDED-TIRE SALES

Sales figures show the tremendous increase in the use of studded tires that has occurred in the United States during the past 10 years. Estimated sales for the 3 years beginning with the 1963-64 winter are as follows (1): 1963-64, 30,000; 1964-65, 250,000; and 1965-66, 2,500,000. It is not surprising that, by the spring of 1966, tire dealers and stud manufacturers were forecasting continued sales increases and a generally bright future for studded tires in the United States.

Sales of snow and mud tires increased more than 30 percent during the period of 1965 to 1969. At least part of this increase must be attributed to public acceptance of studded tires. Shipments of snow and mud tires in 1969 totaled approximately 18,800,000.

During the same period, that is from 1965 to 1969, the annual sales of tire studs increased threefold. Total sales in 1969 were estimated to be 830,000,000 (2). Assuming an average of 100 studs per tire, it would have been possible to produce 8,300,000 studded tires, which is 44 percent of all of the snow and mud tires shipped in 1969. Admittedly, this is only a rough estimate of the availability of studded tires in that year. Actual sales of studded tires in the winter of 1969-70 may have been anywhere from 25 to 50 percent of total snow-tire shipments.

The annual shipments of snow and mud tires have continued to increase. One reason for this increase is greater public interest in all types of winter traction aids prompted by the introduction of studded tires. Shipments of snow and mud tires in 1971 were 19,067,000. Even though overall industry figures are not available, it appears reasonable to expect that one-third of these were equipped with studs when sold by dealers.

OBSERVED USE OF STUDDED TIRES

Although annual sales estimates demonstrate the continuing popularity of studded tires, it is the total number of vehicles with studded tires that is of most concern to highway engineers and administrators. In November 1972, a questionnaire concerning studded-tire use was sent to the highway departments in 45 states.

The response to the questionnaire was excellent. Answers were received from 44 of the states (Table 1). It was not sent to Minnesota, Utah, Mississippi, Louisiana, or Hawaii because the use of studded tires is not legal in those states.

Table 1. Estimated studded-tire use.

State	Use (percent)[a]		Estimate Based on Survey	Interest in	
	1972-73	1976-77		Ban	Tax
Alabama	1	1			
Alaska	61	61	X		
Arizona	1	1			
Arkansas	1	1		X	
California	NA[b]	NA		X	
Colorado	30	40	X	X	X
Connecticut	25	25	X	X	
Delaware	18	18	X		
Florida	NA	NA			
Georgia	NA	NA			
Hawaii	NL[c]	NL			
Idaho	27	5		X	X
Illinois	12	22	X		
Indiana	10	12	X	X	
Iowa	25	40	X	X	
Kansas	7	5			
Kentucky	12	19		X	
Louisiana	NL	NL			
Maine	NA	NA			
Maryland	NA	NA		X	
Massachusetts	32	45	X		
Michigan	12	26	X	X	
Minnesota	NL	NL			
Mississippi	NL	NL			
Missouri	14	14	X		
Montana	60	77	X		
Nebraska	38	38		X	
Nevada	6	6		X	
New Hampshire	30	50			
New Jersey	20	32	X		
New Mexico	NA	NA			
New York	30	35	X		
North Carolina	2	2			
North Dakota	32	32			
Ohio	20	30	X	X	
Oklahoma	1	2			
Oregon	10	11	X		
Pennsylvania	28	37	X	X	X
Rhode Island	NA	NA			
South Carolina	3	3			
South Dakota	40	40	X		
Tennessee	NA	NA			
Texas	0	0			
Utah	NL	NL			
Vermont	60	55			
Virginia	10	30	X	X	
Washington	35	45	X	X	
West Virginia	10	10		X	
Wisconsin	20	32	X	X	X
Wyoming	35	40			

[a]Figures shown are approximately middle values for those states that provided estimated ranges; for example, 20 to 30 percent is listed as 25 percent. Estimated studded-tire use is expressed as the percentage of registered passenger cars equipped with studded tires.
[b]NA = estimate not available.
[c]NL = not legal.

Estimates of the number of vehicles equipped with studded tires (studded-tire use) were reported as a percentage of registered passenger cars by each of 37 states. Estimates were unavailable from 8 states, but it may be assumed that studded-tire use in 4 of these states is less than 1 percent.

Of the 37 states that did provide estimates, 7 reported a studded-tire use of not more than 5 percent. The remaining 30 states reported estimates ranging from 6 to 61 percent. The data from these 30 states may be viewed as indicative of the present status of studded-tire use in the United States north of the 37th parallel—Minnesota and Utah excepted.

An average studded-tire use of 20 percent was obtained by weighting the estimates from each of the 30 states by the estimated number of passenger cars registered in each of the states in 1972. This same figure, 20 percent, was coincidently reported by 3 of the 30 states. Estimates above the average were reported by 16 states and estimates below the average by 11 states. The total passenger car registrations for the 30 states were 57,751,000, and the total number of cars equipped with studded tires was computed to be 11,673,000.

In 20 of the 30 states that reported more than 5 percent studded-tire use, the estimates were based on surveys made during the past 3 years (Table 1). In some instances, the use of studded tires may vary widely within individual states. Such variation is not unexpected in states where winter weather causes driving problems only in the mountainous areas, although considerable variation has been noted even in Iowa where there are no mountains and terrain is not an important factor in winter driving.

FUTURE USE OF STUDDED TIRES

The future for studded tires in the United States will be influenced by many factors, some of which may not even be apparent at this time. Certainly, so long as American motorists continue to want studded tires, there will be a studded-tire industry to satisfy that want. It is possible that new developments in design and manufacture may result in studs that will cause significantly less pavement wear. Likewise, development of other traction aids or changes in tire design could lessen motorists' interest in studded tires.

Perhaps the bare pavement policy, including the frequent use of salt, will have to be modified in response to environmental considerations. This would undoubtedly accelerate the demand for all types of traction aids.

Legislation to ban, tax, or otherwise control the use of studded tires is a possibility in some states. Interest in a ban or tax has been noted in 18 states (Table 1).

The 30 states, each of which estimated studded-tire use in 1972-73 to be more than 5 percent, also provided estimates of studded-tire use in 1976-77. The weighted average of these estimates is 26 percent—an increase of 6 percent over 1972-73.

CONCLUDING REMARKS

Highway administrators and engineers, particularly those living in the northern part of the United States, may feel that average estimates of 20 percent for 1972-73 and 26 percent for 1976-77 are too low. In this regard, two statements made previously merit repetition: First, these are weighted averages; second, the individual state estimates for 1972-73 ranged from 6 to 61 percent.

These averages, just like most average statistics, cannot always be used to properly describe local conditions. In the final analysis, it is the local, or perhaps statewide, estimate of studded-tire use that is most meaningful to the people directly responsible for safe, economical highway facilities.

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EFFECT OF STUDDED TIRES ON VARIOUS PAVEMENTS AND SURFACES

Milan Krukar and John C. Cook, Washington State University

This paper presents results obtained from testing at the G. A. Riedesel Pavement Testing Facility at Washington State University during the period from February 11 to May 4, 1972. The purpose of this project was fourfold: to determine pavement wear caused by studded tires, to evaluate the resistance of different pavement materials and textures used in the states of Washington and Idaho to wear caused by tire studs, to test pavement materials and overlays to reduce tire stud damage, and to study the effect of studded truck tires on pavements. The findings indicate that some pavement materials are more resistant to the effect of studded tires than are others. Different types of studs reduced wear of various pavement materials. All types of studded tires tested caused some pavement wear, and this affected the skid resistance values.

•THIS study of the effect of studded tires was divided into three phases. During phase 1, various pavement materials and surface textures were evaluated in 1971-72. Phase 2 consisted of evaluating various pavement overlays during 1972-73. In phase 3, the results were evaluated and compared with actual highway conditions. This paper is concerned only with phase 1.

DESCRIPTION OF TEST

Ring 5 consisted of three concentric tracks on which 16 tires traveled in eight wheelpaths. The tracks were divided into six sections 43 ft in length and were then further subdivided. The center track had 12 different portland cement concrete surface textures, and the inside and outside tracks were constructed of asphalt concrete and some steel fibrous and polymer concrete sections. A total of 46 sections were tested; there were 20, 12, and 14 sections in the outside, center, and inside rings respectively as shown in Figure 1.

The G. A. Riedesel pavement testing apparatus, which consists of three arms each with dual tires supporting a water tank, was modified so that two sets of passenger tires could be mounted inside the truck duals on the inside track. Two passenger tires were hung on each of the two arms so as to travel on the outside ring in four separate wheelpaths. A total of 16 tires were mounted on the apparatus; each passenger tire carried a 1,000-lb load at 28-psi inflation, and each truck tire carried a 4,000-lb load at 80-psi inflation.

Three of six truck tires, size 11 × 22.5, were studded with 240 type 3 studs. These were the driving tires in wheelpath 6. The outside truck tires, in wheelpath 5, were unstudded and freewheeling. The 10 passenger-car tires were all G78 × 14 with winter snow tread; four were unstudded (wheelpath 8) and four had 112 type 1 studs (wheelpath 7). On the outside track, four passenger-car tires were used on four different wheelpaths. The unstudded, the type 1, the type 2, and the type 3 studded tires were in wheelpaths 1, 2, 3, and 4 respectively.

Types of tire studs are identified by number in the following manner: Type 1 has a controlled protrusion, type 2 has a composite core with small tungsten carbide chips in a soft binding matrix, and type 3 has the conventional solid tungsten carbide pin encased in a steel jacket. There is also the unstudded passenger tire.

Transverse profile measurements were made with the WSU profilometer, the camera box shadow-wire technique, and a straightedge. Temperature measurements of the pavements were taken with iron-constantan thermocouples and were automatically recorded. Skid resistance measurements were made with the California skid tester. Stud protrusion and tread depth measurements were taken at regular intervals.

SUMMARY OF RESULTS

Following is a summary of the study results.

1. Results of tests and comparisons of materials among the three tracks should be made with care and judgment. There were enough differences in the tests that, in some cases, direct comparisons cannot be made. The center track had truck tires, whereas the inside and outside tracks had passenger tires. Each of the tracks had different amounts of wheel passes. Wheelpaths 1 through 4 of the outside track had 542,357 passenger-tire wheel passes; wheelpaths 5 and 6 had 1,627,071 truck-tire wheel passes on the center track. Wheelpath 6 had 1,396,935 studded truck-tire passes and 230,136 unstudded truck-tire passes; wheelpaths 7 and 8 had 1,627,071 passenger-tire passes. Also, the effect of speed with the inside wheels traveling at slightly lower speeds than the outside wheels could have affected the rate of wear.

2. All studded tires caused measurable wear on all surfaces of the test track. Comparative wear ratios, which were calculated only for the outside track (Table 1), show that the type 2 stud caused less wear than either the type 1 or type 3 stud in that order. Pavement surface wear caused by unstudded tires was essentially unmeasurable. It is interesting to note that, even though the type 1 stud did not reach the desired pin protrusion because of the low test speeds, pavement wear was still considerably reduced.

3. The portland cement concrete pavements showed more resistance to studded-tire wear than did the asphalt concrete pavements (Table 1 and Fig. 2). The skid resistance values were considerably lower for the portland cement concrete pavements than for the asphalt concrete pavements (Table 2).

4. Of the asphalt concrete pavements, the class B asphalt concrete sections (100 percent passing the ⅝-in. sieve) showed the most initial resistance to wear by studded tires, followed by the class G (100 percent passing the ½-in. sieve), and then the class E asphalt concrete (100 percent passing the 1¼-in. sieve). The class E asphalt concrete with respect to maximum rut depth and area removed at the end of test was slightly superior to the class G asphalt concrete (Fig. 1).

5. Tests were made on the steel fibrous concrete overlays (Wirand concrete) to study different types of mix designs with respect to their wear resistance to studded tires. The Wirand concrete with ⅜-in. aggregate (section 0-2aC) proved to be the most resistant to wear from studs and to be equal to the ¼-in. polymer concrete overlay in section 0-2bB and regular portland cement concrete. All the steel fibrous concrete sections showed superior skid resistance values as wear progressed (Table 2). Under WSU test conditions, the steel fibers in the studded-tire wheelpaths had a tendency to become dislodged and spread over the track and protrude somewhat out of the pavement.

6. The gilsonite product rejuvenating treatment on two of the asphalt pavements showed little or no improvement over the regular asphalt concrete sections (Table 1). An initial reduction in skid resistance was observed. Final skid resistance was comparable to other types of asphalts (Table 2).

7. The surface materials tested showing the greatest resistance to studded-tire wear were the different types of polymer overlay: the polymer cement and polymer flyash concretes (Table 1 and Fig. 1). These materials showed good resistance to all tire studs. However, their skid resistance values decreased drastically with wear (Table 2).

8. Different surface textures, formed while the portland cement concrete was plastic, showed no great advantage for wear resistance. The reason is that the textures probably consisted of sand-cement mortar that was deficient in coarser aggregate and thus had relatively little strength to resist the tire studs.

Figure 1. Plan view of testing apparatus and pavement sections.

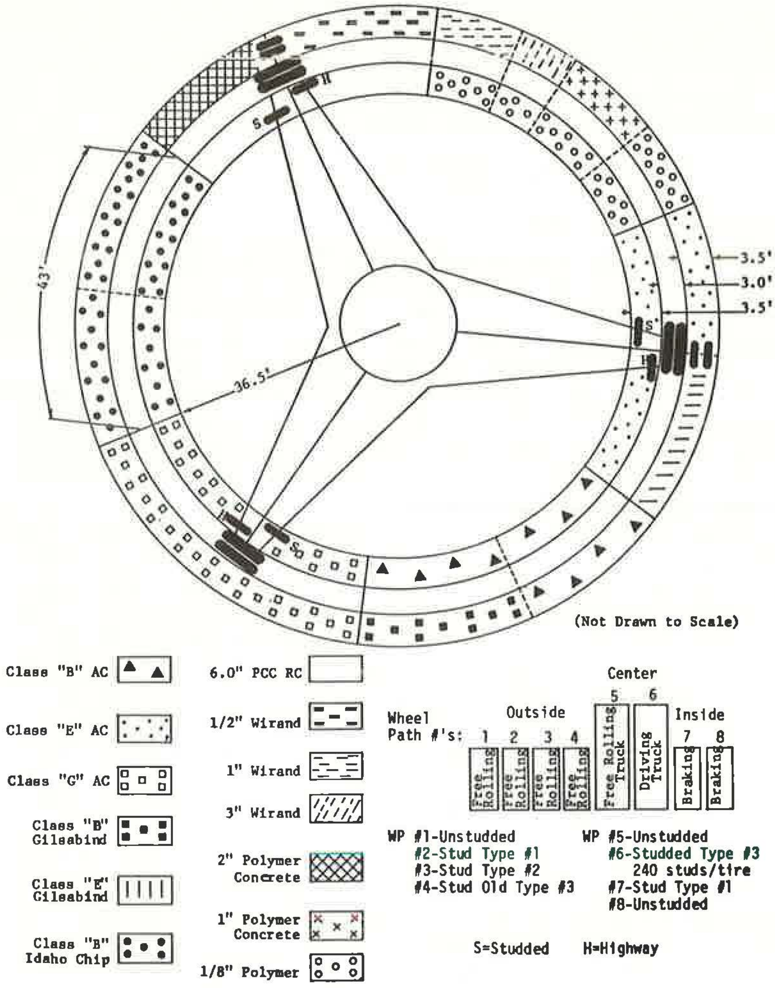
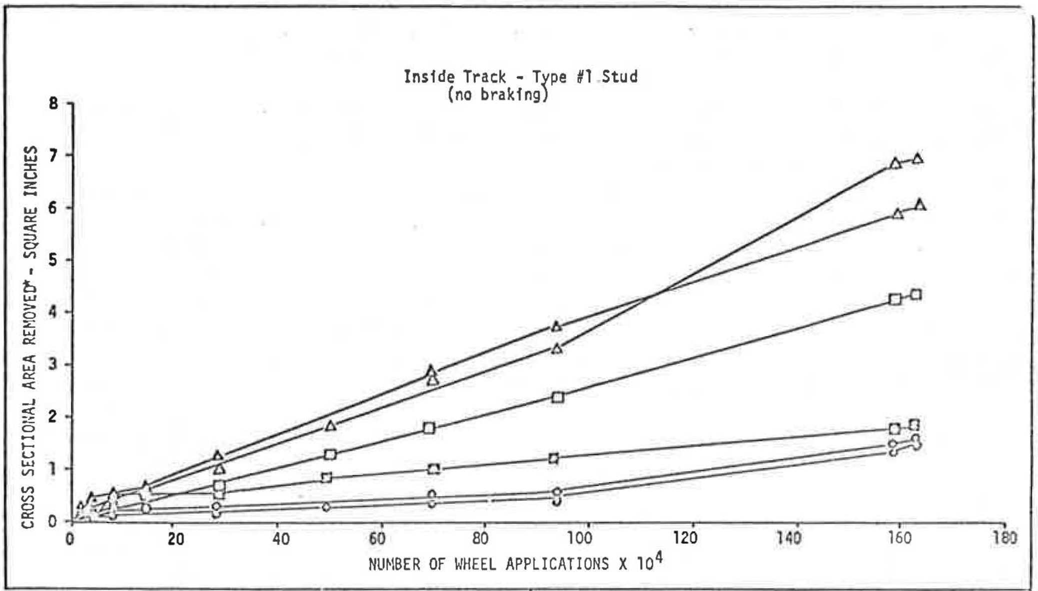


Table 1. Comparative pavement wear (passenger-car tires and outside track only).

Section	Pavement	Wheelpath 1, No Studs		Wheelpath 2, Type 1 Stud		Wheelpath 3, Type 2 Stud		Wheelpath 4, Type 3 Stud	
		Percentage of Wear[a]	Wear Ratio[b]	Percentage of Wear	Wear Ratio	Percentage of Wear	Wear Ratio	Percentage of Wear	Wear Ratio
0-1bA	½-in. Wirand concrete	6.1	16.4	83.6	1.2	47.8	2.1	100	1
0-1bB	½-in. Wirand concrete	0.7	142.9	78.3	1.3	34.8	2.9	100	1
0-1bC	½-in. Wirand concrete	2.4	41.7	117.6	0.8	41.2	2.4	100	1
0-1bD	½-in. Wirand concrete	11.0	9.1	95.2	1.0	47.6	2.1	100	1
0-2aA	1-in. Wirand concrete	3.0	33.3	109.0	0.9	40.9	2.4	100	1
0-2aB	1-in. Wirand concrete	3.1	32.4	75.0	1.3	33.3	3.0	100	1
0-2aC	3-in. Wirand concrete	1.7	60.0	122.2	0.8	77.8	1.3	100	1
0-2bA	1-in. polymer concrete[c]	0.75	133.3	183.3	0.6	80.0	1.2	100	1
0-2bB	¼-in. polymer concrete	0.83	120.5	75.0	1.3	108.3	0.9	100	1
0-3a	Class E asphalt concrete	10.4	9.7	82.1	1.2	50.0	2.0	100	1
0-3b	Class E asphalt concrete, Gilsabind	2.1	47.1	71.9	1.4	46.9	2.1	100	1
0-4a	Class B asphalt concrete	4.5	22.3	96.6	1.0	41.4	2.4	100	1
0-4b	Class B asphalt concrete, Gilsabind	4.7	21.4	96.7	1.0	43.3	2.3	100	1
0-5a	Class G asphalt concrete	6.7	15.0	73.3	1.4	46.7	2.1	100	1
0-5b	Class G asphalt concrete	2.4	40.8	76.3	1.3	39.5	2.5	100	1
0-6a	Idaho chip seal	—	—	—	—	—	—	100	1
0-6b	Idaho chip seal	19.5	5.1	30.0	3.3	55.0	1.8	100	1

[a]Percentage of wear = type Y stud average wear/type 3 stud average wear x 100 percent.
[b]Wear ratio = 100/percentage of wear.
[c]Some of the wear was due to poor bond.

Figure 2. Comparison of area removed with type of material.



* From WSU profilometer measurement transverse of track:

Actual wear profile, average of three inch longitudinal of track, times actual wheel path width.

LEGEND
Polymer Cement Concrete
Polymer Flyash Concrete
Portland Cement Concrete
Class "B" Asphalt Concrete
Class "E" Asphalt Concrete
Class "G" Asphalt Concrete

Table 2. Comparison of percentage of reduction in skid resistance values.

Section	Pavement	All Passes[a]	Unstudded Wheelpaths 1 and 8	Percentage of Reduction	Wheelpath 1, Studs 2 and 7	Percentage of Reduction	Wheelpath 2, Stud 3	Percentage of Reduction	Wheelpath 3, Stud 4	Percentage of Reduction
I-1a	Portland cement concrete	47	34	28	27	43	—	—	—	—
I-1b	Portland cement concrete	47	38	19	27	43	—	—	—	—
0-1bA	½-in. Wirand concrete	45	21	53	37	18	31	31	28	38
0-1bB	½-in. Wirand concrete	43	17	60	38	12	27	37	30	30
0-1bC	½-in. Wirand concrete	43	14	67	30	30	24	44	23	47
0-1bD	½-in. Wirand concrete	45	18	60	28	38	30	33	33	27
0-2aA	1-in. Wirand concrete	44	22	50	31	30	25	43	33	25
0-2aB	1-in. Wirand concrete	46	23	50	34	26	30	35	30	35
0-2aC	3-in. Wirand concrete	46	25	46	30	35	25	46	27	41
I-2aA	⅛-in. polymer cement	41	30	27	16	61	—	—	—	—
I-2aB	⅛-in. polymer flyash	25	22	12	14	44	—	—	—	—
I-2bA	⅛-in. polymer flyash	23	29	+26	13	43	—	—	—	—
I-2bB	⅛-in. polymer cement	25	26	4	14	44	—	—	—	—
0-2bA	1-in. polymer concrete	40	24	40	18	55	24	40	16	60
0-2bB	¼-in. polymer concrete	38	27	29	17	55	16	58	18	53
I-3a	Class E asphalt concrete	36	31	14	25	31	—	—	—	—
I-3b	Class E asphalt concrete	43	37	14	27	37	—	—	—	—
0-3a	Class E asphalt concrete	42	26	38	32	24	28	33	31	26
0-3b	Class E asphalt concrete, Gilsabind	35	23	34	35	0	24	31	33	6
I-4a	Class B asphalt concrete	39	32	18	25	36	—	—	—	—
I-4b	Class B asphalt concrete	45	31	31	25	44	—	—	—	—
0-4a	Class B asphalt concrete	40	24	40	28	30	22	45	29	28
0-4b	Class B asphalt concrete, Gilsabind	26	30	+15	39	+50	30	+15	26	0
I-5a	Class G asphalt concrete	34	30	12	32	6	—	—	—	—
I-5b	Class G asphalt concrete	44	37	16	26	41	—	—	—	—
0-5a	Class G asphalt concrete	40	31	23	40	0	32	20	43	+8
0-5b	Class G asphalt concrete	38	30	21	36	5	33	13	33	13

[a]Taken from the entire section. [b]Minus values except where noted.

9. The initial rate of wear was in most cases higher than the medium, final, and average rates for almost all test pavements. This indicates that there would be high initial wear that would decrease as stud protrusions and tires wear down. In the real world, one might expect high wear rates at the beginning of winter when tires and studs are new.

10. Skid resistance values dropped with wear caused by the studded tires (Table 2). The portland cement concrete value reduction was particularly noticeable and showed a polishing effect in the worn wheelpaths.

11. The effect of studded truck tires was a high initial wear rate that slowed noticeably. This was due to the fact that, as the studded driving truck tires wore a groove, the weight of the truss shifted to the freewheeling truck tires. Hence, the wear rates are not indicative of those found elsewhere for studded truck tires.

12. The wear rates and some results compared favorably with those obtained at the American Oil Company tests, but they seem to be low for those obtained from field highway data. This may be because of the conditions of tests.

13. Comparison of wheelpath measurements with different methods and procedures shows that the results were quite comparable.

14. Poor construction weather affected some results—especially the 2.0-in. thick polymer concrete, where epoxy replaced the cement in a regular portland concrete mix. Low temperatures resulted in poor bonding of the aggregate, which quickly came loose with wheel passes. Therefore, the data on this material are excluded from this report.

15. The Idaho chip seal sections were also placed under extremely poor weather conditions with the result that the chips did not adhere to the rubberized asphalt. In areas where the chips were retained, the pavement showed good resistance to tire studs. However, data are sparse and included whenever they were available (Table 1).

ACKNOWLEDGMENTS

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STATUS OF NCHRP RESEARCH ON THE SAFETY ASPECTS OF STUDDED TIRES

John E. Burke, Highway Research Board

•THE primary objection to the use of studded tires has been an economic one, that is, the high cost of the additional highway maintenance required to repair the damage they cause. Visual evidence of this damage exists, and means are available for estimating the probable cost. Information is lacking on the safety benefits that should be weighed against these costs for making decisions on the future of studded-tire use. Three problem areas are still to be addressed:

1. The direct effect of studded tires on accident frequency and severity,
2. The potentially deleterious effect of studded tires on accident frequency and severity because of their capacity to modify pavement surfaces, and
3. The potential of studded tires for accelerating the loss of pavement markings.

NCHRP Project 1-13 (Effects of Studded Tires on Highway Safety) is directed toward providing the quantitative information required in the first problem area. NCHRP Project 1-13(2) (Effects of Studded Tires on Highway Safety—Nonwinter Driving Conditions) is a first step in a series of several that probably will be needed if a significant amount of quantitative information in the second and third areas is to be obtained.

Project 1-13 was undertaken by Cornell Aeronautical Laboratory (now Calspan) of Buffalo, New York, in April 1971 and is scheduled for completion late in 1973.

An earlier completion date was originally anticipated, but some inconsistencies in the taped data that required rectification midway in the study slowed progress. As its title suggests, Project 1-13 addresses the problem of identifying and quantifying the overall effects of the use of studded tires on the incidence and severity of traffic accidents. The immediate objective of the project is to measure, by a study of accident records, accident investigations and to study the effect of studded-tire use on the incidence and severity of accidents occurring under winter driving conditions. The exposure of vehicles with and without studded tires to accident occurrence is a consideration.

Both Minnesota and Michigan have made data available for the study. The discontinuance of the general use of studded tires in Minnesota before the 1971-72 winter has provided a unique and valuable opportunity for a "before-and-after" investigation that adds measurably to the value of the study.

The essential data elements for the frequency studies are accident occurrence, type of tire (studded or unstudded), and type of driver (user or nonuser of studded tires before the ban). A second group of accident variables (those required for specific substudies) are injuries, road cover condition, location, and date.

Accidents included in both the Minnesota and Michigan studies have been limited to those reported by police.

The desired data are being obtained from various sources including accident records, magnetic-tape storage, license and vehicle registration files, and questionnaire returns. The data are then integrated to provide the required data sets.

For the Minnesota before study, data for the winter portions of 1970 have been used. For the after study, data for the winter of 1971-72 have been used. Details for more than 18,000 vehicle involvements for the before condition, and more than 20,000 for the after condition, are available for analysis.

Although the specific level of quantification that can be achieved in the project results will not be known until the data have been studied, the quantity of data available for analysis favors an expectation that the major results can be presented at levels no lower than percentage of change.

Results that are reported at the percentage-of-change level can be used in estimating the probable change in accident cost that can be expected to result from the banning of studded tires.

The primary function of the Michigan before study is to establish a broader data base to allow a greater generality of results. To do so, data collected in Michigan reflect the same variables studied in Minnesota. The collection period was January through March 1972. Data on 52,000 accidents that occurred during the period have been used in the study.

Although the analysis of the Michigan data is incomplete (as of January 1973), a sufficient amount of analytical work has been done to show that, if the present trend continues, the final results will indicate a minor safety advantage for studded tires.

Project 1-13(2) was undertaken by the Highway Safety Research Institute of the University of Michigan in February 1972 and was scheduled for completion in November 1972. The purpose of this project has been to formulate a plan of attack for determining the magnitude of the effects on highway safety of pavement wear and lane-marking wear by studded tires. This is apart from the economic issue of extra maintenance cost due to pavement wear and from the issue of safety under icy pavement conditions.

The relations that exist among the factors involved in the nonwinter safety aspects of studded tires are complex, and the present project is only an initial step toward an assembly of the body of knowledge needed for quantification of the nonwinter effects of studded tires.

Project 1-13(2) has included a synthesizing of present knowledge of the nonwinter driving effects of studded tires, generally qualitative modeling of these effects, and the preparation of experimental plans for exploring areas where present knowledge is lacking.

The effects that were determined to have the greatest hazard potential, listed in the order of estimated decreasing hazard, are as follows:

1. Tire hydroplaning and wet skid,
2. Road repair and maintenance hazard (the result of pavement surface and pavement marking restoration),
3. Splash and spray,
4. Vehicle lateral placement shifting,
5. Vehicle transverse force and steering effects,
6. Driver fatigue resulting from noise and vibration,
7. Ejected studs thrown from high-speed vehicles, and
8. Vehicle component degradation.

As had been expected, existing information was found to be insufficient for determining the magnitudes of these hazards. Of much importance among the missing information are accident data adequate for differentiating studded-tire effects on nonwinter driving conditions. Experimental research has been recommended for several of the effects that appear to have greatest significance.

AFTER STUDS IN MINNESOTA

C. K. Preus, Minnesota Department of Highways

After six winters of legalized use in Minnesota (1965 to 1971), studded tires were prohibited during the winters of 1971-72 and 1972-73. Comparisons are made in this report of the effects observed after 1 year without studs as against the previous 6-year period with studs. Observations were made over several winters on various types of roads and streets to ascertain the proportion of time that icy cover conditions prevailed when studded tires could have some beneficial effect. Up to 44,000 such observations were made in the winter of 1971-72. Icy conditions prevailed no more than 1 percent of the time in the metropolitan area on predominantly high-volume and high-speed roads. On low-volume and low-speed roads and streets, icy conditions occurred much more frequently. Traffic accident data were assembled and analyzed by the Minnesota Department of Public Safety comparing the records for the 1971-72 winter without studs against the preceding three winters with studs. For snowy or icy roads, the winter without studs compared favorably with the previous winters with studs. All things considered, there was no appreciable increase in traffic accidents because of discontinuance of studded tires. Noise level measurements indicated that pavements badly worn by studded tires and having coarse aggregate particles exposed could yield noise levels almost twice as high as the original surface texture might produce.

•FOR the second winter season, Minnesota resident motorists are now driving without studded tires after previously having experienced six winters, from 1965 to 1971, during which the use of studs was permitted. The 1971 legislature did not legalize studded tires for Minnesota residents for the 1971-73 biennium. This situation has therefore provided a rather unique opportunity to compare observations and recorded data from last winter when studded tires were not used against the records for the previous winters when studs were in use. This report will present comparisons on pavement surface wear, studded-tire use in Minnesota, winter road cover conditions, traffic accident data, and pavement surface effect on traffic noise.

PAVEMENT SURFACE WEAR

Since studded tires were first legally introduced in Minnesota in 1965, the Minnesota Department of Highways has made field observations and measurements on pavement surfaces to determine the degree of wear that was associated with the use of studs. Initially only six wear measurement sites were established, but this was increased to 85 sites that were distributed about all regions of the state to obtain representation of various pavements, traffic volumes, and geographic locations.

The measurements were in all cases obtained from dial gauge readings taken at 1-in. intervals across the wheelpath from a frame set on metal plugs embedded in the pavement surface. From these measurements there was established, for each of several pavement types, a relation between the rate of wear and the number of studded-tire applications.

Following the ban on studded tires, the pavement wear measurements were continued on the previously established test points. In addition, a number of new test points were established on several new pavement sections that had never been subjected to the previous volumes of studded-tire traffic. The measurements, therefore, on the new pavements following the winter of 1971-72 represent the wear induced by normal traffic with sand and salt applications but with virtually no studded tires.

The annual and cumulative depths of surface wear that occurred at a number of typical measurement points are given in Table 1. From these data, it is evident that, after the winter of 1971-72 and with the ban in effect, pavement wear was reduced to virtually nil. Similarly, on the other test points the results were the same, thus confirming the conclusions of all our previous studies that the pavement wear was unquestionably related to the studded-tire applications.

STUDDED-TIRE USE

The proportion of passenger vehicles in the state that were equipped with studded tires was determined by making a series of wintertime surveys at various locations throughout the state. It was found that the percentage had increased from about 3½ in the first winter to approximately 40 in the winter of 1969-70 and somewhat less in the winter of 1970-71.

As a follow-up to the ban on studs, another statewide survey of the extent of their use was conducted last winter. This was of particular interest because the 1971 law permitted limited use of studded tires in Minnesota by nonresidents, up to a maximum of 30 calendar days in a year. This survey was made by checking on nearly 4,000 parked cars, a large portion of which were in a number of cities located fairly close to the borders of adjacent states that did not ban studs.

The out-of-state vehicles composed less than 8 percent of all vehicles checked, varying from about 4 percent in the metropolitan Minneapolis-St. Paul area to about 12 percent in communities in southeast Minnesota, including Rochester, the medical mecca. Of the out-of-state vehicles, less than 11 percent were equipped with studded tires. Therefore, less than 1 percent of all vehicles had studded tires, even in the areas where out-of-state cars were most numerous and studded-tire concentration might be expected to be greatest.

Only 3 Minnesota-licensed vehicles out of the 4,000 checked were found to have studs, indicating a high degree of compliance on the part of Minnesota residents.

ROAD COVER CONDITIONS

The road cover conditions existing day by day on the streets and roads were observed and recorded during each of the winters of 1969-70, 1970-71, and 1971-72. The cover conditions were classified into three categories: bare pavement, loose snow or slush, and ice or hard-packed snow. Six types of roadways were observed. The proportion of time that each of the cover conditions occurred on each type of road was computed.

For the first 2 years, about 18,000 observations were made each winter on representative thoroughfares in the Twin Cities metropolitan area, including adjacent rural areas. In the 1971-72 winter, however, the observations were extended to represent all areas of the state, and more than 44,000 recordings were noted. Observations were made in both the morning and afternoon of each workday from October 15 to April 30, covering the calendar period in which studs were allowed until the time of the ban.

The indications from the 1971-72 survey suggested that, for the purpose of summarizing the data, the state could be divided into three regions: north, south, and metropolitan. Accordingly, the data given in Table 2 indicate the percentage of time during the winter driving season that each cover condition prevailed on each type of road in each of the three regions.

It is evident that, for all types of roads, the pavements are for most of the winter season either bare or covered with loose snow or slush. Under such conditions it then follows that, for the majority of the time, studded tires offer no potential stopping advantage and may at times display a small disadvantage.

For condition 3 (ice and hard-packed snow), where studs have been shown to provide a stopping advantage, the data show that such conditions prevail from 1 to 33 percent of the winter driving season, with the higher proportion being on roads and streets carrying low traffic volumes and generally at lower speeds. On the state trunk highways where traffic volumes and maintenance are typically at higher levels, the icy occurrence is 4 percent or less. Icy conditions occur less than one-sixth of the time on arterial streets and county roads. Only on township roads and on residential streets in out-state areas, where traffic volumes and speeds are lowest, do the icy conditions prevail up to one-third of the wintertime. These findings substantially corroborate those reported from the earlier surveys.

TRAFFIC ACCIDENT DATA

The 1971 report that the Department submitted to the legislature on studded-tire effects concluded that "if studded tires were discontinued there would be little appreciable change in traffic safety in Minnesota." Statistics covering accidents during the winter of 1971-72 when studs were banned have been compared with the records for previous years when studs were in use. Data compiled by the Minnesota Department of Public Safety are summarized in Tables 3 and 4.

The numbers of accidents vary considerably from year to year, and even more so from month to month and day to day, depending greatly on road conditions. The apparent small increases in accidents in each of the past 2 years are within the variation that might be expected from winter to winter with the normal increase in traffic of about 5 percent per year.

Considering the data given in Table 3 on all winter accidents, the record for the 1971-72 winter without studs compares favorably with the preceding winter with studs and even more so with the averages for the three preceding winters when studs were used. Indeed, in terms of fatal accidents, the studless winter was 15 percent lower than the winter before with studs. Although the total number of accidents last winter was slightly higher than the winter before (by only 3 percent), it was nevertheless lower than the average for the three preceding winters.

The data given in Table 4 for accidents that occurred on snowy or icy roads—where studded tires should have provided their greatest advantage—show that the record for 1971-72 without studs again compares quite favorably with the previous winters when studs were used, notwithstanding the slightly higher number of fatal accidents. However, the fatal accidents are so relatively few in number that chance influences the statistics to a much greater degree than it does for property damage accidents. Some of the apparent small increase in police-reported fatalities may be due to administrative changes in the Minnesota Highway Patrol accident reporting procedures in which some accidents in 1969-70 were not coded as to road conditions.

Traffic volumes were about the same for the three winters preceding the winter of 1971-72. Data for 1972 are not yet available. The snowfall average statewide was slightly less in the early months of last winter, but the total (52.6 in.) was about average for the past three winters. In general, the weather last winter was not substantially different from previous winters.

All things considered, it can be concluded that there has been no appreciable increase in traffic accidents in Minnesota because of the discontinuance of studded tires.

The accident study conducted by Cornell Aeronautical Laboratory, Inc., for the Minnesota Department of Highways and reported to the 1971 legislature showed a slight benefit for studded tires in accidents involving sliding on icy or snowy road surfaces. Following that study, the Highway Research Board under the National Cooperative Highway Research Program contracted with Cornell Aeronautical Laboratory, Inc., for further studies including a "before-and-after" study in Minnesota and a before study in Michigan. The statistical analysis of the Minnesota data is not complete, and the findings are not expected until late winter or spring of 1973. Details of more than 18,000 accident situations for both the before and after conditions are available for analysis.

PAVEMENT SURFACE EFFECT ON NOISE

One effect that studded tires have indirectly produced but that has not received much attention is the increase in traffic noise level caused by stud-roughened pavements. Inside a car, the sound often becomes a noisy rumble when traveling over rough, stud-worn wheelpaths. Outside the vehicles, a rough road surface texture such as produced by studded tires accentuates the noise generated by tire-pavement interaction.

In an attempt to quantify the differences in noise level produced by various pavement

Table 1. Depth of pavement surface wear at typical test points (in inches).

	TP 6[a]		TP 33[b]		TP 32[c]		TP 83[d]	
Winter	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative
1966-67	0.04	0.04						
1967-68	0.07	0.11						
1968-69	0.07	0.18	0.09	0.09	0.10	0.10		
1969-70	0.05	0.23	0.07	0.16	0.03	0.13	0.08	0.08
1970-71	0.05	0.28	0.06	0.22	0.07	0.20	0.07	0.15
1971-72	0.00	0.28	0.00	0.22	0.00	0.20	0.01	0.16

[a]Test point 6, portland cement concrete, gravel aggregate.
[b]Test point 33, portland cement concrete, limestone aggregate.
[c]Test point 32, asphaltic concrete, high type.
[d]Test point 83, bituminous, intermediate type.

Table 2. Road cover conditions, winter 1971-72 (percentage of time prevailing).

	Condition 1, Bare			Condition 2, Loose Snow or Slush			Condition 3, Ice or Hard-Packed Snow		
Type of Road	North	Metropolitan	South	North	Metropolitan	South	North	Metropolitan	South
Divided highway	87	92	91	9	7	5	4	1	3
Undivided highway	87	91	91	10	8	5	4	1	4
County road	69	83	82	16	14	9	15	2	10
Township road	52	59	62	18	34	9	29	7	29
Arterial street	68	79	73	16	17	13	16	4	14
Residential street	49	51	59	18	36	12	33	12	28

Table 3. Accidents on all roads, November through April.

Type of Accident	1968-69	1969-70	1970-71	3WA[a]	1971-72
Fatal	332	320	334	329	284
Personal injury	11,747	11,402	11,148	11,432	11,507
Property damage only	49,074	41,978	43,405	44,819	44,762
Total	61,153	53,700	54,887	56,580	56,553

[a]3WA = 3-winter average; studs in use.

Table 4. Accidents on snowy or icy roads, November through April.

Type of Accident	1968-69	1969-70	1970-71	3WA[a]	1971-72
Fatal	78	69	78	75	82
Personal injury	4,372	3,246	3,865	3,828	4,078
Property damage only	19,374	11,081	12,150	14,202	12,730
Total	23,824	14,396	16,093	18,105	16,890

[a]3WA = 3-winter average; studs in use.

surfaces, a limited study of preliminary nature was conducted last fall in which noise measurements were taken on a series of five bituminous pavements and five portland cement concrete pavements located in the Twin Cities metropolitan area. Each of the two types of pavements included surfaces that were classified as smooth and others that were rough-textured in varying degrees.

The noise level intensity was measured with a standard B&K sound meter, model 2204, mounted on a tripod 4 ft above pavement level and set at a distance of 25 ft from the edge of the pavement. A 1970 Ford 4-door sedan was driven past the meter at constant speed of 45 mph, with the motor running but under no acceleration while passing. Care was taken to avoid any noise interference from other vehicles in the vicinity. All tests were made with a windscreen attached to the microphone and only when wind velocity was under 15 mph.

The smoothest one of the bituminous pavements, constructed in 1972 and not exposed to studded tires, produced a sound level of 72 dBA. The reading on another bituminous surface abraded by 7 years of moderate traffic, including 6 years of studded tires, reached a level of 78 dBA. Other surfaces that have been more severely roughened by much higher traffic volumes would obviously produce even higher noise levels. Unfortunately, it was not possible to obtain readings on any such section because of extremely heavy traffic and time limitations during the period of the survey. Therefore, the difference in noise level between the smoothest and roughest bituminous surfaces in this area would be well in excess of the 6 dBA.

Of the portland cement concrete pavements, the lowest noise level was 73 dBA on a slab constructed in 1966 but not opened to traffic. The highest reading, 82 dBA, was recorded at a section of Interstate highway that has been under extremely heavy traffic for 14 years including 6 years with studded tires. The difference of 9 dBA from the lowest to the highest in this instance would represent almost a doubling of the perceived loudness because of the studded-tire wear.

The results of these tests, though very preliminary, indicate that the surface texture and composition of both types of pavements have a significant influence on the noise level that emanates from the roadway surface.

Because of public complaint over traffic noise in an urban residential area traversed by an Interstate route carrying more than 100,000 vehicles per day, an experimental section of asphaltic concrete overlay was placed in 1971 over the portland cement concrete pavement that had been moderately roughened by studded tires. The noise reduction achieved in that case measured about 3 dBA. Though seemingly this is not a great reduction by itself, this amount together with that expected on completion of erection of a noise barrier consisting of an earth mound surmounted by a timber wall will go a long way toward alleviating the noise problem for the residents adjacent to this area.

The public reaction to this project, where the pavement roughness was relatively moderate, has been generally favorable. It led, in fact, to placement of a similar overlay on a section of a nearby county expressway that had been more severely roughened by studded tires. This overlay reportedly reduced the neighborhood noise levels by 6 dBA, and the effect has been acclaimed by residents.

As a result of these trial projects, others are being planned to cover pavements that have suffered severe abrasion from studs. It seems likely that, in the future, as vehicle mechanical noise emissions are reduced through regulatory restrictions, pavement-generated tire noise will become the more prominent source of traffic noise. If severe pavement wear, as from studded tires, is expected in noise-sensitive areas, pavement compositions will apparently have to be designed to more effectively resist or compensate for such roughening effects.

WINTER ACCIDENT EXPERIENCE IN ONTARIO WITH AND WITHOUT STUDDED TIRES

P. Smith, Ministry of Transportation and Communications, Ontario

Total collision and personal injury accidents on the highways of Ontario during the winter of 1971-72 (without studded tires) are compared with those during the previous winter (with studded tires). Analysis is made, both overall and on a regional basis, of the specific road condition reported at the accident site and the condition generally prevailing. In spite of the general upward trend, summer and winter, in highway accidents, the proportion of accidents on icy, snowpacked, snowy, or slushy roads declined following discontinuance of the use of studded tires.

•THE evidence that led to the prohibition of the further use of studded tires in the province of Ontario after April 30, 1971, has already been documented (1-6). In brief, the literature indicates that studs not only cause serious pavement wear that is difficult and costly to prevent or repair, but also cause loss of traffic markings, reduction of skid resistance of certain types of surfacings, and ruts in the wheel tracks. Although performance tests indicated that use of studded tires might be expected to be of benefit when driving on icy surfaces, it was found in fact that icy road conditions only prevailed to a very limited extent. Most importantly, there were no data (though there were lots of claims) that any performance advantages, such as increased traction and maneuverability on ice near the freezing point, equated with actual safety benefits when driving under winter conditions.

In North America, two investigations found that the use of studded tires had no significant effect on winter accidents (2, 7). A third and fourth study were by no means conclusive, though a slightly lower involvement of cars with studded tires is indicated after appropriate treatment of the data (8, 9). One of these studies (8) has been extended as NCHRP Project 1-13(1) utilizing data from Michigan as well as Minnesota. Another NCHRP project, 1-13(2), has been addressed to effects of studded tires on highway safety, nonwinter conditions. Neither of these studies has been reported at the time of writing. In Europe, little beyond subjective claims of the type "with studded tires on all 4 wheels, winter accident rates have not increased in spite of the increase in traffic volume" appear to have been reported.

As succinctly stated by Professor E. Nakkel in his general report for the International Research Symposium on Pavement Wear in Oslo, Norway, in June 1972:

> One fact is indeed remarkable. Nowhere, as yet, has sufficient evidence been established to prove that studded tires in winter road conditions really reduce the risk of accidents. This might be explained by the "risk running behavior", i.e., a general over-estimation of the degree of safety expected from the use of studded tires, an opinion which, at least in the years before, was strengthened by the tire industry itself through advertising methods motivated by self-interest rather than objectivity.

Against this background the purpose of this paper is to provide a simple comparison of the immediate before-and-after winter accident record to determine if the highways of Ontario are in fact generally safer without the use of studded tires.

The accident data are those published by Ministry of Transportation and Communications in the annual report, Highway Traffic Collisions in Ontario, as compiled from a uniform style of police report used throughout the province for all property damage incidents estimated at $200 or more ($100 prior to January 1, 1970) and all personal injury or fatal accidents. In addition, the accidents occurring during the winter months (October to March) of 1970-71 and 1971-72 were abstracted from the general statistics so that each occurrence could be analyzed against the road condition reported by the police at the time of investigation. The data presented on the prevalence of various road conditions over the two winters were obtained in the same manner as for an earlier report (2), from the daily reports (November to April) of the Ministry's highway maintenance patrols.

GENERAL ACCIDENT TREND

Figure 1 shows the general trend of total collisions in Ontario for each calendar year from 1966 to the end of 1971. Even though the increases in vehicle registration and miles of vehicle travel mean that accident rates may actually be lower at the end of the period on certain classes of highways, the fact remains that there is, unfortunately, an increase each year in total collisions. The rate of increase varies only slightly from year to year, though it should be noted that, within this annual variation, 1970 was a low year and 1971 was a high year.

Table 1, covering the same period (1966-71), gives the distribution of the total collisions in each calendar year in relation to the condition of the road surface on which they occurred. The pattern is strikingly consistent, and, specific to this enquiry, it should be noted that, over the years in which studded tires came into increasing use, there was no corresponding reduction in the proportion of accidents on icy or snowpacked roads where studded tires were claimed to be of some advantage.

The information given in Table 2, which covers the summer, fall, and early winter months of 1970 and 1971 in greater detail, indicates that the increase in total collisions and personal injury accidents from the fourth quarter of 1970 to the fourth quarter of 1971 (which was the first winter period when the use of studded tires was not permitted) was of the same order as that between the immediately preceding three summer month periods. Preliminary examination of the accident statistics for the spring and summer of 1972 shows that this trend continues unabated.

Against this background of more accidents every year, a situation that is of course not peculiar to Ontario, the accident statistics for the period October 1, 1971, to March 31, 1972 (the first complete winter without studded tires), may be compared with those for the corresponding period of the previous winter and account taken of differences in the prevailing road conditions from one winter to the next.

WINTER ACCIDENT EXPERIENCE OF 1971-72 AND 1970-71

Two main accident indicators were selected for analysis against the road condition reported at the site of each accident. Total collisions and nonfatal personal injury accidents are used in the analysis, covering the whole of the province as one unit. In view of the similarity in trends found between the two, only total collisions are analyzed in the regional breakdown when comparing conditions on provincial highways with those on all roads. Fatal accidents are not included in the analysis because, fortunately, the small number of these does not provide a statistically valid basis on which to work.

Province-Wide Winter Accident Experience

Table 3 gives total collision and personal injury accidents for the winter of 1971-72 (without studded tires) with those occurring over the same period in 1970-71 (with studded tires) for all highways in Ontario. In addition, that fraction of the total collisions that occurred on provincial highways is shown separately.

In terms of actual numbers (although there was an increase from 85,099 to 99,279 from the winter of 1970-71 to that of 1971-72 in total collisions in the province), the number of collisions that occurred on icy or snowpacked roads remained almost the same, 22,348 and 22,324 respectively. Similarly, for personal injury accidents (although the total increase in these was from 25,845 to 30,727), those that occurred on icy or snowpacked roads only increased from 5,297 to 5,502.

With the magnitude of the overall numbers in mind, it is simpler to talk in terms of percentage of increase or decrease in order to place the accidents occurring in various road conditions in perspective. Considering all highways in the province, total collisions in icy and packed snow and in snowy or slushy road conditions show a reduction of 0.1 percent and 2.0 percent respectively. These reductions assume greater significance when viewed in light of the 16.7 percent overall increase in total collisions because of the substantial increase in dry and wet road accidents of 21.4 percent and 40.0 percent respectively. The trend is similar with personal injury accidents. Though there was a slight increase in those that occurred in icy and snowpacked road conditions (3.9 percent) and in snowy or slushy conditions (3.7 percent), these increases vary much less than those occurring in dry (19.7 percent) or wet (35.8 percent) conditions, which accounted for almost all of the 18.9 percent overall increase recorded in personal injury accidents.

Thus, provided the winter of 1971-72 was no less severe than its predecessor, especially with respect to the prevalence of icy roads, it appears that the relative incidence of accidents occurring in road conditions where studded tires have been claimed to provide greater safety in fact declined once studded tires were no longer used.

Regional Winter Accident Experience

Because of the size of Ontario, the province-wide experience may be of little solace to a motorist sliding on ice toward an impact at Red Lake. Accordingly, the total collision experience was examined on a regional basis. For this purpose, the province was divided into seven areas (following county or other administrative boundaries, which permitted segregation of the accident data from the available records) within each of which generally similar climatic, physiological, economic, and road-use characteristics occurred. Obviously, different splits could be made, but most people who know the province will recognize those chosen as representative of regions, alike within themselves, yet different from each other.

Tables 4 and 5 give these regional data, and for ease of display the percentage of increase or decrease in total collisions for each road condition of interest is indexed against the applicable region shown in Figure 2. This figure also shows a ranking against each road condition on a scale of 1 to 4 where 1 represents the largest decrease (or smallest increase) and 4 represents the greatest increase in the percentage of accidents occurring on a particular road condition. This ranking system permits a quick grasp of what otherwise would be a lengthy explanation of the differences that occurred in accidents between the winter in which studded tires were not permitted and the previous winter.

In three areas, southwestern, snowbelt, and urban counties, bordering on Lake Ontario, there was a significant reduction last winter (without studded tires) in accidents on icy or snowy roads, which ranks these and 1 or 2 (best) on the 1 to 4 scale. This ranking applies also to south central and eastern Ontario, though in these areas there was an increase in accidents on icy or snowy roads. In north central and northern Ontario the ranking changes, however, so that in both of these areas dry roads become 1 (showing the smallest increase) and ice and snow become 2 and 4 in north central and 3 and 2 in northern Ontario respectively.

Therefore, in spite of the general increase in collisions, in no case (north or south) did collisions on icy roads show the largest increase. In most cases, accidents in these conditions showed the greatest decrease or smallest increase. The icy road condition, of course, is the one in which studded snow tires are claimed to provide a safety advantage.

INFLUENCE OF ROAD CONDITIONS

The road conditions likely to be met by a motorist driving on a main highway in Ontario during the winter of 1969-70 were assessed in an earlier report (2) on the basis of the number of day-miles where a particular condition prevailed in each of three main areas (when the data from each of the individual districts grouped therein indicated that there were characteristics in common). Table 6 gives similar data but in summary form for the two succeeding winters of 1970-71 and 1971-72. The Appendix discusses data for the winter of 1972-73.

Figure 1. Trend in total collisions.

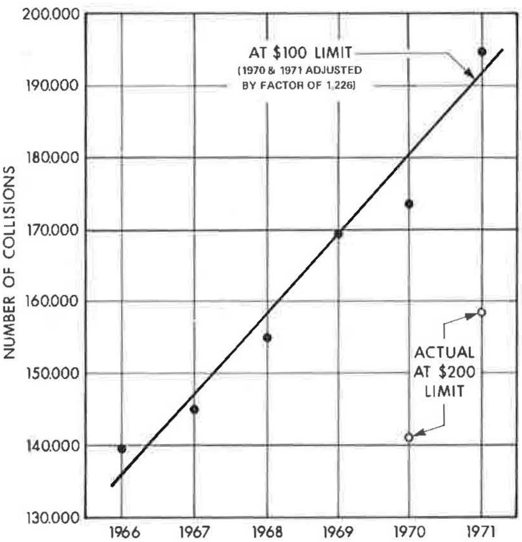


Table 1. Annual distribution of total collisions by road condition, 1966-71.

Road Surface Condition	Calendar Year by Percentage 1966	1967	1968	1969	1970	1971
Dry	56.5	55.0	57.8	60.4	55.5	53.8
Wet	25.6	25.5	22.1	22.1	24.0	22.2
Snow and slush	6.2	6.7	6.2	5.6	8.3	8.2
Ice and packed snow	10.4	11.5	12.6	10.8	11.1	14.4
Other[a]	1.3	1.3	1.3	1.2	1.1	1.4

[a]Includes mud, loose sand, gravel, etc.

Table 2. Total collisions and personal-injury accidents.

Month	Total Collisions 1970	Total Collisions 1971	Percentage of Increase, 1971 Over 1970	Personal-Injury Accidents 1970	Personal-Injury Accidents 1971	Percentage of Increase, 1971 Over 1970
July	11,704	13,105	11.97	4,670	5,513	18.05
August	10,985	12,936	17.76	4,574	5,340	16.75
September	11,388	12,281	7.84	4,538	5,077	11.88
October	12,853	14,699	14.36	4,827	5,703	18.15
November	12,545	16,347	30.31	4,409	5,409	22.68
December	17,585	18,126	3.08	5,014	5,681	13.30

Table 3. Total collisions and personal-injury accidents by road surface condition, 1970-72.

	All Highways in Ontario						Provincial Highways Only[a]		
Road Surface Condition	Total Collisions, Winter 1970-71	Total Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71	Personal-Injury Accidents, Winter 1970-71	Personal-Injury Accidents, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71	Total Collisions, Winter 1970-71	Total Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71
Dry	26,948	32,716	21.4	9,757	11,677	19.7	5,287	5,948	12.5
Wet	20,950	29,339	40.0	7,157	9,718	35.8	3,289	3,902	18.6
Snow and slush	14,245	13,958	-2.0	3,427	3,554	3.7	2,942	3,395	15.4
Ice and packed snow	22,348	22,324	-0.1	5,297	5,502	3.9	5,998	5,732	-4.4
Other[b]	608	942	55.0	207	276	33.3	46	56	21.7
Total	85,099	99,279	16.7	25,845	30,727	18.9	17,562	19,035	8.4

[a]Provincial highways are those maintained by the province of Ontario and exclude roads and streets under municipal jurisdiction.
[b]Includes mud, loose sand, gravel, etc.

Table 4. Total collisions in Ontario by region.

	Southwestern[a]			Snow Belt[b]			Urban Counties Bordering Lake Ontario[c]			South Central[d]		
Road Surface Condition	Collisions, Winter 1970-71	Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71	Collisions, Winter 1970-71	Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71	Collisions, Winter 1970-71	Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71	Collisions, Winter 1970-71	Collisions, Winter 1971-72	Percentage of Increase, 1971-72 Over 1970-71
Dry	4,382	5,350	22.1	1,679	2,222	32.3	14,032	17,522	24.9	1,893	2,295	21.2
Wet	3,024	3,935	30.1	1,437	2,036	41.7	11,414	16,175	41.7	1,513	1,965	29.9
Snow and slush	1,561	1,442	-7.6	1,625	1,343	-17.4	5,646	5,591	-1.0	1,199	1,343	12.0
Ice and packed snow	3,117	2,428	-22.1	2,888	2,508	-13.2	7,256	6,714	-7.5	2,724	2,834	4.0
Other[e]	126	190	50.8	62	98	58.1	232	355	53.0	61	82	34.4
Total	12,210	13,345	9.3	7,691	8,207	6.7	38,580	46,357	20.2	7,390	8,519	15.3

[a]Includes the following counties: Brant, Elgin, Essex, Haldimand, Kent, Lambton, Middlesex, Norfolk, and Oxford.
[b]Includes the following counties: Bruce, Dufferin, Grey, Huron, Perth, Waterloo, and Wellington.
[c]Includes the following counties: Halton, Lincoln, Ontario, Peel, Welland, Wentworth, and York.
[d]Includes the following counties: Durham, Frontenac, Hastings, Lennox and Addington, Northumberland, Peterborough, Prince Edward, Simcoe, and Victoria.
[e]Includes mud, loose sand, gravel, etc.

Table 5. Total collisions by region.

Road Surface Condition	Eastern[a] Collisions, Winter 1970-71	Eastern[a] Collisions, Winter 1971-72	Eastern[a] Percentage of Increase, 1971-72 Over 1970-71	North Central[b] Collisions, Winter 1970-71	North Central[b] Collisions, Winter 1971-72	North Central[b] Percentage of Increase, 1971-72 Over 1970-71	Northern[c] Collisions, Winter 1970-71	Northern[c] Collisions, Winter 1971-72	Northern[c] Percentage of Increase, 1971-72 Over 1970-71
Dry	2,252	2,813	24.9	1,969	1,707	-13.3	741	807	8.9
Wet	1,991	2,940	47.7	1,242	1,675	34.9	329	613	86.3
Snow and slush	2,772	2,371	-14.5	908	1,259	38.7	534	611	14.4
Ice and packed snow	2,849	3,510	23.2	2,310	2,485	7.6	1,204	1,843	53.1
Other[d]	56	74	32.1	55	104	89.1	16	39	143.8
Total	9,920	11,708	18.0	6,484	7,230	11.5	2,824	3,913	38.6

[a]Includes the following counties: Carleton, Dundas, Glengarry, Grenville, Lanark, Leeds, Prescott, Renfrew, Russell, and Stormont.
[b]Includes the following districts: Haliburton, Manitoulin, Muskoka, Nipissing, Parry Sound, Sudbury, and Timiskaming.
[c]Includes the following districts: Cochrane, Kenora, Rainy River, and Thunder Bay.
[d]Includes mud, loose sand, gravel, etc.

Figure 2. Percentage of increase or decrease in collisions, 1970-72.

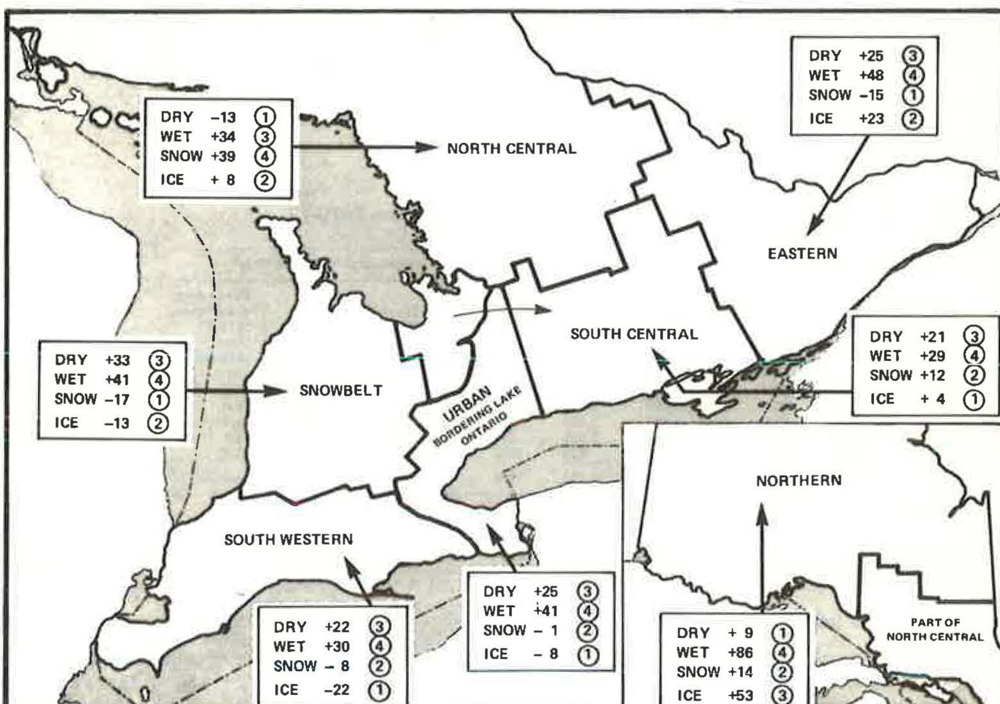


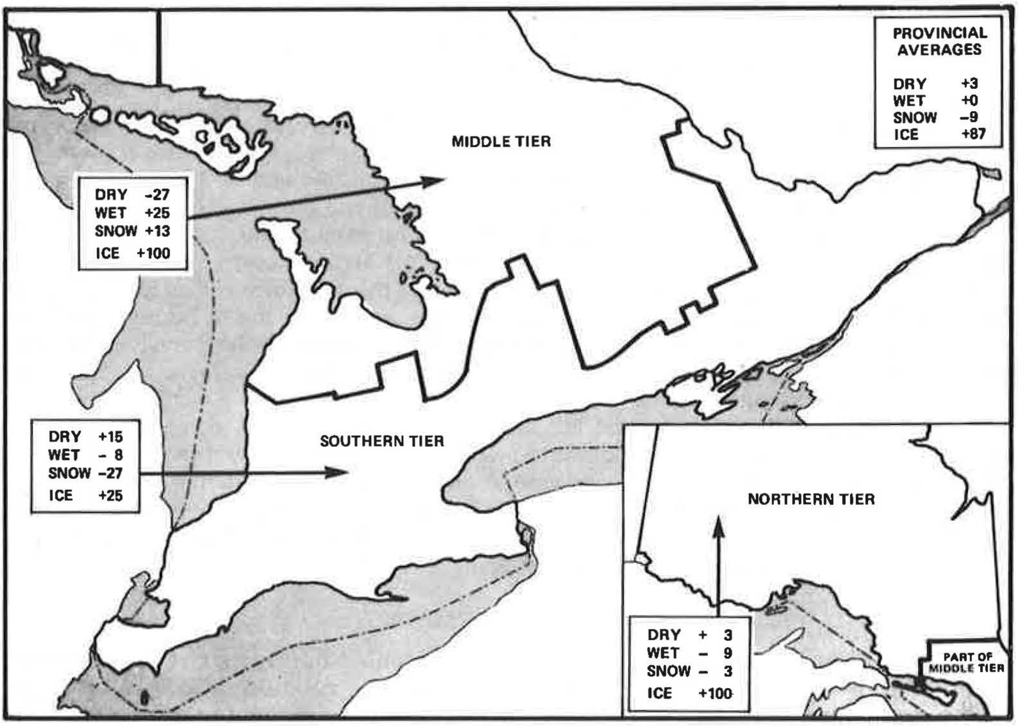
Table 6. Winter road conditions in Ontario.

Area[a]	Provincial Highways Total Miles[b]	Winter Road Conditions (percent)							
		Bare Dry		Bare Wet		Snow or Slush		Icy	
		1970-71	1971-72	1970-71	1971-72	1970-71	1971-72	1970-71	1971-72
Southern tier	6,547	48.9	56.1	33.1	30.3	17.2	12.6	0.8	1.0
Middle tier	3,563	42.3	31.0	26.7	33.4	30.2	34.0	0.8	1.6
Northern tier	4,882	27.0	27.7	30.0	27.3	40.0	39.0	3.0	6.0
Total	14,992	39.4	40.6	29.9	30.0	29.2	26.6	1.5	2.8

[a]Southern tier includes Chatham, London, Stratford, Hamilton, Toronto, Port Hope, Kingston, Ottawa, M.T.C. Districts; middle tier includes Owen Sound, Bancroft, Huntsville, North Bay, Sudbury, M.T.C. Districts; and northern tier includes New Liskeard, Cochrane, Sault Ste. Marie, Thunder Bay, Kenora, M.T.C. Districts.

[b]Provincial highways include those highways maintained by province of Ontario and exclude roads and streets under municipal jurisdiction. Mileages shown are in the following order: 10,536; 5,734; 7,857; and 24,127 km.

Figure 3. Percentage of increase or decrease in road conditions.



First, it should be noted that, on a province-wide and regional basis, there was an increase in icy road conditions recorded each winter. For example, there was an increase province-wide from 1.1 percent in 1969-70 (2) to 1.5 percent in 1970-71 to 2.8 percent in 1971-72.

The regional road condition data are shown in Figure 3 in terms of the nearest whole percentage of increase or decrease in each condition. This shows that, in the southern tier, the increase in icy road conditions was of the order of 25 percent, whereas in both the middle and northern tiers the increase was 100 percent. A rough comparison can be made (Fig. 2) against the increase or decrease in icy road accidents even though the "accident" regional areas do not follow the same boundaries. Generally in the south, the 25 percent increase in icy road conditions was not matched by a corresponding increase in icy road accidents among the vehicles exposed to traveling in these conditions. Indeed, in three of the southern accident areas there was actually a decrease in icy road accidents. Turning to the middle and northern tier road conditions, which cover the north central and northern accident areas, the increase in icy road accidents in these areas of +8 percent and +53 percent respectively is much less than the 100 percent increase in icy road conditions that prevailed in both.

The other significant differences between the two winters appear to be that, in the south, there was less snowy, slushy, and wet pavements, whereas in the middle tier there was an increase in these conditions.

The data for the analysis of road conditions were gathered only from roads maintained by the province, and the corresponding data are not available for roads under municipal jurisdiction, which may have lower standards of winter maintenance. Province-wide, about one-third of the total collisions on icy roads occurred on provincial highways, and the decrease in the case of the 1971-72 winter compared to the 1970-71 winter was 4.4 percent as compared with only 0.1 percent when all highways were taken into account.

This observation [and findings such as the report of the dramatic reductions in stopping distances that occur irrespective of the type of tire in use once ice at higher temperatures is sanded (5)] suggests that a more detailed examination of the relative influence of weather conditions, maintenance practices, natural clearing, and resulting road conditions would be worth undertaking.

This possibility is being examined, but at present there is a lack of detailed and comparable data that appears to preclude a full rationalization of winter maintenance standards on the basis of accident or economic considerations. Pending this, caution must be exercised to ensure that the level of service achieved by present standards of winter road maintenance is not allowed to decline in face of increasing costs and because of pressures to reduce pollution from spent road salting.

CONCLUDING REMARKS

The analysis of accidents and road conditions presented in this report of necessity paints a broad picture. In so doing, although this may not relate to a particular community, rural or urban, or to a particular freeway or back road or to the experiences of an individual driver, it does appear to answer beyond reasonable doubt the question, "Are the highways of Ontario in general safer in winter without the use of studded tires?"

In the face of the continuing trend of increasing highway accidents, summer and winter alike, the proportion of winter accidents occurring on icy roads declined in the first winter following prohibition of the use of studded tires. Considering the prevalence of icy road conditions, this relative decline occurred in all regions of the province, north and south.

Naturally, there is cause for grave concern in the number and continuing increase in accidents where cessation of the use of studded tires cannot have a direct influence. Research and countermeasure efforts are being addressed to this problem. Studies of the circumstances of winter (and summer) accidents on particular highways in specific localized areas and time periods might throw light on a common cause. Equally, past experience of accident causation studies indicated that the results might well be inconclusive because of the nature of the data available, the number of unknowns, and the vast range of interacting variables. Such an investigation would have to take into account not only local variations in road and weather conditions, traffic volumes, and driver-vehicle operating characteristics, but also continuing highway serviceability deficiencies such as the reduction in skid resistance of certain types of pavement surface and the consequences of wheel-track wear rutting caused during the period when studded tires were in use (2, 6).

It would be of interest to know why the physical performance promise of studded tires in reducing stopping distances and improving traction and maneuverability on icy surfaces at temperatures above 0 F is not apparently translated into tangible improvements in safety in actual driving circumstances on icy highways. Although there are physical differences between tests on smooth ice and actual driving in traffic on road ice, seemingly other, nonphysical factors govern. It may prove both difficult and pointless to try to determine these factors.

Whatever the answer on these points may be, there is a real need for winter driving aids that provide both the convenience of increased traction and the assurance of better vehicle control in adverse conditions. If the present level of mobility and favorable accident experience is to be maintained, it would be imprudent to reduce levels of winter maintenance in response to financial or pollution constraints at least until such winter driving aids are available and proved effective.

As pointed out as the final conclusion of the very first report on the studded tire investigation in Ontario, research and development work on alternative winter driving aids is the one of most potential benefit (1). Since then, a promising start has been reported in devising and performance testing alternatives to the conventional studded snow tire (5, 10). Many other ideas and products are in the initial stages of development or evaluation by their manufacturers, and an NCHRP project for evaluation of winter driving traction aids is being developed. It is hoped that the findings of this report will spur such efforts rather than the continuance of postmortems on conventional studded-tire performance or the mitigation of the adverse effects of their use.

ACKNOWLEDGMENTS

The author is indebted to L. Lonero and J. Pierce of the Systems Research Branch, Ministry of Transportation and Communications, for the collation and analysis of the winter accident data drawn on in this report.

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APPENDIX

WINTER ACCIDENT EXPERIENCE IN ONTARIO, 1972-1973

The winter of 1972-73 has been the second since the use of studded tires was prohibited in the province of Ontario. Before-and-after winter accident experience in relation to the prevailing road conditions has already been presented up to the end of the 1971-72 winter, and this brief addition to that report is intended to update the data.

Briefly and generally, the new data appear to amply confirm and extend the earlier conclusion that the proportion of winter accidents occurring on icy or snowpacked and on snowy or slushy roads declined in Ontario following discontinuance of the use of studded tires.

Looking at the accident picture in terms of total collisions and personal injury accidents for the whole province (Table 7), there was an increase in both wet- and dry-road accidents. For example, though the amount of wet road increased by only 1.8 percent from 30 to 31.8 percent, there was an increase in total collisions of 17.7 percent and in personal injuries of 12.1 percent. With regard to snow and slush or icy road conditions, dramatic decreases in collisions and personal injury accidents were experienced ranging from 13.3 to 28.9 percent. In the case of snow and slush conditions, these reductions were of the same order as the reduction in the prevalence of these conditions. However, on icy roads—considering that in the southern and middle tiers icy road conditions increased 50 percent over the previous year—the reduction in accidents is much greater than would have been expected from the prevailing road conditions.

Updated accident information for the winter of 1972-73 on a regional basis is given in Tables 8 and 9 and is shown in Figure 4. Increases in dry- and wet-road accidents occurred in all regions except the north central area where all accidents were down. The decrease in accidents on icy and snowpacked roads prevailed in all regions. On snowy or slushy roads there was a decrease in all regions except the northern area where a minor increase of 5.6 percent, corresponding to 34 additional collisions, occurred.

Road condition data (Table 10) generally confirm the common experience that last winter was a kind one for driving. In the province as a whole there was less snowy or slushy and less icy road conditions than the winter before. Correspondingly, there was an increase in both bare dry and bare wet pavements. These differences prevailed on a regional basis except in the southern and middle tiers of Ontario where there was a significant increase in icy roads.

It is, of course, in these icy circumstances that studded tires have been claimed to provide additional safety. The experiences in Ontario over the past two winters show this is simply not true. Without studded tires, the proportion of winter accidents occurring on icy or snowpacked roads has declined.

In light of the foregoing evidence, no change in policy toward use of studded tires would appear warranted; however, in recognition of the need for winter traction aids, a close watch on new developments is being maintained.

Table 7. Total collisions and personal-injury accidents by road surface condition, 1971-73.

Road Surface Condition	All Highways in Ontario: Total Collisions, Winter 1971-72	Total Collisions, Winter 1972-73	Percentage of Increase, 1972-73 Over 1971-72	Personal-Injury Accidents, Winter 1971-72	Personal-Injury Accidents, Winter 1972-73	Percentage of Increase, 1972-73 Over 1971-72	Provincial Highways Only: Total Collisions, Winter 1971-72	Total Collisions, Winter 1972-73	Percentage of Increase, 1972-73 Over 1971-72
Dry	32,716	35,857	9.6	11,677	11,806	1.1	5,948	6,674	12.2
Wet	29,339	34,532	17.7	9,718	10,898	12.1	3,902	5,312	36.1
Snow and slush	13,958	12,098	-13.3	3,554	2,913	-18.0	3,395	2,923	-13.9
Ice and packed snow	22,324	16,254	-27.2	5,502	3,910	-28.9	5,732	4,457	-22.2
Other	942	734	-22.1	276	241	-12.7	56	54	-3.6
Total	99,279	99,475	0.20	30,727	29,768	-3.1	19,035	19,420	2.0

Figure 4. Percentage of increase or decrease in collisions, 1970-73.

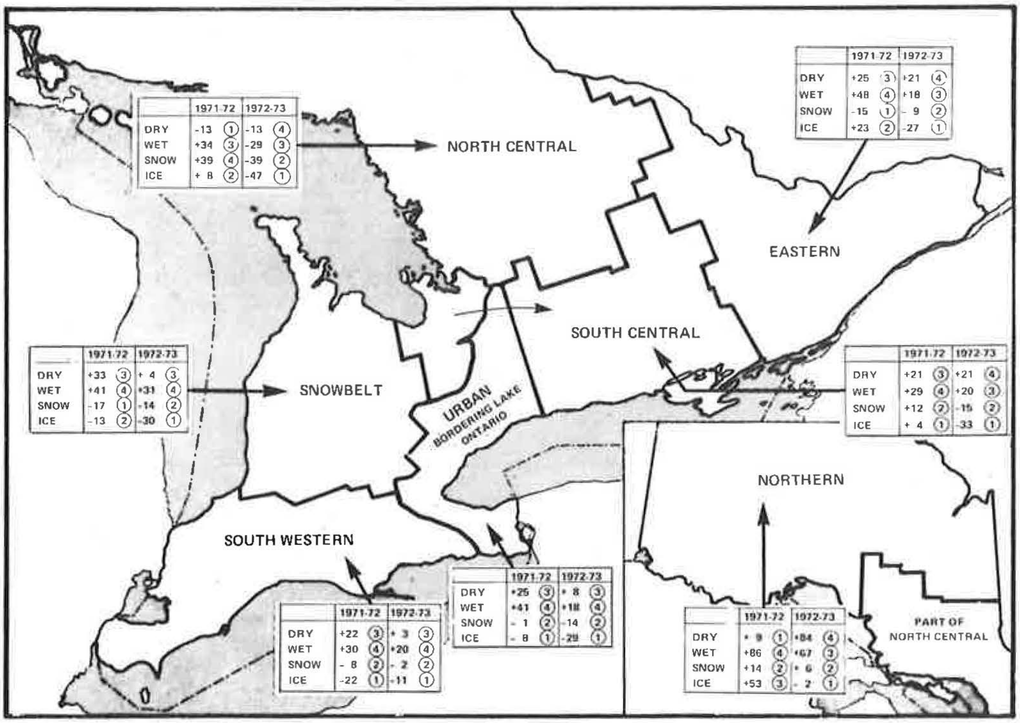

Table 8. Total collisions by road surface condition.

Road Surface Conditions	Southwestern			Snow Belt			Urban Counties Bordering Lake Ontario			South Central		
	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72
	1971-72	1972-73		1971-72	1972-73		1971-72	1972-73		1971-72	1972-73	
Dry	5,350	5,503	2.9	2,222	2,299	3.5	17,522	18,885	7.8	2,295	2,783	21.3
Wet	3,935	4,720	20.0	2,036	2,662	30.7	16,175	19,113	18.2	1,965	2,361	20.2
Snow and slush	1,442	1,410	-2.2	1,343	1,152	-14.2	5,591	4,835	-13.5	1,343	1,142	-15.0
Ice and packed snow	2,428	2,153	-11.3	2,508	1,758	-29.9	6,714	4,767	-29.0	2,834	1,891	-33.3
Other	190	151	-20.5	98	73	-25.5	355	276	-22.3	82	49	-40.2
Total	13,345	13,937	4.4	8,207	7,944	-3.2	46,357	47,876	3.3	8,519	8,226	-3.4

Table 9. Collisions by road surface condition.

Road Surface Condition	Eastern			North Central			Northern		
	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72	Collisions, Winter		Percentage of Increase, 1972-73 Over 1971-72
	1971-72	1972-73		1971-72	1972-73		1971-72	1972-73	
Dry	2,813	3,414	21.4	1,707	1,486	-12.9	807	1,487	84.3
Wet	2,940	3,457	17.6	1,675	1,191	-28.9	613	1,028	67.7
Snow and slush	2,371	2,148	-9.4	1,259	766	-39.2	611	645	5.6
Ice and packed snow	3,510	2,567	-26.9	2,485	1,320	-46.9	1,843	1,798	-2.4
Other	74	65	-12.2	104	58	-44.2	39	62	59.0
Total	11,708	11,651	-0.49	7,230	4,821	-33.3	3,913	5,020	28.3

Table 10. Winter road conditions.

Area	Provincial Highways, Total Miles	Winter Road Conditions (percent)											
		Bare Dry			Bare Wet			Snow or Slush			Icy		
		1970-71	1971-72	1972-73	1970-71	1971-72	1972-73	1970-71	1971-72	1972-73	1970-71	1971-72	1972-73
Southern tier	6,547	48.9	56.1	56.7	33.1	30.3	32.1	17.2	12.6	9.5	0.8	1.0	1.7
Middle tier	3,563	42.3	31.0	37.8	26.7	33.4	35.4	30.2	34.0	24.4	0.8	1.6	2.4
Northern tier	4,882	27.0	27.7	37.5	30.0	27.3	27.5	40.0	39.0	30.9	3.0	6.0	3.4
Total	14,992	39.4	40.6	44.1	29.9	30.0	31.8	29.2	26.6	21.6	1.5	2.8	2.5

BRAKES AND SKID RESISTANCE

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This paper gives a general review of passenger car antilock braking systems, describes their manner of operation, and discusses their effects on vehicle braking performance and stability. Particular emphasis is placed on the influence of antilock brakes on vehicle stability and stopping performance in straight-ahead braking and cornering situations over a broad range of speeds and pavement conditions. Antilock system options and the relative merits of two- and four-wheel systems are discussed along with possible future prospects.

•THE forces that govern the motion of the automobile over the road are generated at the tire contact patches. The magnitudes of these forces are functions of road surface condition, vehicle weight, and input variables from the three potential magnitudes of forces at the tire-road interface and are determined by a traction coefficient, or skid number, μ (Fig. 1) (1).

Several types of braking devices, intended to improve braking performance when traction coefficients are low, have been proposed and tested during the past 20 years. These devices have, in general, been designed to adjust the front-to-rear or side-to-side braking loads, as required, for nonuniform pavement conditions or varied vehicle load distribution. Devices such as load-sensing hydraulic proportioning valves and brake torque-limiting schemes have been tried with varying degrees of success.

Foremost among the more recent developments is the antiskid or antilock brake system. This paper reviews existing antilock systems, their manner of operation, and their effects on vehicle performance.

BASIS OF OPERATION

The antilock brake system is designed to prevent wheel lock and the consequent possible loss of control and to make the most efficient use of the available traction to stop the vehicle. One example is the Ford Sure-Track system (Fig. 2). This package consists of a drive line speed sensor, a solid-state control module, and a vacuum-powered hydraulic actuator. Other available systems on U. S. passenger cars are similar, with variations in the number of axles or wheels being controlled. The functions of these systems are to detect impending wheel lock through information supplied by the speed sensor to the control module and to modulate braking line pressure to prevent wheel lock by means of the hydraulic actuator responding to commands from the control module. The resulting modulation is similar to the pumping action that a skilled driver would execute manually in a panic braking situation.

The potential of these systems is clarified by examining the characteristic tire torque capacity versus wheel slip (or μ-slip) curve (Fig. 3) (2). The braking capacity of a tire on some types of surfaces is less at 100 percent slip, or wheel lock, than at some lower value of slip. If the brakes are applied and released cyclically in a manner that will maintain braking torque at or near its maximum and wheel slip at less than 100 percent, lateral stability is more likely to be maintained. In addition, with a higher average braking torque, stopping distance can be reduced to less than the locked-wheel stopping distance.

Figure 4 (2) shows the capacity of a tire to resist side loads at various values of wheel slip. The advantage of keeping μ-slip at a low value is clear. In the locked-wheel condition, the ability to react to side loads has vanished. The effect of locked

Figure 1. Concept of traction envelope.

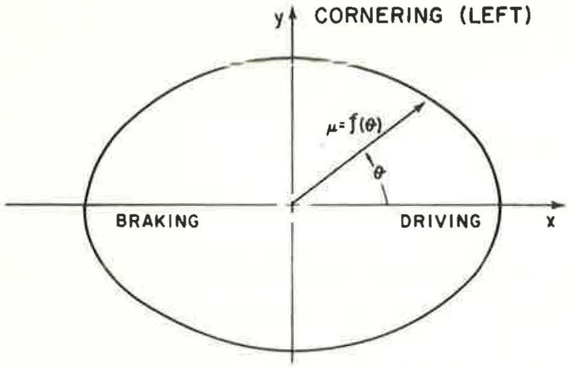


Figure 2. Sure-Track system components.

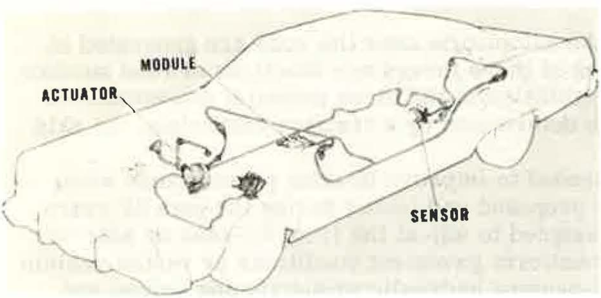


Figure 3. Representative tire-brake force.

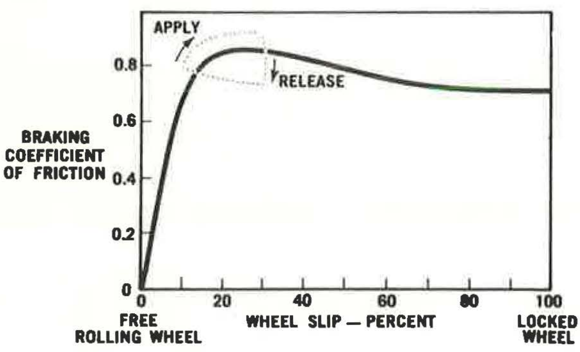
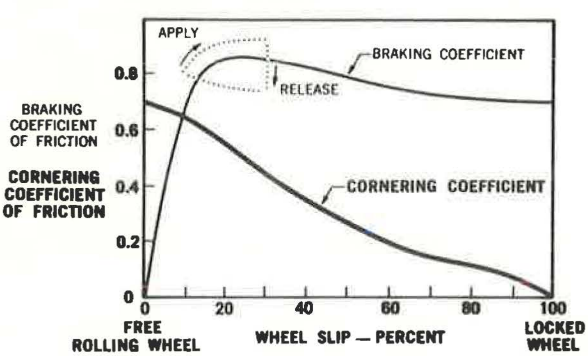


Figure 4. Representative tire-brake and cornering forces.



wheels is different for front and rear wheels. Locked front wheels cannot develop cornering traction. This means that the car will not respond to steering wheel movements and will tend to "mush" in a straight-ahead path of travel, unable to negotiate a curve in the road. On the other hand, locked rear wheels during a cornering maneuver can result in rear-end breakaway with the car tending to move either into an oncoming traffic lane or off the roadway, depending on the initial direction of travel. These critical consequences are the primary justification for antilock brake systems. The reduction of stopping distance is an additional benefit to be realized on certain types of pavement surfaces but not on others, as will be seen.

PERFORMANCE VARIABLES

The performance of an antilock system varies with pavement conditions and also with the speed of the vehicle. Figure 5 (2) shows steady speed μ-slip curves for ice at 20 and 30 mph. The 30-mph curve shows a peak to locked torque ratio greater than one, and it appears that some improvement in stopping distance might be expected with an antilock system. The 20-mph curve, however, shows maximum friction with locked wheels and therefore no prospect of shortened stopping distance. Ice-covered pavements in general show a wide variation in μ-slip characteristics with speed and also with ice temperature. The presence of snow over ice further confounds the consistency of stopping performance on ice. As a practical matter, characteristics of tire-pavement surface combinations for ice and other materials vary enough that, from the standpoint of stopping distance, the performance of the antilock system can be better than, the same as, or less than the performance of the vehicle with locked wheels.

Antilock systems generally perform best on surfaces that exhibit a high peak to locked wheel torque ratio, as on wet asphaltic concrete (Fig. 6) (3).

When braking torque is maximum at the locked-wheel condition, stopping distance will be longer with the antilock system because it will prevent the wheels from locking. In the absence of a distinct peak at low slip in the μ-slip characteristic curve, no improvement over locked-wheel stopping distance can be expected, and some deterioration of performance is likely.

Table 1 (4) shows that four-wheel antilock performance, as compared to locked wheels, can effect as much as 41 percent shortening of stopping distance on wet Jennite or can appreciably lengthen the stopping distance, as on gravel. The performance on dry concrete was not impressive with a 3.8 percent increase, but it improved to 11.5 percent shortening on wet concrete. The 11 percent improvement on snow and ice is an average for various environmental conditions. Gravel is one of those surfaces where peak friction occurs at 100 percent slip; therefore, the antilock stopping distance is greater than that for locked wheels.

A common condition on winter highways is a patch or narrow strip of ice or snow adjacent to a strip of dry pavement. At a speed of 25 mph and for surface coefficients of 0.85 on the right and 0.25 on the left, split-friction performance is as follows (5):

System	Yaw Angle (deg)
Rear-wheel antilock	
Minimum	5
Maximum	30
Average	17.8
Conventional (out of control, all stops)	>90

These data were observed on a vehicle with a rear-wheel antilock system. In executing the stops, the front wheels were locked while the antilock system prevented rear-wheel lock. With the right-side wheels on a 0.85-μ surface and the left-side wheels on a 0.25-μ surface, the vehicle deviated an average of about 18 deg from its intended path during panic stops, compared to complete loss of control with antilock system turned off.

Figures 7 and 8 (5) show the results of similar tests on pavements with uniform coefficients. On wet asphalt from 60 mph with the rear-wheel antilock system operating,

Figure 5. Characteristic tire-brake force (ice at 30 F).

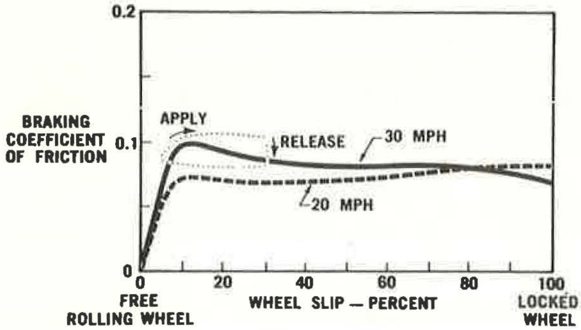


Figure 6. Characteristic tire-brake force (asphaltic concrete covered with 0.04 in. of water).

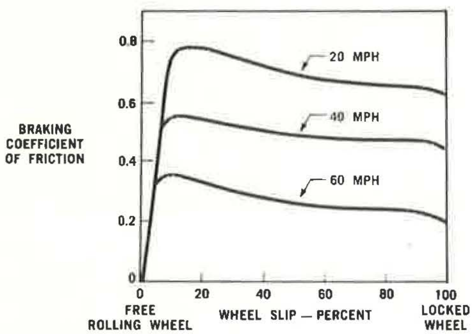
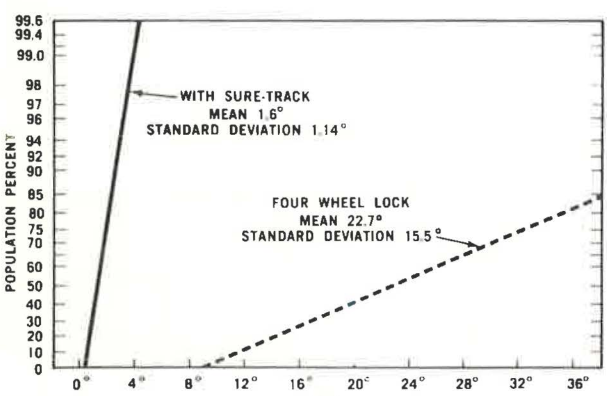


Table 1. Performance of four-wheel antilock brake system.

Speed (mph)	Condition	Stopping Distance (ft) Locked Wheels	Stopping Distance (ft) Four-Wheel Antilock	Percentage of Improvement
60	Dry concrete	159	165	-3.8
60	Wet concrete	200	177	+11.5
30	Gravel	52	65	-25.0
45	Wet Jennite	315	186	+41.0
45	Snow and ice	255	227	+11.0

Figure 7. Improved yaw control (stopping at 60 mph on water-covered asphalt).



the mean yaw angle was 1.6 deg compared to 22.7 deg for the same vehicle with the antilock system inoperative and all four wheels locked. On a hydrolube surface at 20 mph with 0.05 μ (Fig. 8), mean yaw angle was 6.8 deg with antilock and 59 deg without. On an overall basis the antilock system provides appreciable yaw reduction.

Judging from the μ-slip curves, studded snow tires are not likely to shorten antilock stopping distance on ice because there is no peak at low slip (Fig. 9) (3). Plain snow tires exhibit a slight peak, and brake modulation at low slip could theoretically effect a reduction in stopping distance. Snow and studded snow tires have not yet been adequately investigated as to their effects on antilock performance, however, and conclusions are difficult to reach. In any case, the antilock system would tend to prevent loss of control.

SYSTEM OPTIONS

Antilock systems now available to the public are similar in the basic hardware employed. A choice exists, however, as to which wheel combinations are selected for control. The ultimate system might have individual control on each of the four wheels. Figure 10 shows a system with independent control on each of the front wheels and independent wheel speed sensing on the rear wheels, with the rear wheels sharing a common actuator. In this system, each front wheel's braking load is determined by the coefficient of friction at each tire-pavement interface. In the rear, however, both brakes are modulated alike. When wheels are paired in this manner, a logic circuit may be built into the control module to select the wheel that is on the surface having the lowest coefficient as the control feedback. In this way, the braking at the rear wheels is governed by the wheel that is nearest to skidding.

The four-wheel system versus the two-wheel system is a subject that could be debated at length. The most obvious advantage of four-wheel control is the ability to steer the vehicle during panic braking. The importance of good directional control as compared to maintaining a straight stopping path is substantiated in accident studies that show that lack of directional control is a more frequently observed pre-impact behavior than lack of stopping ability (6). Against the advantage of directional control must be weighed the increased cost, complexity, and reduced reliability of the four-wheel system.

From the standpoint of stopping ability, it would appear that the four-wheel system should perform better than the two-wheel system, particularly because the two front wheels normally carry the largest share of the braking load, and on some surfaces this is the case. In other instances, however, the expected improvement is not realized. On gravel, for example, locked front wheels may plow aside the looser material and allow the rear-wheel system to operate on a firmer surface than would be possible with the front wheels rotating. On wet pavements, the locked front wheel has a more effective wiping action than the rotating wheel so that the rear wheel, following in its track, may be operating on a thinner water film or even on virtually dry pavement. The locked front wheel thus can contribute to the efficiency of the two-wheel system in some instances.

FUTURE PROSPECTS

Antilock systems will undoubtedly undergo further refinement. Improvements probably can be made in both the control systems and the conventional brake components that they control. Reduction of system response time and use of continuous rather than cyclic or on-off control appear to be important goals for the future, both in passenger cars and in trucks, where the application can be much more complex.

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Figure 8. Improved yaw control (stopping at 20 mph on hydrolube surface).

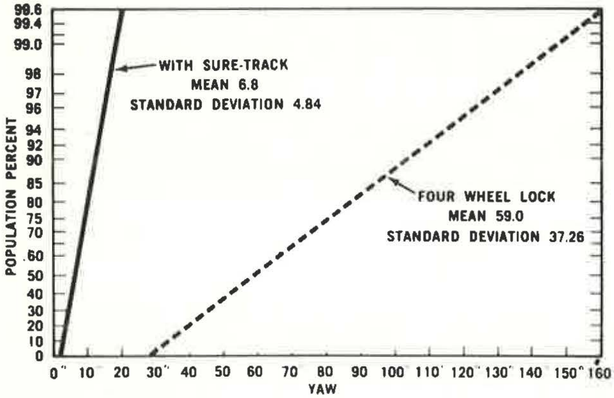


Figure 9. Characteristic tire-brake force (ice at 25 F and speed of 20 mph).

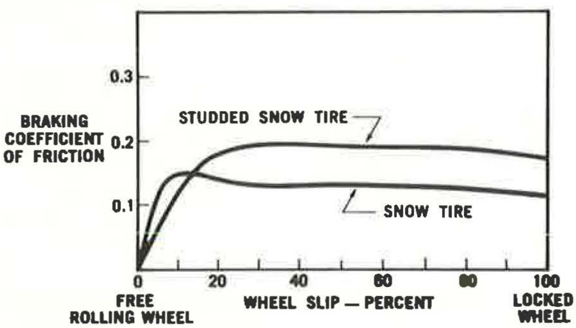
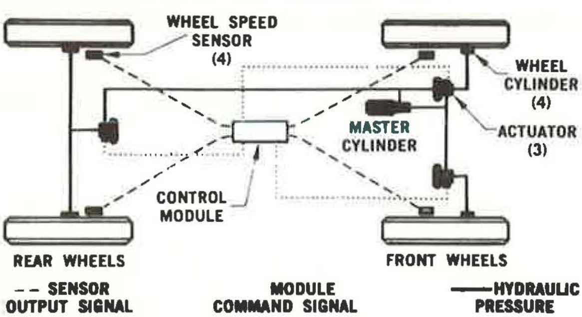


Figure 10. Elements of antilock brake system.



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LIMITED-SLIP DIFFERENTIAL AS A WINTER DRIVING TRACTION AID

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The conventional differential divides the driving force equally to both rear wheels. The total driving force is limited by the wheel that has the least amount of traction. Therefore, if one wheel is on ice, snow, or mud, it will spin, and the driving force is lost. Limited-slip differentials direct more of the driving force to the wheel with better traction, thus improving the mobility of the vehicle. Limited-slip differentials and studded tires are complementary to one another. Studded tires increase the amount of traction available, and limited-slip differentials enable vehicles to use more of the traction that is available. The performance of the limited-slip differential is generally independent of the driver. It does its job automatically so that no special action is required except reasonable care not to abuse it.

•A CONVENTIONAL automotive differential allows the driving wheels to rotate at different speeds while dividing the driving torque equally between them. This function is ordinarily desirable and satisfactory. However, the total driving torque can be no more than double the torque at the wheel having the least traction. When traction conditions are not the same for both driving wheels, a portion of the available traction cannot be used.

Under certain common driving conditions, the conventional differential imposes serious limitations on mobility. If one wheel is on ice, snow, or mud, the wheel will spin, and the driving force is lost. The potential total traction of the vehicle is seriously reduced because of the equal torque balance of the differential. The wheel that is on the more slippery surface can develop only a small amount of torque and will not allow the other wheel to utilize its more favorable traction. The maximum driving force is limited to twice the traction force of the slipping wheel.

OPERATION

The limited-slip differential was conceived to improve motor vehicle mobility in situations where the traction conditions are not the same for both driving wheels. More driving force is directed to the wheel having the better traction to improve the ability of the vehicle to pull out of mud or snow. Even though one driving wheel may be on a low friction surface, the other wheel can develop additional torque before wheel spin will occur.

In a typical friction-type limited-slip differential, the added traction is achieved by use of clutch assemblies mounted between the side gears and the differential case. These clutches resist differential motion and tend to hold the side gear stationary relative to the differential case. Because of this resisting clutch torque, the differential will not differentiate until external torques exceed the capacity of the clutch, at which time the clutch will begin to slip.

The clutch application force comes from both a preload spring or spring pack and side-gear separation loads. Because the separation load of the gear teeth is a function of torque, the clutch capacity is also a function of torque. If no preload mechanism were used and the unit had to depend solely on side-gear separation loads for clutch application force, it would provide very little advantage over the conventional differential when one wheel is on wet ice. However, the preloading device provides clutch application force even when one driving wheel of the vehicle is off the ground.

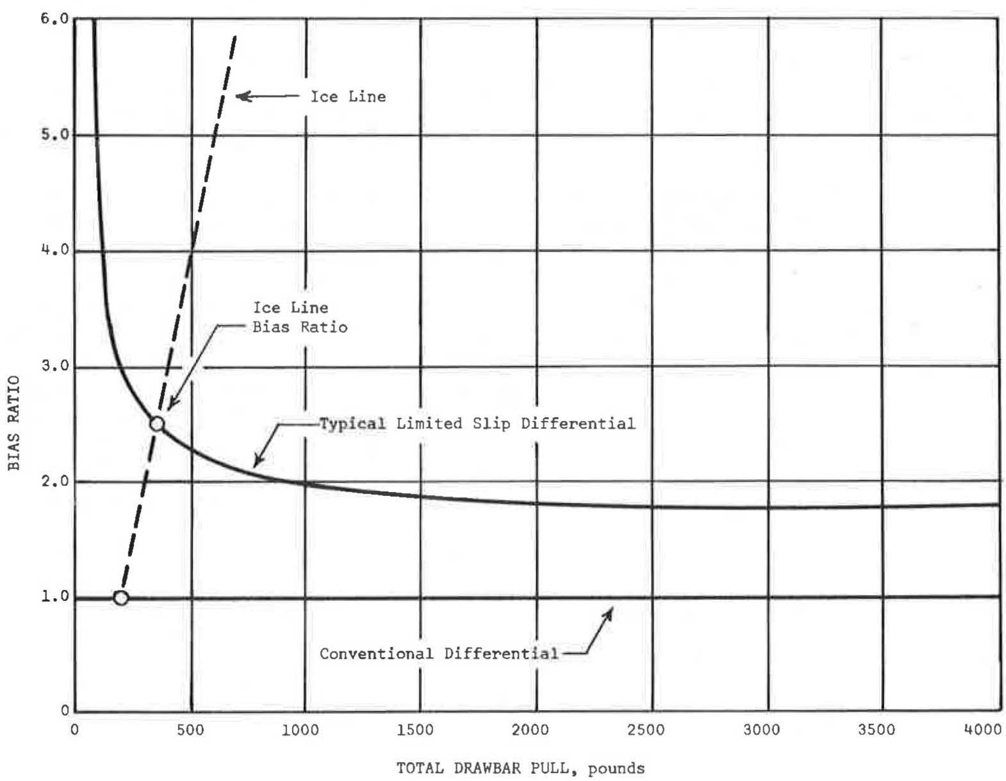
EFFECTIVENESS

The performance of a limited-slip differential is generally evaluated in terms of the ratio of the torque that can be developed by the high traction wheel to that that is developed by the low traction wheel (1). This ratio is called the "bias ratio" and is expressed as follows: Bias ratio = static wheel torque/slipping wheel torque. The slipping wheel has the unfavorable traction condition such as ice, snow, or mud, whereas the static wheel has the better traction condition and therefore the greater torque capability.

The bias ratio is a rating of the maximum effectiveness of a differential in improving the traction capability of the vehicle. It is measured at the point at which the unit begins to differentiate, that is, when the clutch begins to slip and the low traction wheel starts to spin. A larger bias ratio indicates greater traction capability of the vehicle, whereas a smaller ratio indicates lesser traction capability. The conventional differential has a bias ratio of one, and it is always constant. The limited-slip differential has a bias ratio greater than one, and it varies with the torque output.

Figure 1 shows a typical bias ratio curve. Normally, the most severe operating condition occurs when one wheel is on wet ice. This is represented by one point on the bias curve and is generally used to compare the effectiveness of two similar units. This point is designated as the "ice line bias ratio." The ice line is the broken line in the figure, and it represents a skid number of 10 for the slipping wheel. This results in a slipping wheel torque of about 100 ft-lb for an average-weight car having a drive axle weight of approximately 2,000 lb. The ice line bias ratio is 2.5 for the particular curve

Figure 1. Bias ratio curve for limited-slip and conventional differentials.



shown, and the vehicle produces a total drawbar pull of approximately 350 lb (100 lb from the low traction wheel plus 250 lb from the higher traction wheel).

The shape of the bias ratio curve can be changed by changing either the clutch capacity or the spring preload force. Increasing the clutch capacity results in an increased bias ratio throughout the complete torque range, whereas a reduction in clutch capacity lowers the curve across the total range (1). Similarly, the bias ratio can be increased by added spring preload. Because the total clutch application load is the sum of the spring preload and the side-gear separation load, an increase of the spring force is more effective at the lower torque levels.

At first, one might expect that the bias ratio should be as high as possible to maximize traction capabilities. This, however, is not practical. The design of the limited-slip differential must be optimized to satisfy traction requirements and yet result in a satisfactory operating vehicle during all maneuvers.

If the bias ratio is too high, the differential assembly will overly resist differentiation and will lock up when making a turn. If it does not slip while going around a turn, the vehicle will shudder because of the difference in distance traveled by the inside and outside wheels. The vibration is caused by scrubbing of the tires on the pavement, which, in turn, causes the complete drive line to go into a resonant vibration. The shudder is more pronounced during a hard acceleration. It also is more severe when the pavement is slightly damp, reducing the torque level at which the tires will slip. Obviously, for overall satisfaction, the bias ratio must be tuned to match the overall requirements of the vehicle.

Although numerous variations in the design of a limited-slip differential can be made to alter certain characteristics under specific conditions, each change also introduces new limitations along with the improvements. It becomes apparent, therefore, that the characteristics designed into a unit must be a compromise to best satisfy all expected driving conditions.

ADVANTAGES

The primary performance goal of a limited-slip differential is to improve the traction of the vehicle during adverse traction conditions. The advantage offered on ice- and snow-covered roads is fairly obvious. It also provides improved mobility for motor vehicle operators who encounter adverse conditions when they leave the hard-surfaced roads to travel into camping areas or other off-road locations. For boat owners, it frequently affords that little bit of extra traction needed to pull a trailer from a boat launching point.

The driver of a high-performance vehicle is at a distinct disadvantage when trying to utilize the maximum capability of his vehicle if it is not equipped with a torque biasing differential. The effect of the limited-slip differential can be seen at the drag strip where on acceleration both rear wheels leave an even strip of rubber. Generally, a car with a conventional axle and a stock suspension will have the right rear wheel smoking while the left is barely moving. A similar condition occurs during hard acceleration on sweeping turns, when the centrifugal force tends to unload the inner driving wheel.

Another benefit derived from a limited-slip differential is a reduction in shock loading to the drive line due to an airborne wheel returning to the ground, as experienced on a bumpy road surface. With a conventional axle, the wheel in the air tends to accelerate and induces a shock load on the drive train on returning to the road surface. A limited-slip differential tends to restrict the acceleration and dampens the impact on return, thus reducing the shock load.

It is significant that limited-slip differentials and studded tires both provide improved overall traction capabilities for the vehicle on which they are installed, but neither can replace the other. Studded tires increase the amount of traction available on snow- or ice-covered surfaces, whereas limited-slip differentials enable vehicles to utilize more of the traction that is available regardless of surface condition. It follows, therefore, that a limited-slip differential and studded tires used together offer greater improvement in vehicular mobility than either one used separately.

LIMITATIONS

Although the manufacturers of limited-slip differentials attempt to optimize their designs, they are compromises, and certain inherent limitations must be recognized.

Certain caution must be exercised when accelerating with both rear wheels on a very slippery surface. If too much throttle is applied, particularly when cornering, lateral stability will be lost, and the rear of the car will go into a slide. This occurs when both wheels spin together without differentiation (i.e., the clutch capacity exceeds the road's ability to induce differentiation).

Under other road surface conditions, the differential may not have enough capacity to develop the traction required to move a vehicle. If one wheel should start to spin independently of the other, the capability of the unit has been exceeded. Any further spinning will only result in possible permanent damage to the unit.

Other precautions that are not related to the operation of the vehicle on slippery roads must also be observed.

A vehicle equipped with a limited-slip differential should never be run in gear with only one driving wheel jacked up. If the unit is operating properly, the vehicle will run off the jack.

Dynamic balancing of rear wheels while still on the car should be avoided. Independent spinning of one wheel can ruin the friction device.

Car washes that clean the tires by inducing independent spinning of the wheels should be avoided for the same reason.

The lubricant used in limited-slip differentials is a most crucial item. It must maintain an acceptable ratio between the static and dynamic coefficients of friction within the clutch to prevent noise. Only the lubricant specified by the manufacturer should be used when adding to or refilling the rear-axle sump.

DEMAND

In spite of the particular traction advantages offered by the limited-slip differential, it has steadily declined in popularity as a factory-installed option on domestic passenger cars over the past 5 years. The percentage of domestic passenger car production and the number of units equipped with limited-slip differentials for each of 5 model years (2) are as follows:

Factor	1968	1969	1970	1971	1972
Percentage of car production	10.8	9.2	8.3	5.5	4.4
Number of units	874,895	758,527	656,537	416,381	392,936

The downward trend in owner demand for limited-slip differentials on new automobiles may be partly due to the special cautions that must be observed. However, the decline in their use has occurred concurrently with an increase in use of studded tires. This leads to speculation that new car purchasers may have elected to forgo the special advantages of the limited-slip differential in favor of studded tires, perhaps not realizing that the two are complementary rather than being substitutes for one another.

Inasmuch as several states have taken action to outlaw use of studded tires or are seriously considering such action, it would seem appropriate that a renewed demand for limited-slip differentials should appear. Even though a driver must observe a few special precautions in the operation and care of his vehicle equipped with a limited-slip differential, the improved traction capabilities outweigh any operational inconveniences.

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THE ROLE OF TREAD DESIGN IN SKID RESISTANCE UNDER WINTER DRIVING CONDITIONS

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•SO-CALLED winter tires are a relatively recent nomenclature for tires that appear to be more aggressive than winter is slippery. In the past, this emphasis on aggression produced tires that were uniquely noisy, unstable, rough riding, and unsuitable for any mode of motion except excavation. These were designs that bit into the surface in hope of finding dry, hard ground underneath. As tire technology improved, the "mud-and-snow" tire was permitted to remold and grip the surface rather than trench it.

The problem with evolution is that, although progress is certain, it is equally resistant to instant improvement. Hence, the public concept of a good winter tire today still requires that the tire tread be designed to look like a trenching tool. In spite of this constraint, winter tire designs that balance lug-edge pressure for surface penetration with a sufficient contact patch to minimize pressure melt and void ratio with lug shearing area to stabilize rather than displace the snow are measurably more effective in winter driving environments than a ribbed highway design.

However, what the tire tread design will do as compared with what it is supposed to do is best explained by quantifications generated in a two-season winter test program that we conducted recently.

Under winter test conditions that were categorized as virgin snow, soft- and hard-packed snow, and dry and wet ice-covered roads, tires were evaluated for acceleration traction and slip velocity, braking traction and slip velocity, and lateral traction. A tire whose tread design appeared to be classically "winter" rated 84, whereas a tire whose tread design was classically "highway" rated 109 in terms of the performance of a neutral mud-and-snow winter control tire rated at 100.

This particular program, because of its extensive nature, permitted us to draw the following conclusions:

1. There is no justification for the designation of a tire as a mud-and-snow tire solely on the classic appearance of its tread design without regard for its construction or compounding.
2. No single measure of winter tire performance is meaningful. High relative values in one category of winter tire performance are not necessarily associated with high values in another. Tire wear introduces further changes in relative ranking, not necessarily as a function of tread depth but as a function of wear pattern.
3. Because of the very real variability of winter conditions, any attempt to reduce this variability by reducing the quantity of testable environments results in a reduction in the significance of ranking relative winter tire performance based on these tests.
4. Any attempt to influence the interactive tractive potential of paired driving tires on winter surfaces by the use of a locking differential to force paired drive tires to rotate at equal rpm regardless of differences in rolling radii eliminates the possibility of measuring the relative influence of tread design, carcass construction, and tread compounding on tire traction. It is essential in measuring tire traction in a full-scale world on a full-scale vehicle that each driving tire achieve its peak tractive effort at essentially the same time rather than at the same rpm. It is, therefore, necessary that the test surfaces under each driving tire have substantially equal resistance values and that the loads carried by each driving tire be equally consistent. No locking differential can equalize the traction of paired drive tires; it can only reduce the tractive force differential between significantly dissimilar road resistance values by forcing the

Figure 1. Characteristic winter tire acceleration.

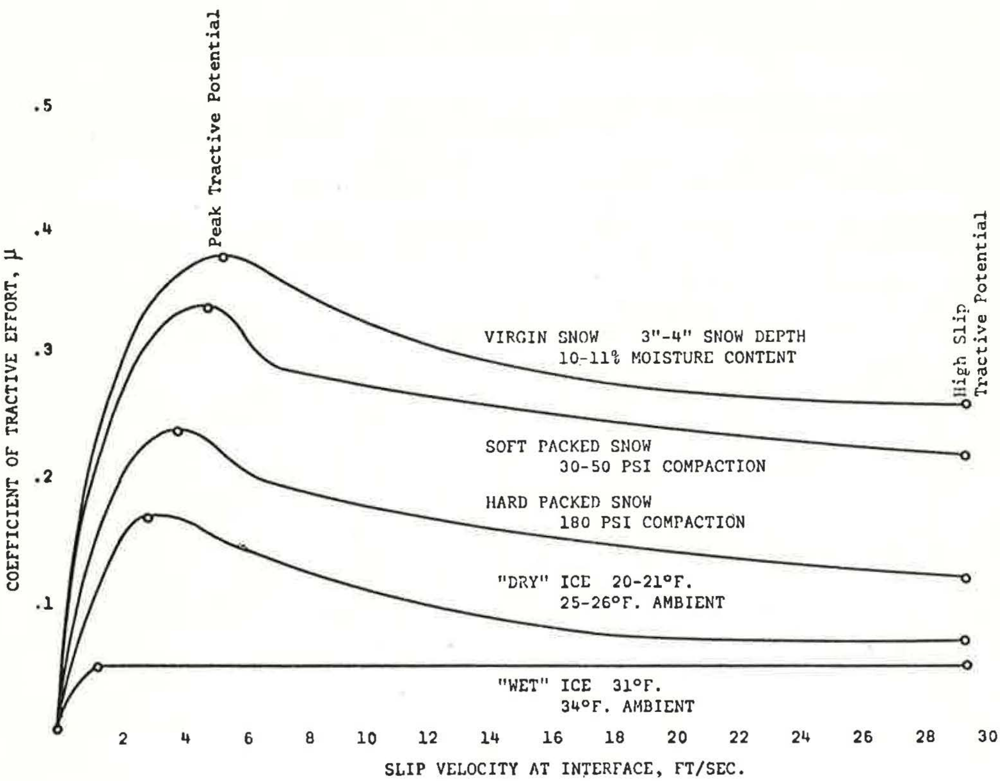
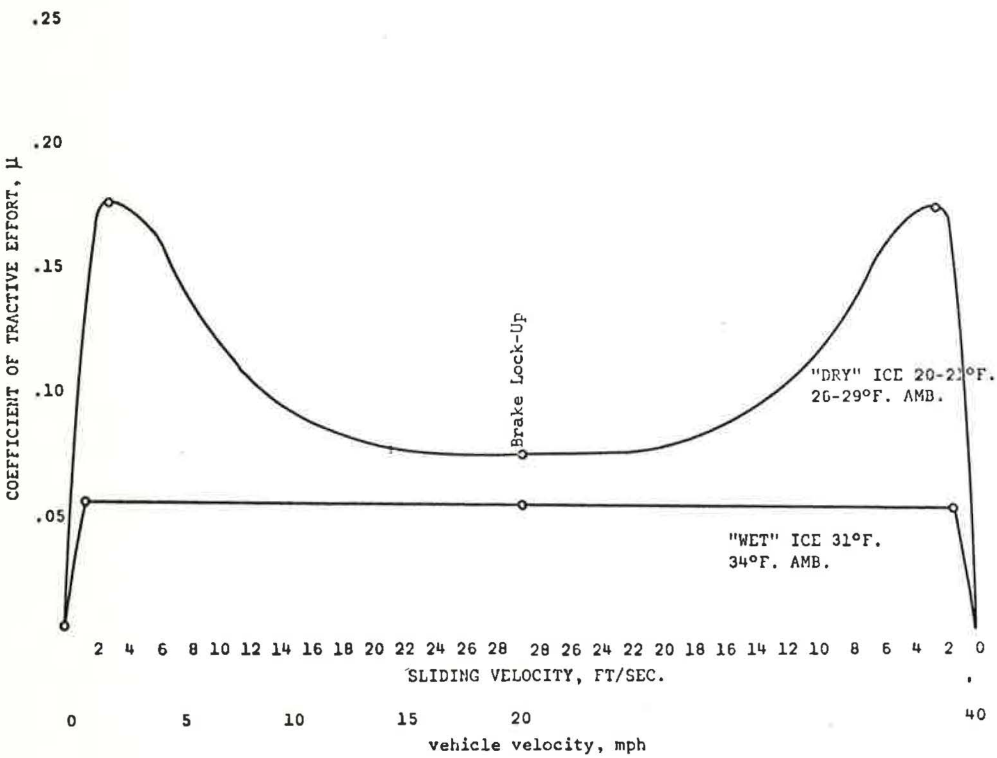


Figure 2. Characteristic winter tire braking.



tire on the surface with the highest tractive resistance to drag the other tire along. These reactions can be clearly identified if individual torque meters are applied to each driving wheel.

5. With proper measurement techniques any practical separation among tire designs that have acceptable winter performance from those that do not will probably take the form of weighted numbers that express winter performance as some multiple of the weighted performance numbers earned by a standard control tire.

In summary, the role of tread design in skid resistance under winter driving conditions is considerable, providing the tire is not operated at differential interface velocities that exceed the peak tractive effort of the tire balance by the maximum tractive resistance of the material on which the tire is driven. In simple terms, the tire must continue to turn if the tread design is to be meaningful in skid resistance. Figure 1 shows the relative tractive performance of the same paired drive tires over a range of specific winter environments. Note that on wet ice no change in tractive effort occurs as a result of increased wheel slip velocity. These measured values are pure sliding friction values of a wet tire on wet ice without the additive coupling of elastic deformation of the contact interface between the tire and the ice because of the thin film of water that separates them. Figure 2 shows that tire traction on dry ice is dependent on sliding velocity rather than on vehicle speed. It clearly identifies the critical loss of tractive effort because sliding velocity increases after peak tractive effort has been achieved. On wet ice, this tire's traction is again independent of sliding velocity. It shows that the characteristic traction-sliding velocity relation is independent of driving mode, whether the tire is accelerating or decelerating.

If we cannot control tire lock-up in winter driving, elements must be added to the tire that spike the road surface and lock the tire to the ground by mechanical means rather than the more efficient method of harnessing the peak traction values available through elastic and plastic deformation of the contact patch interface.

SAFER WINTER TIRES USING OIL-EXTENDED NATURAL RUBBER

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The grip of oil-extended natural rubber winter tires made of both cross-ply and radial-ply construction has been assessed during three separate trials in Scandinavia. The tests have been carried out on ice and hard-packed snow at temperatures as low as -15 C. The variability of ice makes it difficult to obtain reliable data unless a large number of measurements are made on several different occasions. It has not been possible to correlate the variability of the results with the more obvious climatological factors such as temperature or amount of sunshine. The results presented here show that oil-extended natural rubber has better grip than conventional high hysteresis synthetic tire treads and may even perform better than studded conventional tires on some occasions. The use of oil-extended natural rubber winter tire treads would make a significant contribution to road safety under winter conditions.

•TIRES have to perform satisfactorily under a wide variety of conditions; therefore it is not usually possible to improve one feature without changing other characteristics. Winter tires are no exception. Their primary purpose is to give better grip than ordinary tires under winter conditions. However, performance on roads not covered with snow and ice must also be satisfactory, and this restricts the choice of compounds. The formulations given here have better wear properties under low ambient temperature conditions and have equal grip in the wet when compared with conventional synthetic tires.

Tire manufacturers have concentrated their efforts to improve winter tires on changes in tread design to give better grip on soft snow and have paid relatively little attention to the type of tread compound. In practice, the majority of tire manufacturers use the same compound for the treads of winter tires and ordinary tires. The object of this paper is to show that natural rubber and, in particular, oil-extended natural rubber treads will make better and safer winter tires.

Two methods are available for producing an oil-extended natural rubber (OENR) compound. Either the oil and rubber are mixed in an internal mixer during the normal factory processing, or an oil-extended masterbatch can be used. The final product is the same whichever method is chosen. Mixing schedules where up to one-third of the rubber is replaced by oil have been published (1) for factory-sized mixers.

One of the most important properties of a winter tire is its grip on ice and hard-packed snow. A convenient way of measuring the skid resistance in the laboratory is by means of the Road Research Laboratory portable skid tester (2). Results for typical compounds are shown in Figure 1. Above 0 C on wet concrete, the conventional tread rubber, which is a blend of oil-extended styrene butadiene rubber and butadiene rubber (OESBR-BR), has higher friction than natural rubber; however, below 0 C on ice, the position is reversed and natural rubber is better. The OENR compound is a useful compromise having good skid resistance on both surfaces.

FULL-SCALE TIRE TRIALS ON SNOW AND ICE

Results such as those shown in Figure 1 have led to three full-scale trials during the past few years using winter tires with natural rubber treads. The first trial was carried out in Sweden on a road surface covered with hard-packed snow (3). The tread compounds are given in Table 1 (compounds 1 through 6) and were used to retread tires of cross-ply construction (size 6.40 × 13). The tests were carried out using a two-wheeled trailer originally designed for wear tests (4).

The trailer and car were first accelerated to a constant speed, the car was allowed to free wheel, and then the trailer brakes were applied rapidly using compressed air. The distance the car and trailer traveled before stopping was recorded automatically. The deceleration of the car and the force at the towing point on the car were also recorded. The friction coefficient was calculated from these measurements, and the results in Table 2 are given in the form of ratings relative to a conventional tire tread compound (OESBR-BR) that has been arbitrarily given a rating of 100.

In all cases, the natural rubber-based compounds are better than the SBR-based compounds. The addition of BR tends to reduce the friction coefficient, whereas studs improve the friction. However, the advantage of OENR over OESBR is still apparent with the studded tires.

A second trial was also carried out in Sweden (5) with retreaded cross-ply tires. The compounds used are given in Table 1 (compounds 7 through 11), and the tests were carried out on smooth ice, which was a frozen lake surface, or on a hard-packed snow-covered road surface. As before, skid tests were carried out using the test trailer, and the results obtained on lake ice are given in Table 3. The unstudded tires show the advantages of the natural rubber-based compounds over SBR-based compounds. The differences between the studded tires are not significant at the 10 percent level, whereas the differences between the unstudded tires are significant at the same level. The results on hard-packed snow are given in Table 4. On this surface, there is no significant difference between the unstudded compounds, but there are differences in favor of OENR that are statistically significant for the studded tires.

As well as the tests just described, circle tests using the car alone were also carried out. A circle 33 meters in diameter was marked out on the lake ice, and the car was driven around it as fast as possible using each set of tires in turn. The results are given in Table 5. Under these conditions, the superiority of OENR in both the studded and unstudded tires is apparent.

These two trials illustrate the difficulty of characterizing the frictional behavior of tires on ice and hard-packed snow. The results show that, under some conditions, there are no differences between compounds, whereas under other conditions the OENR compounds are significantly better than conventional OESBR-BR compounds.

The current trend in tire design is toward radial-ply tires, and a third trial was carried out during the early part of 1971 in Norway on radial-ply winter tires (size 185 × 15) (6). It was apparent from the previous trials that a more comprehensive trial was required with a large number of repetitions so that the significance of the results could be improved.

The compounds tested are given in Table 1 (compounds 12 through 14), and the tests were again carried out using the car and test trailer as before. In addition to the instruments described previously, a side-force measuring device had been added to the trailer, and the compressed air system had been modified to allow the brakes to be applied progressively as well as instantaneously. The side force is a measure of the friction coefficient under cornering conditions. The magnitude of the side force depends on the slip angle, the tire construction, and the friction coefficient. Because all the tires are of the same construction and the angle of the wheels is constant, the side force is a measure of the friction coefficient measured while the wheel is rotating. It is a more reliable method than circle tests with the car because the skill of the driver is not brought into play during the measurements.

The first part of the trial was concerned with evaluating different test methods, and for this purpose only two compounds, OENR and OESBR-BR, were used. There was no evidence that one test method was more discriminating than any other, and the results in individual comparisons varied from no effect on some occasions to a rating of 144 for OENR and an OESBR-BR rating of 100 on other occasions. The averages of all the results obtained are given in Table 6 where it can be seen that OENR is 15 percent better than OESBR-BR. This superiority is reflected in the results on studded tires as well.

Table 1. Compounds used in full-scale tire trials.

Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Natural rubber[a]	67	—	53.6	—	40.2	—	100	80	70	56	—	75	60	—
SBR 1712	—	92	—	73.8	—	55.2	—	—	—	—	77	—	—	72.5
BR[b]	—	—	13.4	13.4	26.8	26.8	—	—	—	14	14	—	15	22.5
HAF black	55	55	55	55	55	55	50	55	55	55	55	—	—	—
ISAF black	—	—	—	—	—	—	—	—	—	—	—	55	55	55
Aromatic oil[c]	36	11	36	15.9	36	21	5	21.6	32.6	32.6	11.6	25	25	5
Zinc oxide	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Stearic acid	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Antioxidant[d]	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Sulfur	2	1.4	2	1.4	2	1.4	2.5	2	2	2	1.4	1.5	1.5	1.4
CBS	0.4	0.8	0.8	0.8	0.8	0.8	0.5	0.8	0.8	0.8	0.8	1.75	1.75	0.8
TMTD	—	—	—	—	—	—	0.025	—	—	—	—	—	—	0.05
Percentage of BR[e]	0	0	20	20	40	40	0	0	0	25	25	0	25	30
Percentage of oil[e]	33	33	33	33	33	33	0	20	30	30	30	25	25	25

[a]Compounds 1 through 6 are RSS1; compounds 7 through 11 are HC and SMR20; and compounds 12 through 14 are SMR5.
[b]Compounds 1 through 11 are Intene 55NF; and compounds 12 through 14 are Europrene Cis.
[c]Sundex 8125.
[d]Isopropyl paraphenylene diamine.
[e]Relative to total rubber content.

Figure 1. Skid resistance of winter tires using OENR compounds.

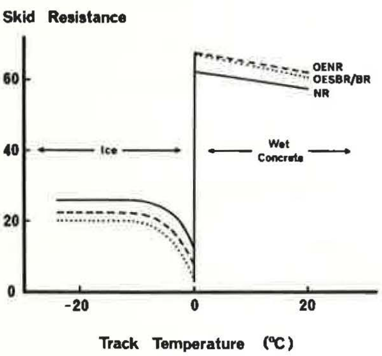


Table 2. Skid ratings on road ice at a surface temperature of -6 C to -2 C.

Percentage of BR	Unstudded		Studded	
	OENR	OESBR	OENR	OESBR
0	131	100	135	121
20	127	92	138	120
40	104	91	118	102

Note: Ratings are expressed relative to the unstudded OESBR tire containing no BR, which is arbitrarily given a rating of 100.

Table 3. Skid ratings on lake ice at a surface temperature of -2 C.

Mix	Unstudded	Studded
Natural rubber	119	119
OENR	118	119
OESBR-BR	101	137
Commercial tire (60 SBR and 40 BR)	100	123[a]
Level of statistical significance	10 percent	None at 10 percent

Note: Friction coefficient of unstudded commercial tire is 0.106, and this is arbitrarily given a rating of 100.

[a]This tire contained 133 studs compared with 100 studs in each other tire.

Table 4. Skid ratings on hard-packed snow at a surface temperature of -6 C.

Mix	Unstudded	Studded
Natural rubber	99	157
OENR	109	173
OESBR-BR	103	123
Commercial tire (60 SBR and 40 BR)	100	155[a]
Level of statistical significance	None at 20 percent	1 percent

Note: Friction coefficient of unstudded commercial tire is 0.141, and this is arbitrarily given a rating of 100.

[a]This tire contained 133 studs compared with 100 studs in each other tire.

In another series of experiments on another lake surface, the differences between the compounds were much smaller (about 4 percent). Measurements on hard-packed snow, which had been compacted so that the tires left no impression on the surface, under similar conditions showed larger differences between the compounds. The average results (significant at the 5 percent level) are as follows:

Mix	Unstudded	Studded
OESBR-BR	100 ± 3	112 ± 4
OENR	114 ± 7	—

It can be seen that the unstudded OENR tires perform better than both studded and unstudded OESBR-BR tires.

The results of the two earlier trials and particularly of the last trial illustrate the difficulty of making reliable measurements on ice. Such is the variability of ice that many repeat measurements are required to establish an effect. The situation is further complicated because it appears that both compound and stud effects may disappear under some conditions. An example of the variability of the results is shown in Figure 2 where the results obtained in the third trial using different test methods and on different occasions are shown in the order in which they were obtained. A particular set of tests may show relatively small scatter with a mean standard deviation of less than 4 percent compared with a mean standard deviation for all tests of 16 percent. This indicates that a small number of results, obtained under one set of conditions only, may be misleading with regard both to the mean friction coefficient and to the scatter in the results. Other factors come into play over a longer period of time, which affect the relative performance of the compounds. It is obvious, therefore, that many tests under a variety of conditions are necessary to ensure a reliable estimate of the behavior of the compounds under investigation. It has not been possible to correlate the effects with the more obvious climatological factors such as ice temperature, air temperature, or amount of sunshine during tests.

In spite of the complications and difficulties experienced in obtaining reliable data, an important conclusion can be drawn. During all the measurements that have been made in three separate trials under a wide variety of conditions and test methods, conventional OESBR-BR treads have never consistently outperformed OENR. The most recent and comprehensive set of data obtained using a variety of test methods shows an average improvement of 15 percent for OENR over OESBR-BR. This was the result of more than 200 tests on each compound. Each test consisted of several measurements of the friction coefficient.

CONCLUSIONS

It can be concluded that the grip of OENR tires whether of cross-ply or of radial construction on ice and hard-packed snow is superior to that of conventional OESBR-BR treads under many conditions and has never been found to be significantly worse than OESBR-BR compounds. In some circumstances, the OENR tire without studs may be better than an OESBR-BR tire with studs although studs can be beneficial to all compounds. The variability of ice makes it necessary to carry out a large number of measurements to establish the improvements to be gained from compounding or from studs.

The wet skid resistance of OENR compounds is comparable to conventional high hysteresis (OESBR-BR) compounds. The wear resistance of OENR treads is better than that of OESBR-BR treads at low tire surface temperatures such as are encountered under winter conditions.

All the results described in this paper substantiate the claim that the grip of winter tires on ice and snow could be significantly improved, and consequently winter driving could be made safer if the tread compound of winter tires was made from oil-extended natural rubber.

ACKNOWLEDGMENT

This work forms part of the research program of the Natural Rubber Producers' Research Association.

Table 5. Velocity ratings in closed-circle breakaway tests at a temperature of -1.5 C to -1 C.

Mix	Unstudded	Studded
Natural rubber	124	131
OENR	111	120
OESBR-BR	92	111
Commercial tire (60 SBR and 40 BR)	100	127[a]

Note: Ratings are expressed relative to the commercial tire, which is arbitrarily given a rating of 100.

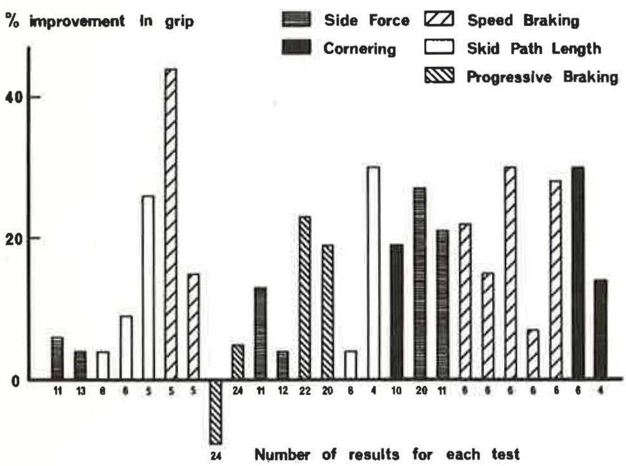
[a]This tire contained 133 studs compared with 100 studs in each other tire.

Table 6. Friction ratings using various test methods on ice at a surface temperature of -8.5 C to -0.3 C.

	Unstudded		Studded	
Test Method	OESBR-BR	OENR	OESBR-BR	OENR
Side force	100	114	107	131
Cornering	100	121	114	133
Speed braking	100	123	142	151
Skid	100	112	–	–
Progressive braking	100	109	–	–
Mean	100 ± 2	115 ± 2	120 ± 4	138 ± 5

Note: The unstudded OESBR-BR tire is the control and is arbitrarily given a rating of 100. Limits of means are quoted at the 5 percent level of statistical significance.

Figure 2. Safety characteristics of winter tires using OENR compounds.



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WINTER TRACTION: EFFECT OF TREAD COMPOUND

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•IN winter driving conditions, we are concerned with tire traction on ice and snow. This paper considers specifically traction on ice because apart from the well-known benefits of winter tread patterns on snow similar considerations apply. The work was carried out by the Dunlop Research Center in Birmingham, England, using a laboratory friction tester.

The low friction of rubber on ice arises from its self-lubricating property. Frictional heating due to sliding rubber melts the ice and produces a film of water between tire and ice. Unlike in hydroplaning conditions, providing drainage of the water does not help because more water will be formed when the tire reaches unmelted ice.

Figure 1 shows the effect of ice temperature on the coefficient of friction of styrene butadine rubber (SBR). As the temperature of the ice is decreased, friction rises from about 0 on melting ice and then levels off at about 3.0. For comparison, a value of about 2.0 would be expected from the same compound on smooth dry surfaces under the same test conditions.

Friction on ice shows some dependence on compound hardness. Figure 2 shows data plotted for natural rubber and a 35 percent styrene SBR at various black loadings.

Figure 3 shows coefficients of friction of various butadiene-styrene polymers at an ice temperature of 27 F, plotted as a function of styrene content. A natural rubber compound is included. Again, the coefficients of friction are low, but they increase with decreasing styrene content. Increasing styrene content raises the second-order transition temperature of a polymer and therefore increases low-temperature stiffening. This suggests that the ice-friction of polymers is related to their hardness at the test temperature.

In Figure 4, hardness and ice-friction have been plotted for natural rubber, SBR, and a 45 percent styrene SBR over a range of test-piece temperatures. There appears to be a correlation between ice-friction and compound hardness with no evidence of specific polymer effects.

The hardness effect is thought to arise from the fact that the true area of contact is greater with soft compounds. In fact, a similar law holds for dry friction.

Winter road-hold tests in Sweden have confirmed these findings, but the effect of compound changes has been found to be small. Moreover winter tires are used for a considerable part of their life on either wet or dry pavements. Softer compounds would lead to loss in wear resistance, instability, and high heat buildup.

The use of very high polybutadiene blends would increase ice friction because of their low hardness in very cold conditions, but this would lead to loss of traction on wet and dry pavements. Natural rubber also performs well at low temperatures for the same reason, and NRPRA have shown that, when the material is oil-extended, it can have acceptable grip on wet surfaces although there is generally an abrasion penalty.

However, in the temperature range of 32 to 10 F, the influence of the polymer on winter traction appears to be small and the intermediate SBR-BR blends used in North America are probably near optimum for overall performance.

Figure 1. Effect of ice temperature on coefficient of friction of SBR.

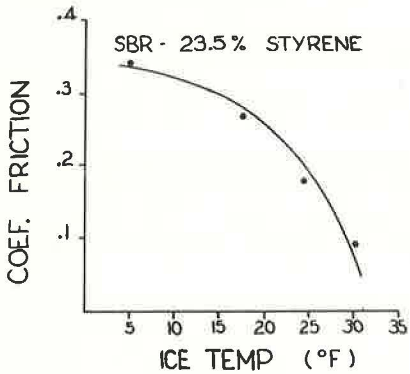


Figure 2. Effect of compound hardness on friction.

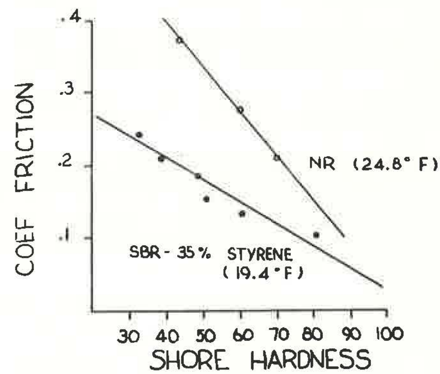


Figure 3. Effect of styrene content on coefficient of friction of various polymers.

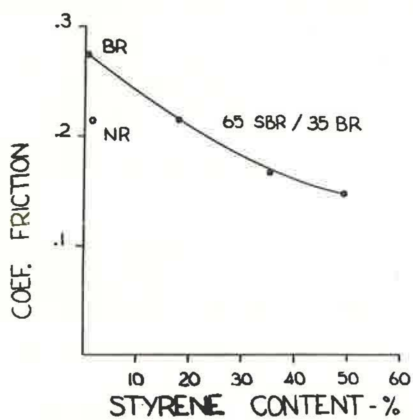
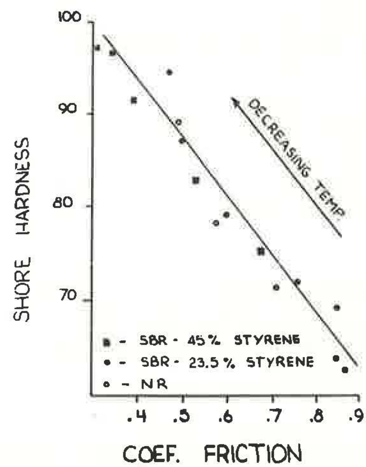


Figure 4. Correlation of ice-friction and compound hardness.



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