HIGHWAY RESEARCH RECORD

Number 352

Studded Tires Versus Pavement Wear and Safety

4 Reports

Subject Areas

31	Bituminous Materials and Mixes
32	Cement and Concrete
40	Maintenance, General
51	Highway Safety

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FOREWORD

This RECORD is part of a series on the effects of studded tires. Highway Research Records 136 and 171 forecast a pavement wear problem if studded tires usage became widespread. That this forecast was accurate was shown in an award-winning paper by Smith and Schonfeld and a paper by Hode Keyser published in Highway Research Record 331 and a paper by C. K. Preus published in Highway Research Record 341. Smith and Schonfeld, Hode Keyser, Preus, and Smith, Ewens, and Clough provide additional information in this RECORD on the magnitude of pavement wear. Normand and Canner present findings from studies of the effects of studded tires on winter driving safety.

Smith and Schonfeld estimate that additional costs of construction and maintenance due to the continued use of studded tires for the 1970-79 period will total almost $127 million. Wisconsin Division of Highways officials have estimated that maintenance costs will increase $12 million per year and Michigan officials have estimated their annual increased maintenance cost at approximately $26 million per year if studded tire usage is continued. Other snow-belt states project similar costs.

These substantial costs have been justified by manufacturers of tire studs and by users on the basis that they contribute to winter driving safety, and tests by the Committee on Winter Driving Hazards have shown that studded tires do indeed reduce stopping distances on glare ice. The paper by Normand and the discussion by Canner on tests in Quebec and in Minnesota respectively indicate, however, that the reduction in accidents that can be attributed to studded tire use is not statistically significant.

Serious wear effects increase already overloaded maintenance budgets and, further, no practical system currently exists to repair portland cement concrete pavements damaged by studded tires. Yet, a large percentage of motorists in snow-belt states seemingly favors continued use of studded tires. Such findings create a dilemma for authorities responsible for recommending passage of legislation controlling the sale and use of studded tires and for legislators responsible for making the ultimate decisions on public policy.

Maintenance engineers, materials people, administrators, legislators, and travelers have an interest in the contents of this RECORD and the decisions that will be influenced by the conclusions of researchers reporting their findings here. It is small wonder that numerous bills have been introduced in U. S. legislatures to ban studded tires, that Ontario Province has banned studded tires, and that hearings on studded tires have been included in the agenda of U. S. congressional hearings.

CONTENTS

STUDIES OF STUDDED-TIRE DAMAGE AND PERFORMANCE IN ONTARIO DURING THE WINTER OF 1969-70

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Measurements and observations during the winter of 1969-70 show that, with 32 percent of passenger vehicles in Ontario equipped with studded tires, substantial pavement wear and widespread loss of traffic markings continue and that the prior estimates of the remedial work that may be required over the next decade remain unchanged. The performance to date of experimental wear-resistant concrete and bituminous pavements and of traffic markings indicates that although improvements are possible no lasting solution has yet been found. Studded-tire performance tests carried out by the Ontario Provincial Police and the Canada Safety Council are reviewed. Data are presented on the occurrence of various road conditions in winter and the analysis of accidents. Little benefit is established from the use of studded tires except in icy conditions that occur relatively infrequently in Ontario.

•UNUSUALLY SEVERE WEAR on pavement surfaces and loss of traffic markings have become increasingly obvious on Ontario highways during each recent succeeding winter. The damage and its extent and severity have been coincident with the increasing use of studded snow tires. Similar effects causing widespread concern have been observed in other Canadian provinces, in the northern part of the United States, and in the Scandinavian countries.

In 1967 the Ontario Department of Highways launched a study to measure the extent of this damage, to devise remedial measures, and to predict the economic consequences over a 10-year period. The results of this investigation up to the start of the winter of 1969-70 have already been reported (1). During the winter of 1969-70, additional studies (2, 3, 4, 5, 6, 7, 8, 9) were undertaken to validate the predictions of future wear and cost and to determine the effectiveness of studded tires in the conditions that prevail on highways in Ontario during the winter. As a result of these studies, certain conclusions can be drawn as to the benefits and disbenefits of using studded tires in Ontario.

USE OF STUDDED TIRES

The use of studded tires has been permitted in Ontario between October 1 and April 30 each year provided that they are fitted on all four wheels or both rear wheels of a vehicle. Each winter, counting surveys have been made of the vehicles equipped with studded tires throughout the province. Table 1 gives the province-wide averages and the predicted increase, which were used to compile data in an earlier report (1). Considerable differences were found in the number of studded tires in use throughout the province. For example, Ottawa (48 percent, the highest recorded), Sault Ste. Marie, Thunder Bay, and Kenora areas all recorded that over 40 percent of passenger vehicles were equipped with studded tires. Less than 20 percent use was recorded in Chatham (12 percent, the lowest recorded), Hamilton, Kingston, Bancroft, and Cochrane areas. In the heavy traffic volume areas around Toronto, 30 to 35 percent of the vehicles had studded tires. Although the province-wide average of studded-tire use at 32 percent is slightly less than the 35 percent anticipated for last winter, the difference is not sufficient to warrant change to earlier predictions that 60 percent of passenger vehicles

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Sponsored by Task Force on Effect of Studded Tires and presented at the 50th Annual Meeting.

will be fitted with studded tires by the winter of 1971-72, if their use continues to be unrestricted.

TABLE 1

PERCENTAGE OF VEHICLES EQUIPPED WITH STUDDED TIRES

Winter	Actual	Range	Predicted
1966-67	2		
1967-68	8		
1968-69	18	2 to 27	
1969-70	32	12 to 48	35
1970-71			50
1971-72			60

Studded tires are mainly used on only the rear wheels of vehicles in Ontario, and an extension of their use to all four wheels of passenger cars or to heavier vehicles will likely increase the anticipated pavement damage discussed in the next section.

New types of tires (bias-belted and radial-ply) are gaining an increasing share of the market. It is not known whether studs in these tires will be less damaging to pavements than those in conventional tires, even though this has been suggested (11). The studded tires used in the Canada Safety Council stopping distance tests (12) were bias-belted, and the marks caused by these tires, when braking on ice or pavement, appeared similar to those caused by studs in conventional snow tires.

PAVEMENT WEAR

The nature of the pavement wear occurring to both bituminous and portland cement concrete pavements in Ontario and the method of measuring the depth of wear are both described in a previous report (1). Briefly, two types of wear have been identified. Where a pavement surface contains aggregate of similar wear resistance (hardness) to that of the matrix in which it is embedded, the surface generally wears down uniformly. However, where the aggregate particles are much harder, the softer matrix is preferentially denuded until a point is reached where the harder particles are dislodged by the studs because of the lack of embedment.

The photographic method of measuring pavement wear, developed by the department, allows the progression of wear to be observed from successive positions of a shadow line cast on the pavement surface by a thin wire stretched between reference pins. The reference pins are set at fixed height and placed on each side of the wheel tracks where concentrated wear occurs. Other areas of extreme wear are at locations where vehicles stop, start, or turn. At intersections and other places where vehicles rapidly change speed or direction, the wear may be more general and is usually more severe. Except for these special circumstances, there is a direct relationship between the amount of wear and the number of passes of the studded tires. If present traffic volumes and studded-tire use are known and an estimate of the likely increase in both can be made, it is then possible to use the relationship established to predict the amount of future wear that is likely to occur.

In predictions of the consequences of pavement wear in Ontario in terms of remedial measures that would be required and their cost, 1 in. (25 mm) of wear in the wheel track was established arbitrarily as the point at which resurfacing would be required. The highway network in the province was examined in terms of amount of pavement in each of a number of traffic volume ranges from 2,000 AADT (annual average daily traffic) upward. This was done to determine when resurfacing might be required. Costs were ascribed, by financial year, allowing for resurfacing work that would be required under normal maintenance demands irrespective of studded-tire wear. Other additional costs were also determined, such as those required to provide more wear-resisting traffic markings and pavement surfaces for new construction. From these data the additional costs that might be expected to be incurred in each financial year were tabulated to 1978-79 for both the provincial highways and the municipal roads and streets.

These estimates, made in the fall of 1969, are given in Table 2. More recent measurements of the wear that has occurred in one additional winter are now available for examination. These measurements permit the accuracy of earlier predictions of wear and costs to be checked.

Actual and Predicted Pavement Wear

Table 3 gives the wear recorded at the various measuring stations during the winter of 1968-69. It also gives the wear that was anticipated from these measurements for

TABLE 2

ESTIMATED ADDITIONAL COSTS FOR NEW CONSTRUCTION AND MAINTENANCE WORK ON PAVEMENT DAMAGED BY STUDDED TIRES

Year	Department of Highways				Municipalities				Grand Total
	New Pavement Construction	Resurfacing and Patching	Traffic Marking	Total	New Pavement Construction	Resurfacing and Patching	Traffic Marking	Total	
1970-71	608,000	589,000	1,078,000	2,275,000	458,000	470,000	1,078,000	2,006,000	4,281,000
1971-72	625,000	1,533,000	902,000	3,060,000	469,000	1,226,000	902,000	2,597,000	5,657,000
1972-73	855,000	4,298,000	778,000	5,931,000	641,000	3,438,000	778,000	4,857,000	10,788,000
1973-74	683,000	5,769,000	302,000	6,754,000	512,000	4,615,000	302,000	5,429,000	12,183,000
1974-75	625,000	5,960,000	325,000	6,910,000	469,000	4,768,000	325,000	5,562,000	12,472,000
1975-76	625,000	2,250,000	1,325,000	4,200,000	469,000	1,800,000	1,325,000	3,594,000	7,794,000
1976-77	625,000	8,569,000	1,325,000	10,519,000	469,000	6,855,000	1,325,000	8,649,000	19,168,000
1977-78	625,000	18,607,000	1,325,000	20,557,000	469,000	14,886,000	1,325,000	16,680,000	37,237,000
1978-79	625,000	8,578,000	325,000	9,528,000	469,000	6,860,000	325,000	7,654,000	17,182,000
Total	5,896,000	56,153,000	7,685,000	69,734,000	4,425,000	44,918,000	7,685,000	57,028,000	126,762,000

Note: Information is extracted from Smith and Schonfeld (Table 7, 1).

TABLE 3

ACTUAL AND ESTIMATED PAVEMENT WEAR RESULTING FROM STUDDED-TIRES DURING 1969-70 WINTER

Location[a]	Measured Wear in 1968-69 Winter (mm)			Measured Wear in 1969-70 Winter (mm)			Avg Anticipated Wear in 1969-70 Winter[c] (mm)	Avg Measured Wear as Percent of Anticipated Wear (percent)
	Stone[b]	Matrix[b]	Avg	Stone[b]	Matrix[b]	Avg		
Highway 401 (Toronto Bypass)								
Driving lane								
Don Valley, westbound	0.37	1.33	0.85	2.18	2.92	2.55	2.05	124
Avenue Road, eastbound	0.49	2.97	1.73	3.15	3.71	3.43	4.20	82
Spadina Expressway, eastbound	0.49	2.23	1.36	2.40	2.60	2.50	3.28	77
Center lane								
Don Valley, westbound	0.81	2.53	1.67	4.72	4.88	4.80	4.04	119
Avenue Road, eastbound	1.40	4.42	2.91	5.72	6.08	5.90	7.05	84
Spadina Expressway, eastbound	1.10	3.98	2.54	6.55	7.45	7.00	6.15	113
Passing lane								
Don Valley, westbound	0.59	2.87	1.73	7.41	6.49	6.85	4.20	163
Avenue Road, eastbound	1.91	5.68	3.80	7.08	7.42	7.25	9.20	79
Spadina Expressway, eastbound	2.25	5.09	3.67	6.35	6.65	6.50	8.90	73
Highway 126, southbound to Highway 401, westbound ramp	0.00	4.69	2.35	4.00	3.80	3.90	5.46	72
Highway 401								
London, eastbound, east of Highway 126	0.00	3.49	1.75	2.50	2.50	2.50	4.06	62
Highway 400								
Barrie, southbound, north of junction Highway 89	0.24	4.92	2.58	5.20	5.60	5.40	6.00	90

Note: Pavement types are as follows: Toronto Bypass (portland cement concrete); Highway 126, HL3 (bituminous); and Highway 401, London, and Highway 400, Barrie, HL1 (bituminous). Descriptions of these types of pavement are given in the earlier report (1).

[a] Pavements on Highway 11B, Huntsville, which were included in the 1968-69 measurements, where the greatest wear was recorded had to be resurfaced in 1969 and are consequently deleted from the study.

[b] When this table is compared with Table 1 or 2 in the earlier report (1), the terms "stone wear" (which corresponds to minimum wear) and "matrix wear" (maximum wear) are introduced to describe these parameters more clearly.

[c] The anticipated 1969 winter wear was calculated on the assumption that the AADT for 1969 would increase by 5 percent and that the proportion of passenger vehicles equipped with studded tires would increase from 15 percent in 1968 to 35 percent in 1969, i.e., 2.3 times the 1968 figure. The anticipated wear for the 1969 winter was, therefore, 1.05 x 2.3 = 2.42 of the 1968 winter wear. It should be noted that monthly spot counts of the proportion of studded tires varied from place to place; this may partly account for the variations in the rate of pavement wear in different locations within the overall average. For example, the studded tire counts on Highway 401 near London averaged 23 percent in 1969, which can be expected to result in 1.5 times the 1968 wear, and not 2.3 times as estimated on the basis of the overall average for Ontario.

the winter of 1969-70 and the actual 1969-70 measured wear. Data given in the last column of Table 3 show that the actual wear over the winter of 1969-70 ranged from 72 to 163 percent of the anticipated wear, with an overall average of 90 percent.

Considering the many variables involved in studded-tire wear, the authors would have been surprised if their prediction of wear at each of the test locations had been more precise. However, it is felt that, on the basis of the measurements and observations of the damage to pavements and traffic markings during the past two winters, the long-term predictions of remedial work and its associated costs are reasonably accurate.

Measurements at other locations within the highway system are being undertaken to provide more exhaustive validation of actual and predicted wear. This study includes highways with lower traffic volumes that are subjected to different climatic and other conditions from those prevailing on the main highways in southern Ontario that have been measured and reported thus far. It is too early at this time, however, to draw any conclusions from the limited data gathered thus far from other highways.

Obliteration of Traffic Markings

In addition to the wear of pavement surfaces, studded tires have noticeably worn painted traffic markings. Numerous complaints have been received regarding the inconvenience and hazards that this has caused. At places where traffic weaving occurs, at curves where the centerline is frequently crossed, and at stop lines, all traces of conventional paint markings were obliterated before the winter was half over. In the critical areas, the resulting emergency situation was dealt with by repainting the markings on clear days in January and February. However, because of poor adhesion resulting from low temperature, dirt, or moisture, the repainted lines usually lasted only a few days. The performance of experimental (more wear-resistant) markings is discussed in the next section of this report.

Skid Resistance

Because studded-tire wear changes the characteristics of a pavement surface both on a macroscale and on a microscale, this might be expected to have an effect on surface properties such as skid resistance. However, the changes in skid resistance during the past 3 years, as given in Table 4 and shown in Figure 1, are surprisingly small, and the advent of studded-tire wear has neither significantly worsened nor improved the skid resistance of most Ontario pavements.

Pavements containing hard, coarse aggregate (HL1 and some HL4 asphalt mixes) show no overall loss in skid resistance. The pavements that wear uniformly, such as

TABLE 4

CHANGES IN SKID RESISTANCE OF SOME PAVEMENTS IN ONTARIO SINCE INTRODUCTION OF STUDDED TIRES

Pavement Type	Aggregate	Number of Pavements Tested	Test Speed (mph)	Range of Skid Numbers	Average Skid Number of Pavements Tested	Change From Preceding Year (skid number points)		
						1968	1969	1970
Asphalt mix HL1	Traprock coarse	9	30	40 to 62	53	-1	0	+2
			60	24 to 44	35	-1	+1	0
Asphalt mix HL3	Limestone coarse	11	30	38 to 57	51	-4	+1	+3
			60	25 to 40	37	-1	0	0
Asphalt mix HL4	Igneous coarse	5	30	48 to 61	55	-1	0	+2
			60	32 to 49	42	-1	0	+1
Thin bituminous overlays, including asbestos, latex and rubber-modified mixes		19	30	32 to 60	50	-3	-1	-3
			60	24 to 46	37	0	-1	+2
Concrete	Limestone coarse	8	30	31 to 58	47	-7	-5	0
			60	19 to 36	37	-2	-4	-1

Note: The studded-tire proportion of all passenger vehicles increased from 2 percent in 1967 to approximately 32 percent in 1970.

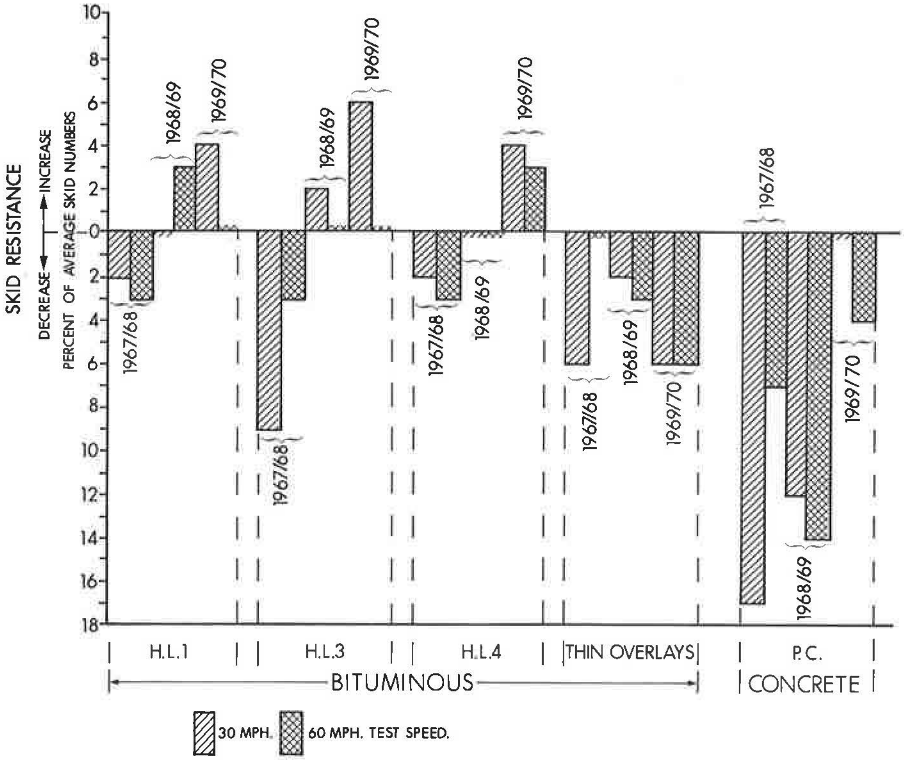

Figure 1. Changes in skid resistance of some pavements in Ontario with increasing use of studded tires.

the thin overlays of finer texture or the concrete pavements that contain softer aggregate and depend on a broom-finished texture for their initial skid resistance, have shown an overall decline in skid resistance. This decline, although small in terms of skid number increments, is more critical because these pavements had lower initial skid-resistance values.

PERFORMANCE OF EXPERIMENTAL WEAR-RESISTANT SURFACES AND TRAFFIC MARKINGS

In a previous report (1), a review was made of the work (largely European) done to develop surfaces for pavements that would be more resistant to damage by studded tires than those presently in use. In general terms, it was concluded that the most promising avenue to explore was the incorporation of the maximum amount of the hardest available coarse aggregate in the surfacing material.

To further evaluate this theory, the department constructed a number of trial sections of concrete pavement in 1968, and sections of bituminous mixtures of different composition were laid in the late fall of 1969. The features incorporated in these experiments are described elsewhere (1). Both trials were on roads subjected to heavy traffic, and the performance results of the concrete sections after two winters and the bituminous sections after one winter are now available. In addition, visual observations of experimental traffic markings after one winter's service can be reported.

Concrete Pavement

Of the 14 concrete sections laid in 1968, only three sections containing traprock coarse aggregate have shown performance that was significantly different from the adjacent

TABLE 5

PERFORMANCE OF CONCRETE AND PLASTIC WEAR-RESISTANT SURFACES

Location	Section	Pavement		Annual Average Daily Traffic	Vehicle Maneuver	Pavement Wear			Skid Number[a]	
		Type	Age (year)			Stone	Matrix	Avg	1969	1970
Highway 401, Toronto Bypass, passing lane at Dixon Road, westbound	1	Traprock coarse aggregate, 100 percent silica sand	2	6,800	Straight	1.50	3.00	3.25	37	45
	2	Traprock coarse aggregate, 67 percent silica sand, 33 percent calcareous sand	2	6,800	Straight	3.50	3.50	3.50	34	44
	3	Traprock coarse aggregate, 33 percent silica sand, 67 percent calcareous sand	2	6,800	Straight	3.00	3.50	3.25	30	42
	4[b]	Limestone coarse aggregate	2	6,800	Straight	3.17	3.54	3.36	22	22
Highway 27, Toronto, southbound, to westbound Q. E. W. ramp	5	Plastic surfacing (polyurethane and glass chips)	1	6,200	Curve	N.A.	N.A.	1.1	48[c]	20[c]
					Ramp	N.A.	N.A.			
Highway 49, Quinte Skyway deck	6	Plastic surfacing (polyurethane and glass chips)	1	800	Straight	N.A.	N.A.	1.0	48	46

[a] Measured by ASTM brake force trailer at 60 mph.
[b] Control section.
[c] Measured at 50 mph.

concrete. After one winter's wear, the traprock aggregate became exposed with wear that was concentrated in the surrounding matrix, and it was postulated (1) that the rate of wear would be slowed down until dislodgment of the coarse aggregate occurred. Table 5 gives the measured wear that occurred during the second winter.

Somewhat disappointingly, the wear measured on the stone is almost equal to that measured on the matrix, and the resulting average wear is no less than that occurring to the adjacent concrete surfaces containing a much softer limestone aggregate. Matrix wear was some 16 percent less in the second section, which had 100 percent silica fine aggregate, and the wear of the coarse aggregate in this section was less than one-half of that in the sections having a less wear-resistant matrix.

The reason for this difference in wear appears to be that some dislodgment of traprock particles has occurred that allowed the studs to further abrade the matrix. Furthermore, the nominal maximum size of the available traprock aggregate used was only ½ in. It would appear that a larger size of hard coarse aggregate and a greater proportion of it in the immediate surface area are required if studded-tire wear on concrete is to be resisted over a long period.

Table 5 also gives the wear during one winter on two experimental sections of a thin polyurethane pavement coating treated with small glass chips. Although the chips were partially lost, the overall wear resistance of this coating was very good. This was probably due to both its toughness and its resilience under stud impact. It remains to be seen, however, if the film, which was only about 40 mils (1.0 mm) thick, will survive another year. This particular material is under evaluation as a waterproof bridge-deck surfacing. However, this and other "resilient" surfacings, although usually expensive, are worthy of further study as an alternative to providing hard abrasion-resistant surfaces to resist stud damage.

Even though considerable wear is occurring in the experimental concrete sections, the presence of the traprock and the differential texture between this and the matrix is maintaining a very high pavement skid resistance as given in the last column of Table 5.

Bituminous Pavements

Table 6 gives details of the experimental bituminous pavements placed on Highway 400, northbound (north of the King Side Road), in the late fall of 1969 and observations

TABLE 6

PERFORMANCE OF BITUMINOUS WEAR-RESISTANT SURFACES

Section	Type of Mix	Mix Composition (percent weight)		Asphalt Content (percent weight of mix)	Avg Wear (mm)	Skid No.[a]		Pavement Wear Comments
		Retained on No. 4 Screen	Pass No. 4 Screen to Make 100 Percent Weight of Aggregate			May 1970	Dec. 1969	
1	HL1 with increasing stone contents	40 TR	LS + LSS, 3:1	5.8	2.9	52.2	46	Sections 1 and 2 moderate loss of FA; section 3 loss of CA; fair performance; mix impermeable
2		50 TR	LS + LSS, 4:1	5.4	2.3	52.5	47	
3		60 TR	LS	4.9	2.2	54.9	49	
4	TR and TRS only, no intermediate sand	40 TR	TRS	4.5	4.0	53.5	57	Very permeable; difficult to compact; large loss of FA and CA; sections 4 and 5 poor performance; section 6 very poor
5		50 TR	TRS	4.3	4.1	53.7	56	
6		60 TR	TRS	4.0	3.6	54.5	56	
7	HL1 as on sections 1, 2, and 3 but with SS and TRS	40 TR	TRS + SS, 2:1	4.8	3.4	51.4	52	All somewhat permeable; sections 7 and 8 moderate loss of FA and CA and fair performance; section 9 good
8		50 TR	TRS + SS, 2:1	4.7	3.0	53.9	51	
9		60 TR	TRS + SS, 2:1	4.1	3.2	52.9	52	
10	Same as on sections 7, 8, and 9 but with the ratio of SS:TRS reversed	40 TR	TRS + SS, 1:2	6.2	3.2	51.5	51	Relatively impermeable; sections 10 and 12 some loss of FA and fair performance; section 11 good
11		50 TR	TRS + SS, 1:2	5.3	2.3	52.2	50	
12		60 TR	TRS + SS, 1:2	4.7	2.2	53.7	51	
13	HL1 with SS and filler	40 TR	SS + 7 percent F	5.8	2.1	49.5	47	Impermeable; slight loss of FA; good performance
14		50 TR	SS + 4 percent F	5.4	2.1	49.0	46	
15		60 TR	SS + 2 percent F	4.8	1.8	53.4	49	
16	Asbestos filler mixes	45 TR	TRS + 2 percent A	6.5	2.0	47.0	47	Somewhat permeable; slight loss of FA; good performance
17		45 TR	TRS + LS, 1:1 + 2 percent A	6.5	1.9	43.2	40	Impermeable; good to very good performance
18	S ½ in. maximum size and regular fine aggregate	30 S	LS + LSS, 3:1	6.7	2.9	53.0	49	Permeability of section 18 to 23 not detectable; visually some loss of FA; performance generally good
19		40 S	LS + LSS, 3:1	6.6	2.7	52.7	50	
20		50 S	LS + LSS, 3:1	6.2	2.0	53.2	52	
21	Same as on sections 18, 19, and 20 but with the addition of TRS	30 S	LS + TRS, 2:1	6.7	2.2	53.9	54	
22		40 S	LS + TRS, 2:1	6.6	2.2	53.7	51	
23		50 S	LS + TRS, 2:1	6.1	2.0	52.7	51	
24	Crusher run, hard steel slag mixes ⅜ in. (2 types)	21 SL 1	SL 1	6.5	2.2	39.4	53	Slight loss of FA; performance good
25		15 SL 2	SL 2	5.8	2.4	41.9	54	
26	Carpet seal with reduced fines content	30 TR	TRS	5.7	4.1	52.2	55	Loss of FA and surfacing slightly removed in patches; variable performance from poor to fair
27[b]	Standard HL3 mix with limestone coarse aggregate for comparison of wear	40 L	LS + LSS, 3:1	6.1	3.8	37.4	59	Considerable wear to both CA and FA; performance fair
28-32	Sections planned but not placed in 1969							
33	Precoated traprock chips rolled in mix 27			6.1	–	–	–	Precoated chips resisted wear; matrix (FA) picked out
34	Precoated Sinopal chips rolled in mix 35			5.7	–	–	–	
35	Regular HL1 surface mix	49 TR	LS + LSS, 3:1	5.7	2.9	–	–	Loss of FA; fair performance

Note: CA = coarse aggregate; FA = fine aggregate; TR = traprock (Marmora), ½ to +4; S = Sinopal (synthetic rock), ½ to +4; L = crushed limestone (Acton), ½ to +4; LS = limestone sand (Harris pit); SL 1 = basic oxygen furnace slag; SL 2 = open hearth furnace slag; LSS = limestone screenings (Uhthoff quarry); TRS = traprock screenings (Marmora); SS = silica sand (Nicholson pit); F = mineral filler (limestone); and A = asbestos fiber.

[a] Measured by ASTM brake force trailer at 50 mph.

[b] Control section.

of pavement performance during one winter (approximately 4½ months). The table includes two columns that give the skid resistance and average depth of wear in the wheelpaths for each type of mix.

Skid-resistance measurements were made with an ASTM type of brake force trailer at 50 mph. Wear measurements were made at five randomly chosen locations in each section, and the average wear was calculated.

The amount of wear was determined by stretching a string line across both wheelpaths of the driving lane at each location. The line was run from an unworn area at the outside edge of the pavement. Three points were randomly chosen along the string line near the center of each wheelpath and the distance was measured from the string line to the pavement surface. The average of the 30 measurements in each section gave the mean pavement wear.

The analysis of variance was applied to the results to determine what results could be considered significant. The mean pavement wear for each section is given in Table 6. Wear measurements were also made by the photographic method, but these are not reported because problems with the camera operation in cold weather prevented a complete set of photographs of the unworn pavement from being obtained.

The following comments can be made on the results obtained, and these may be helpful in selecting more suitable wear-resistant surfaces in the future:

1. The normal HL1 surfacings on Highway 400, adjacent to the trial sections, and most of the trial sections themselves show signs of unusual wear and particularly raveling of the matrix.
2. As the percentage of coarse aggregate was increased (sections 1 to 15 and 18 to 23), wear generally decreased.
3. The best performance of the traprock mixes (sections 1 to 15) occurred in sections 13, 14, and 15. In these cases, a fine, hard sand was used, and this resulted in a dense mix that exhibited only a slight loss of fine aggregate.
4. The use of large amounts of traprock screenings made the mixes more difficult to compact, with the result that the surfaces were more permeable, and there was a greater loss of fine aggregate.
5. The use of asbestos fiber in sections 16 and 17, together with a higher asphalt content that was then possible, produced a tough mix that lost only a slight amount of fine aggregate. Section 17 was better than section 16, because the latter contained traprock screening and was more permeable.
6. The Sinopal coarse aggregate (in sections 18 to 23) exhibits good performance and a brilliant whitish surface after traffic wear. It is difficult, however, to judge the permeability of the surfaces visually because of their light color. Mixes in sections 21, 22, and 23 were equivalent statistically to the traprock mixes in sections 13, 14, and 15.
7. The slag mixes, in sections 24 and 25, have a hard and dense surface and have resisted wear reasonably well.
8. A large, yet even, amount of wear was exhibited by section 27, which was an HL3 mix containing a limestone aggregate. In this case, wear of the coarse aggregate and matrix was uniform and amounted to about 3.8 mm in 4 months (1 in. in about six winters, if wear continues at the same rate). In other sections containing hard traprock, slag, or Sinopal coarse aggregate, wear was not uniform. Even though the matrix surrounding the coarse aggregate particles was considerably eroded, the coarse aggregate particles themselves resisted the wear reasonably well and now stand proud of the surface. So far, only occasional dislodgment of the coarse aggregate has been noted.
9. The sections into which precoated, hard aggregate chips were rolled hot have shown good wear resistance even though the surrounding matrix has been eroded by wear, as in the other sections.
10. Comments 3 and 9 in the foregoing suggest that BS 594 mixes (which could not be placed because of the onset of winter) might perform very well and that trial sections of these mixes should be placed.
11. The performance of the regular HL1 mix, in the passing lane paralleling the trial sections and at the end (section 30), showed a considerable loss of fine aggregate and

poorer performance than some of the trial mixes. From the information obtained from these test sections, it may be possible to generate improvements applicable to HL1 mixes.

The skid numbers for the sections are given in Table 6. The following comments can be made on these results:

1. The traprock and Sinopal mixes (sections 1 to 15 and 18 to 23) generally showed a slight increase in skid resistance after winter wear. This was due to removal of some surface matrix that left the coarse aggregate more exposed. There was, however, one exception in the case of the mix in sections 4 to 6 where the skid resistance decreased. These were the most severely worn sections, and the loss of coarse aggregate caused a drop in skid resistance.
2. The skid resistance of the asbestos mixes was generally lower and remained that way during the winter.
3. The slag mixes (sections 24 and 25) and the HL3 mix (section 27) showed skid resistance to decline earlier than in the case of some traprock mixes, but it appeared to stabilize at about the same level at the end of the present period of observation. Full details of this experiment and the results are given elsewhere (4).

Traffic Markings

Several types of trial markings were laid in the fall of 1969. These were as follows:

1. Broken lines formed by spreading a white thermoplastic material. These were applied on selected asphalt and concrete pavements in the Toronto area. Snowplow and stud damage to these experimental lines is evident, particularly where traffic weaving occurs. In general, however, these markings were clearly visible after one winter. It remains to be seen how long they will last in relation to their greater cost.
2. Parallel grooves cut into the pavement along the original white lines. It was expected that, even though the surface paint would be scraped away by the studs, the white lines would not be removed from the grooves. This experiment has not been successful because, although the grooves themselves remain fairly visible, the paint in them has poor reflectivity.
3. A white synthetic aggregate (Sinopal) embedded in new concrete as the traffic lane marker. The visibility of this material has proved inadequate and must be improved before this method of lane marking can be acceptable for use.
4. White Sinopal aggregate embedded in new asphaltic concrete. It was not possible to test this on a full scale, but some small patches have performed well.

All of the preceding markings were capable of breaking the water film during rain and should increase the visibility of traffic markings under such circumstances. It is too early to assess their long-term suitability, however, and further experiments are planned.

PERFORMANCE OF STUDDED TIRES

Performance tests to evaluate the effectiveness of studded tires have been made by many authorities (14). Differences in test conditions, however, make it difficult to reconcile the various results, most of the stopping distance tests on ice have been carried out only at low speed (20 mph), and the information available on stopping distance on bare, wet, or dry pavements is more limited than that on ice. For these reasons, the Ontario Department of Highways welcomed proposals by both the Ontario Provincial Police and the Canada Safety Council to conduct stopping distance tests and certain maneuverability tests to compare the effectiveness of studded snow tires with other types of tires under the conditions prevailing on highways in Ontario and elsewhere in Canada.

Ontario Provincial Police Tests

Two identical regular police cars were used; one was equipped with snow tires with studs on the rear wheels and the other was fitted with similar snow tires but without studs. Stopping tests were conducted on a number of highways in north-central Ontario and on unprepared (natural) snow-covered ice and packed snow surfaces with the vehicles traveling at speeds of 50 and 30 mph as prevailing conditions permitted.

Although these tests were not performed under the same carefully controlled conditions as were attained in the Canada Safety Council tests, the results are still meaningful. They included locked-wheel braking, hard braking, pumped braking, and emergency stops and are probably representative of what might be expected in similar winter circumstances by a skilled driver. The results of the 35 different comparative tests carried out are given in Table 7.

TABLE 7

LONGER STOPPING DISTANCES REQUIRED FOR STUDDED TIRES THAN FOR SNOW TIRES

Surface	Speed (mph)	Longer Stopping Distance	
		Feet	Percent
Dry asphalt	30	2	6
	50	12	7
Wet asphalt	30	3	8
	50	24	22
Packed snow	30	5	5
Thin snow on ice	50	27	11
Thick snow on ice	50	7	4

The overall analysis indicates that in all cases longer stopping distances were recorded with studded tires than with plain snow tires. However, in 8 of the 35 individual tests, marginally shorter stopping distances were noted for studded tires. No single factor common to these particular results could be pinpointed. In common circumstances, locked brakes produced the shortest stopping distance. With hard or pumped braking, slightly long stopping distances were recorded. However, where brakes are pumped this disadvantage should be offset by less risk of skidding and consequent loss of directional control. Certain additional tests by the Department of Highways were made that confirmed the finding that locked braking produces the shortest stopping distances.

It is interesting to note that the Ontario Provincial Police vehicles are not equipped with studded tires in the winter. Evidently experience has shown that conventional snow tires are quite satisfactory for the winter driving conditions encountered by the police.

Canada Safety Council Tests

A series of studded-tire performance tests (12) were carried out by Damas and Smith Consulting Engineers in March and April 1970 for the Canada Safety Council. Stopping distance tests at 20, 35, and 50 mph with locked brakes were carried out on icy surfaces at temperatures ranging from -5 to 33 F and on both wet and dry bare asphalt and concrete pavements. Limited demonstrations of maneuverability on ice and of stopping distances on sanded ice were also carried out. Details of the tests and the results are contained in a companion paper (12).

The findings of both the Ontario Provincial Police and the Canada Safety Council tests are in line with those reported by other investigators (14). The particular importance of the Ontario tests is that they extend the observations into the speed range of normal highway driving and show that, even though studded tires are of distinct advantage on ice especially when fitted on all four wheels, they afford no advantage on bare, wet, or dry pavements. They also bring out the point that, once an icy road surface is sanded (which is done as soon as possible in normal winter maintenance practice in Ontario), stopping distances with any type of tire are greatly improved and are much less than those of studded tires on unsanded ice.

WINTER DRIVING—ROAD CONDITIONS

In an evaluation of the contribution of studded tires to driving safety, it is necessary to establish how much icy pavement a driver is likely to encounter during the winter as compared with other conditions in which the use of studded tires may be of little or no advantage. This has been determined from the daily road-condition reports made from the beginning of November to the end of March by the district patrols for each King's Highway in Ontario. Because of varying traffic volumes on the different sections of each highway and because the maximum amount of information was desired from the available reports, it was not possible to express pavement conditions in terms of vehicle-miles. They are expressed, therefore, as day-miles; that is, the number of days times the miles where each condition prevailed. Table 8 gives this information. Districts

TABLE 8

WINTER ROAD CONDITIONS

Area[b]	King's and Other Highways		Road Condition[a]								Temperature (percent of days)			
			Bare, Dry		Bare, Wet, or Damp		Snow or Slush		Icy					
	Total Miles	Total Day-Miles	Day-Miles	Percent	Day-Miles	Percent	Day-Miles	Percent	Day-Miles	Percent	<10 F	10 to 30 F	30 to 35 F	>35 F
1	6,547	925,824	558,647	60.3	253,201	27.3	111,413	12.1	2,563	0.3	13.2	49.8	17.1	19.9
2	3,563	530,887	223,676	42.1	94,134	17.7	211,909	39.1	1,168	0.3	24.5	46.7	13.4	15.4
3	4,882	726,335	222,846	30.6	52,289	7.2	431,277	59.5	19,923	2.7	37.2	46.8	7.3	8.7
Total	14,992	2,183,046	1,005,169	46.0	399,624	18.3	754,599	34.6	23,654	1.1	24.7	48.0	12.6	14.7

[a] Based on daily road condition reports submitted by each patrol in each district. Two reports were analyzed: one representing the early morning conditions and the other the midafternoon conditions each day from November 1 to March 30.

[b] Area 1, southern tier of districts (Chatham, London, Stratford, Hamilton, Toronto, Port Hope, Kingston, Ottawa); area 2, middle tier of districts (Owen Sound, Bancroft, Huntsville, North Bay, Sudbury); and area 3, northern tier of districts (New Liskeard, Cochrane, Sault Ste. Marie, Thunder Bay, Kenora).

with a similar pattern of road conditions and weather have been grouped into three geographical areas to show the total day-miles by road condition prevailing in the areas during the past winter. Table 9 gives information on the precipitation and visibility in the three areas during the test period. Corresponding information was not obtained for county, city, and township roads, and estimates cannot be made on the basis of the Provincial roads because road conditions are dependent on the particular maintenance standards employed.

The performance studies have shown that studded tires are advantageous only on icy surfaces. They are particularly advantageous when temperatures are near the freezing point or when freezing rain coats the pavement with ice and when maintenance crews are hard pressed to spread sand and salt on the highways quickly enough. The province-wide road conditions that prevailed on the King's Highways last winter were as follows:

Condition	North	Central	South	Avg
Icy pavements, percent of day-miles	2.7	0.3	0.3	1.1
Temperatures 30 to 35 F, percent of days	17.1	13.4	7.3	12.6
Freezing rain, percent of time		0.5 to 1.0		

The bare, dry pavement condition prevailed 46 percent of the day-miles, and the bare, wet pavement condition prevailed 18.3 percent of the day-miles. In both these circumstances, regular summer tires would have been adequate. Snow tires, not necessarily fitted with studs, would have been preferable on 34.6 percent of the day-miles when the highways were slushy or covered with snow.

Regional differences and differences between King's Highways and county, township, or city roads and streets exist because of varying climatic conditions, level of maintenance, and highway use. However, it is generally true to state that studded tires are not essential to ensure mobility and reasonably safe and convenient use of highways in Ontario during winter conditions.

TABLE 9

AVERAGE PRECIPITATION AND VISIBILITY IN THREE AREAS

Precipitation and Visibility	Percent of Time
Precipitation	
None	75 to 82
Snow	12 to 19
Rain	2 to 6
Freezing rain	0.5 to 1
Visibility	
Adequate	85 to 94
Poor or limited by drifting snow	6 to 15

WINTER ACCIDENT ANALYSIS

This part of the study was an analysis of the accidents in which vehicles with studded tires were involved. The analysis was performed on 2,790 vehicles involved in accidents on King's Highways during February 1970 (932 vehicles in accidents on icy roads and 1,858 in accidents on roads without ice). The analysis consisted of two parts.

The first part was an examination of the percentage of vehicles equipped with studded tires in accidents on roads both with and without ice. The data were obtained from Ontario Provincial Police accident reports. Unfortunately, these data were incomplete, and it was necessary to carry out a questionnaire survey of the drivers involved to determine the extent of the underreporting of vehicles with studded tires. The results of this part of the analysis are given as follows:

Source of Data	On Roads With Ice (percent)	On Roads Without Ice (percent)
Ontario Provincial Police reports	11.2	4.8
Questionnaires (sent only to drivers for whom presence or absence of studded tires was not confirmed on accident report)	19.3	21.3
Revised estimate of vehicles equipped with studded tires involved in accidents	20.6	18.5

Thus, the estimated percentage of vehicles equipped with studded tires involved in accidents on icy roads is not markedly less than the percentage involved in accidents on roads without ice, which is contrary to expectations if studded tires afford a significant contribution to safety. In fact, the estimated percentage involvement of studded tires in accidents on icy roads is greater than in accidents on roads without ice, although the difference is not statistically significant.

However, these figures of 18 to 21 percent are much lower than the approximately 30 percent of the vehicles equipped with studded tires on Ontario roads, as indicated by road counts. This difference could be caused by several factors: inaccuracy in either the estimated population percentage (30 percent) or the percentage of vehicles equipped with studded tires involved in accidents (incomplete questionnaire returns); differences in driving skill; the differences regard for safety between users of studded tires and those who do not use studded tires; or differences in the various driving conditions between users and nonusers (this difference was in fact indicated by the questionnaire returns).

Even though it is recognized that the analysis is based on limited information and a short time period, it seems to indicate that studded tires do not produce improved safety on icy roads, where they are claimed to be most effective. The differences between percentages of vehicles with studded tires in the vehicle population and in accidents can probably be accounted for by differences in driving skill, concern for safety, and exposure to various driving conditions, or by inaccuracies in the data.

The second part of the analysis was a subjective rating of the influence of studded tires in accidents on icy roads. A panel of four people rated each accident as to the usefulness of studded tires in the prevention of the accident or the reduction of its severity. Rating results are summarized as follows:

Usefulness of Studded Tires	Percent of Accidents
Definitely would not have helped	21
Probably would not have helped	20
No decision	38
Probably would have helped	21

Thus, even in accidents on icy roads, studded tires appear to be relevant in about 59 percent of the accidents, although this figure may be as low as 21 percent.

Additional factors affecting accidents and safety, for which no information is available, are the dangers resulting from the premature loss of traffic lane markings in winter; and the year-round effects of pavement rutting caused by studded-tire wear, which might be expected to adversely affect the control of vehicle direction and to contribute to the ponding of water, an increase in splashing, and the risk of skidding.

PUBLIC OPINION SURVEYS

To gage public opinion of studded tires, two questionnaire surveys were made: the first by the Ontario Department of Highways to assist in the analysis of accident data; and the second by the Rubber Association of Canada (10).

Department of Highways Survey

The Department of Highways survey consisted of two types of questionnaires. The direct questionnaire referred to the accident in which the person surveyed was involved. The general questionnaire asked general questions about winter driving habits of the person surveyed. The responses to these two questionnaires are given in Table 10.

In considering the responses in Table 10, it should be kept in mind that, in the direct questionnaire, 15.1 percent of those responding had cars equipped with studded tires, and, in the general questionnaire, 25.8 percent of those responding had cars equipped with studded tires. In both cases, less than 10 percent specifically noted that they considered studded tires to be beneficial, while no opinion was expressed by the majority.

Rubber Association of Canada Survey

The study for the Rubber Association of Canada was carried out by Market Facts of Canada, Ltd., by means of a telephone survey of 1,000 persons "responsible for the maintenance and servicing of the family car." The survey was carried out in five geographical areas of Ontario having climatic and other differences.

The survey was undertaken in March and April 1970 to obtain background information on the knowledge that each person had of studded tires and the attitudes toward studded tires. It also sought to establish the advantages or disadvantages of studded tires from the experiences of those who had used studded tires.

It is not practical in this paper to present the large amount of data obtained from the 22 main questions asked. Instead, the main points of the report (10) are given.

1. The driving public is virtually split on the issue of studded snow tires. They definitely find it difficult to decide whether the advantages of studded tires outweigh the road-damage problem. However, at the present time, a slight majority of drivers believes that studded snow tires should be permitted on the roads.
2. The public is indeed aware of the advantages of studded tires as well as of the criticism that has been directed at this type of tire.
3. Present users of studded tires are convinced that studded tires contribute to safer driving. This belief is held even more strongly by rural drivers.
4. Users of studded tires are in strong agreement that studs improve winter driving performance on icy roads and on hard-packed snow, but they also seriously question their usefulness on dry and wet roads.

TABLE 10

PUBLIC OPINION OF STUDDED TIRES

Comments	Respondents (percent)	
	Direct Questionnaire[a]	General Questionnaire[b]
Accident was result of poor highway maintenance	17.2	
Highway was bare and dry at time of accident	2.8	
Studded tires were useful in winter driving	8.3	9.2
Studded tires were not useful in winter driving	10.0	15.4
Other comment	31.0	19.4
No comment	30.7	56.0

[a] Sample size, 496; percentage responding, 50.6.

[b] Sample size, 496; percentage responding, 35.9.

5. Approximately 80 percent of present users of studded tires intend to purchase this type of tire again.
6. It would appear that the main opposition to not buying studded tires is the lack of any perceived need for them. Ontario drivers essentially believe either that there is no real need for them in their particular area or that regular snow tires do the job just as well.
7. Ontario drivers are not convinced that there needs to be a law requiring snow tires in the Province, and they are even less convinced that there needs to be a law requiring studded snow tires.

Both the survey made by the department and that undertaken for the Rubber Association of Canada produced findings that are not inconsistent with those that might be expected from the performance studies reported previously. These findings suggest that, although the users may feel that studded tires are an aid to safer winter driving on icy roads, studded tires are by no means regarded by the public as essential to winter motoring in Ontario. It is of interest to note that, at the time these surveys were made, the results of the studded-tire performance tests and information on road conditions in Ontario throughout the winter had not yet been published.

CONCLUSIONS

From the studies and observations contained in this report and its predecessor (1), the following may be concluded:

1. The use of studded tires in Ontario has generally increased to about 32 percent of passenger vehicles, and, if unrestricted, the increase appears likely to continue to the extent used in predicting the resulting pavement wear.
2. Wear measurements during the winter of 1969-70 show that serious wear is occurring on all types of pavements other than those carrying only light traffic and is continuing at about the rate predicted.
3. No change is indicated, therefore, in the estimates of the repair costs of remedial work that will be required because of the continued use of studded tires. The total additional costs in Ontario through to financial year 1978-79 are estimated to be $127 million.
4. Experiments to develop more wear-resisting surfaces and traffic markings have been only partially successful. Although improvements to currently used surfacing materials and markings can be recommended at additional cost, there is no assurance as to their long-term value or service life.
5. The performance tests made by the Canada Safety Council and Ontario Provincial Police confirm that studded tires are of benefit in reducing stopping distances on icy surfaces and improving maneuverability, especially when studded tires are fitted on all four wheels. On bare asphalt and concrete pavements, in wet, dry, or snow conditions, studded tires are not superior with respect to stopping ability and are often significantly inferior to conventional snow tires.
6. On icy surfaces, sanding contributes greatly to reduced stopping distances that are applicable to all types of tires.
7. Icy road conditions prevailed on the King's Highways in Ontario for only 1.1 percent of the day-miles. Bare, wet pavements prevailed for 18.3 percent of the day-miles. Slush or snow cover prevailed for 34.6 percent of the day-miles. For the remaining 46 percent, pavements were bare and dry during the winter months.
8. A limited analysis of winter accidents failed to show that studded tires contributed significantly to the reduction of the number and the severity of accidents or the chance of accident on icy roads. No judgment is possible on the adverse effects of the loss of traffic markings or the year-round effects of rutting resulting from wear.

When consideration is given to performance data, prevailing road conditions, accident statistics, and problems and costs associated with pavement and traffic-marking wear, it appears that the use of studded tires offers few benefits to the safe and economical operation of highway transportation in Ontario. As a result of these findings, the use of studded tires in Ontario is prohibited with effect from May 1, 1971 (by Regulation 423/70 under the Highway Traffic Act).

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RESISTANCE OF VARIOUS TYPES OF BITUMINOUS CONCRETE AND CEMENT CONCRETE TO WEAR BY STUDDED TIRES

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The objective of this investigation was to determine through field tests and literature review the resistance of different types of concrete and bituminous mixtures to wear by studded tires and to establish mix design criteria for better resistance to wear. A simple and practical apparatus was developed for measuring wear in the field. The rate of wear, calculated from traffic data and the wear profile, is defined as the average wear depth of a 6-in. wide strip of pavement caused by 100,000 passes of studded tires. The wear rate of concrete slab surfaces during a 4-year period was determined. Six concrete mixtures and six bituminous mixtures were subjected to investigation at a tollgate. Wear rate of pavement on the highway was also estimated by observing the change in color of cylinders inserted in the pavement flush with the surface.

•IN THE PAST few years, many investigations were made to evaluate the safety aspect of studded tires and their effect on the wear of road surfacing. A list of publications dealing with the subject is given elsewhere (1) and is also included in this report (11 through 33).

Almost all published data concerning the relative resistance to wear of different types of bituminous and cement concrete surfaces by studded tires are of European origin. Through special studies and literature survey, this report attempts to (a) give an indication of the rate of wear of conventional portland cement concrete and bituminous concrete mixtures used in the United States and Canada; (b) identify the relative importance of factors affecting wear; and (c) establish mix design criteria for wear-resistant mixtures.

DEFINITION OF RATE OF WEAR

In this paper the rate of wear is defined as the average wear in depth of a 6-in. wide strip of pavement in the wheelpath produced by 100,000 passes of the studded tires.

$$W_{100,000} = \frac{\delta 10^5}{(a + 2b)T\phi}$$

where

δ = maximum wear depth along the wheelpath;
T = total number of vehicles passing in a given traffic lane;
a = fraction of vehicles with rear wheels equipped with studded tires;
b = fraction of vehicles with front and rear wheels equipped with studded tires; and
ϕ = fraction of vehicles passing in the 6-in. strip of pavement (average width of tire) with maximum wear.

Sponsored by Task Force on Effect of Studded Tires and presented at the 50th Annual Meeting.

The value of ϕ is derived from the shape of the wear profile as follows:

1. If the shape follows a rectangular distribution pattern, then $\phi = 6$ in./ω, where ω is the width of the wheelpath.
2. If the shape follows a normal distribution pattern, then ϕ is equal to the area under the normal curve between ±3 in. from the center.

MEASUREMENT OF WEAR

A special instrument was developed to measure the change in profile of the pavement in the wheelpath. As shown in Figure 1a, the instrument is a 12- by 36-in. rigid aluminum frame with a mobile beam to which a recording device is attached. The measuring device shown in Figure 1b can be moved freely in the channel of the frame by turning the wheel. Any change in the profile is recorded on profile paper by virtue of a device that amplifies the vertical displacement of the contact point with the pavement.

At each station, the instrument is set on three initially fixed reference points in the pavement, and the first profile is recorded. Prior to each measuring of any change in profile, the instrument is set at zero with the end points of the initial profile. Readings in time are recorded on the original profile paper for each station.

The apparatus weighs 30 lb. It can be used to record a profile of 30 in. maximum width and $^3/_4$ in. maximum depth. Only a few minutes are required for tracing the profile at a test site. The repeatability of the profile is approximately $^1/_{60}$ in.

GENERAL TESTING CONDITIONS

The rate of wear of a pavement by studded tires is influenced by many factors (1). The measurements were carried out under the following atmospheric conditions:

	Winter			
Condition	1966-67	1967-68	1968-69	1969-70
Snowfall, in.	73.9	52.7	90.8	77.3
Freezing index	1725	1893	1518	2064

The pavement surface condition was nearly always clean because of snow removal and salt spreading. The percentages of cars equipped with studded tires were as follows: 9 percent, 1966-67; 22 percent, 1967-68; 47 percent, 1968-69; and 38.5 percent, 1969-70. No trucks were equipped with studded tires. The number of studded tires per car was as follows: 98.9 percent had studded tires (90-120) on rear wheels, and 1.1 percent had studded tires on front and rear wheels.

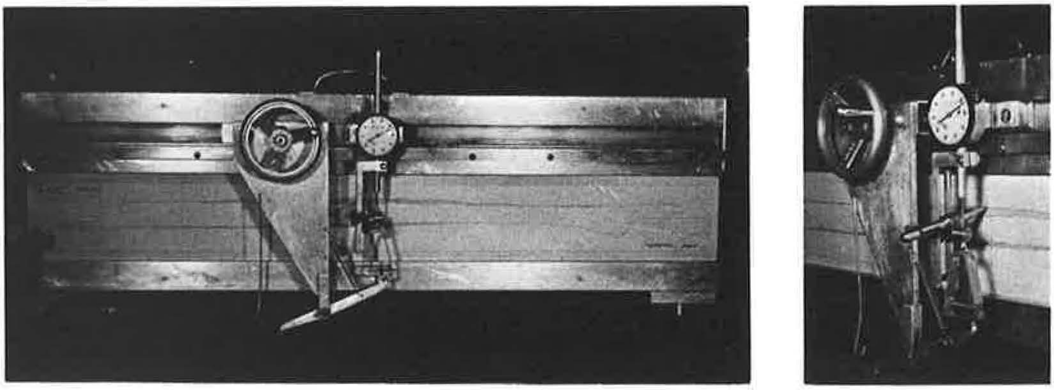

Figure 1. Profilometer used for wear measurements along wheelpath.

The nature of surfacing materials used and the traffic conditions to which the pavement was exposed during the different tests are described in the paper.

All the mixtures tested in this investigation were laid at the tollgate. The selection of a tollgate was motivated by the fact that (a) all cars are channeled in well-defined wheelpaths, (b) the number of cars passing through the lane is automatically recorded, and (c) the percentage of cars equipped with studded tires can be easily determined through periodic surveys.

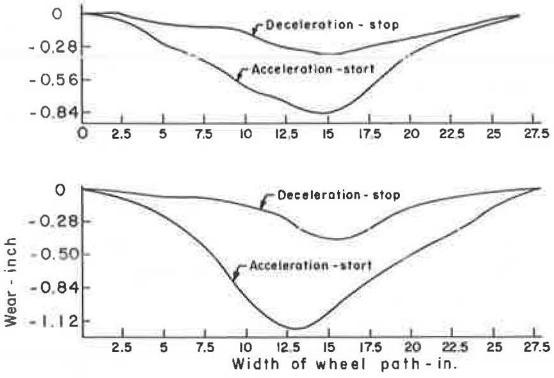

Figure 2. Typical profiles of pavement wear near Laval tollbooths.

WEAR PROFILES ACROSS WHEELPATH

The profile of wear of a pavement surface depends on the distribution of wheel loads across the wheelpath. Examination of wear profiles of numerous pavement sections investigated suggests that the shape of the wear profile along the wheelpath depends on its width, and may vary from the shape of a normal distribution for a narrow wheelpath to the shape of a more or less rectangular distribution (more exactly a flat-topped platykurtic distribution) for a wide wheelpath.

Figure 2 shows two typical profiles of pavement wear near a tollbooth where the wheel loads were channeled in a 27.5-in. wheelpath. The amount of wear decreases systematically from the point of maximum wear to the edges of the wheelpath.

Figure 3 shows a comparison of the shape of the wear profile along the wheel track and the shape of normal distribution. Each point on the graph represents the sum of 14 wear values taken from the wear profiles of the individual tollbooth lanes made with the same concrete at an equal distance from the maximum value. The wear profile follows very closely the pattern of the curve of a normal distribution.

If the traffic is not channeled, as is the case on unmarked pavement or on pavement where the white line has disappeared during the winter, the profile of wear of the pavement surface follows more or less a rectangular distribution. Many profiles measured along the wheelpath of the pavement of the Montreal Laurentian Autoroute substantiate this statement.

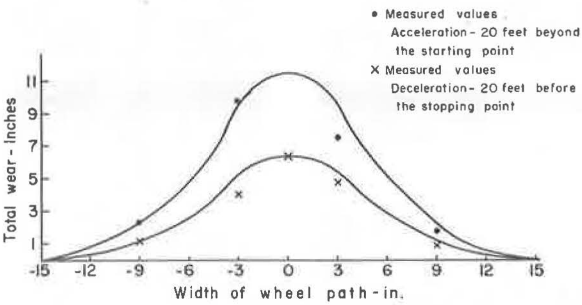

Figure 3. Wear of pavement surface near 14 tollbooths at Laval.

Figure 4 shows the results of measurements taken of wheelpath widths at intersections in Montreal. These measurements were made during the fall and represent the width of the worn portion of a transverse pavement marking across the wheelpaths. The width of wheelpath is less than 2.5 ft for most streets, but in some cases it may reach 4.75 ft. It is, thus, reasonable to assume that the wear pattern may vary between the shape of a normal distribution curve and the shape of a rectangular distribution curve.

As shown earlier in this paper, to determine the rate of wear of a pavement surface, one must take into account the width of the wheelpath and the profile of the wear. Figure 5 shows the influence of the shape of the distribution and the width of the wheelpath on the calculated rate of wear. The relative wear is the ratio, expressed in percent, between the wear that would be caused with a given width of wheelpath and wear profile and the wear that would be caused if the traffic were centralized on a 6-in. band (average width of a tire). For example, if the wheelpath is 30 in. wide, the relative wear will be about 45 percent if the wear is centralized in a narrow band, which follows a normal distribution, and only 20 percent if the shape of the wear follows a rectangular distribution.

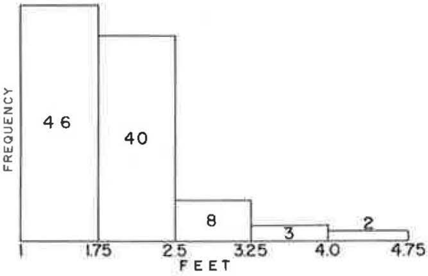

Figure 4. Width of wheelpath on pavement at 99 intersections in Montreal.

If a road is to be resurfaced whenever the wear in the wheelpath reaches a certain depth, more vehicles will have passed over a given section of road before it reaches critical depth if the pattern of wear is rectangularly distributed (125 percent more for the preceding example). Perhaps a way could be found to cause wheelpath wear to follow a more or less rectangular distribution pattern.

EFFECT OF STUDDED TIRES ON WEAR OF CONCRETE PAVEMENTS

Ordinary Concrete Pavement

The purposes of this test was to determine the rate of wear of an ordinary concrete pavement by studded tires during a 4-year period. The pavements of the lanes were built with the same 3,000-psi minimum compressive strength concrete made with coarse-crushed limestone aggregate and silica sand.

The wear measurements were made at two locations along one of the two wheelpaths of each of the 14 lanes: 20 ft from the starting point of the rear tires where the cars accelerate and 20 ft from the stopping point of the front tires where the cars decelerate. A summary of the calculated rate of wear is shown in Figure 6. Examination of the results indicates the following:

1. The average rate of wear after 100,000 passes of studded tires is 0.26 in. at the point of acceleration and 0.10 in. at the point of deceleration.
2. The average ratio between the rate of wear at the acceleration point and at the deceleration point is 2.3 in the north direction and 2.9 in the south direction. The difference between wear rates in both directions could be explained by the impatience of the drivers going to work in Montreal in the morning or driving back to Montreal after the weekend.

An evaluation was made of the rate of wear of the slabs during the 1969-70 winter season. Two lanes out of 14 were not resurfaced and were subjected to additional wear measurements. The results in-

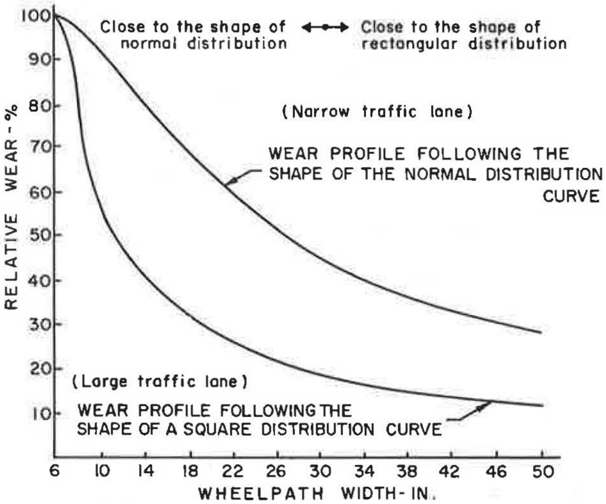

Figure 5. Relative wear of pavement in relation to shape of wear profile and width of wheelpath.

indicate that the wear rate obtained during the fifth winter (1969-70) is very close to those obtained during the four preceding years. The appearance of the wheel track after 400,000 passes of studded tires is shown in Figure 7.

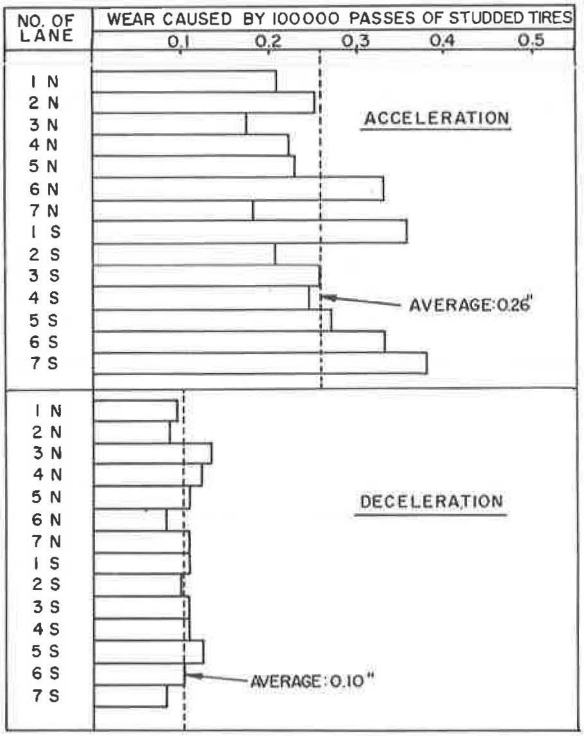

Figure 6. Average wear on concrete lanes at Laval tollbooth.

Concrete Properties and Its Constituents

A testing program was prepared to determine whether the type of coarse aggregate, its nominal size, or concrete compressive strength has significant influence on the rate of wear of concrete pavement by studded tires. The characteristics of the test slabs are given in Table 1. The type of concrete and the constituents used in this study comply with the CSA and the ASTM standards for ready-mixed concrete.

The relationship between the number of passes and the rate of wear is shown in Figure 8. The relationship is curvilinear at the beginning and linear after a number of passes. In the case of acceleration, the wear rate stabilizes at about 0.2 in. after 100,000 passes of studded tires, whereas, in the case of deceleration, the wear rate stabilizes at about 0.1 in. after 80,000 passes. For acceleration as well as for deceleration, the wear rate after 10,000 passes is about three times greater than the wear after 100,000 passes.

The effect of nominal size of aggregate, the nature of coarse aggregate, and the compressive strength on the wear rate are shown in Figure 9. For purposes of comparison, Figure 9 also shows the wear rate of the concrete slabs after 4 years of service at the Laval tollgate and the additional wear of the nonsurfaced slabs during the winter of 1969-70. These data indicate the following:

1. There is no significant difference between the wear rate of a concrete slab manufactured with a maximum size of limestone aggregate of 1½ in. and that of one manufactured with a maximum size of limestone aggregate of ¾ in.;
2. There is a significant difference between the rate of wear of a concrete slab manufactured with an igneous hard aggregate (lamprophyre) and that of one manufactured with a limestone aggregate (Fig. 9); and
3. There is no significant difference between the rate of wear of a concrete slab having a compressive strength of 5,000 psi and that of one having a compressive strength of 8,000 psi.

Figure 7. Appearance of concrete surface after 400,000 passes.

TABLE 1

CONCRETE TEST SLABS AT STE. THERESE TOLLGATE

Section	Compared Variables	Type of Coarse Aggregate	Nominal Size of Particles (in.)	Slump (in.)	Air Content (percent)	Compressive Strength (psi)
3N	Nominal size	Limestone	¾	3.25	7.8	4,140
6N	Nominal size	Limestone	1½	3.0	6.7	4,170
4N	Type of coarse aggregate	Limestone	¾	2.0	4.8	5,320
3S	Type of coarse aggregate	Lamprophyre	¾	3.0	6.2	4,970
5N	Type of coarse aggregate	Limestone	1½	3.5	7.6	3,645
6S	Type of coarse aggregate	Lamprophyre	1½	4.5	8.2	3,840
4S	Compressive strength, psi	Lamprophyre	¾	2.5	5.4	8,135
3S	Compressive strength, psi	Lamprophyre	¾	3.0	6.2	4,970

Discussion of Concrete Wear

A literature survey reveals that three previous studies have been made on the wear of portland cement concrete by studded tires (2, 3, 4). The New Jersey study (2) and the Maryland study (3) were carried out on concrete pavements, whereas the Swedish study (4) was made on laboratory and field samples in the laboratory.

The New Jersey study was carried out on a test track. The average pavement wear was about 0.01 in. for 4,990 abrupt stops and 0.013 in. for 1,400 panic stops. Assuming that the wear is concentrated along a wheel track of 24 in. and that the initial wear is about three times higher than the stabilized wear in a long term, the calculated rate of wear for abrupt stops will be about 0.25 in. for 100,000 passes of studded tires. This value is close to the one obtained at the point of acceleration at the Laval tollbooth.

In the Maryland study on an experimental road, the average wear after 10,000 passes was found to be 0.009 and 0.030 in. respectively for a passenger vehicle test loop and a truck test loop. If the same assumptions given previously for the New Jersey study are used, the calculated rate of wear becomes 0.12 in. for a passenger car, which is close to 0.10 in. per 100,000 passes found at the point of deceleration in this study.

The study by B. Örbom of the National Swedish Road Research Institute (4) was carried out in the laboratory with a special wheel-test machine installed in a cold room. The

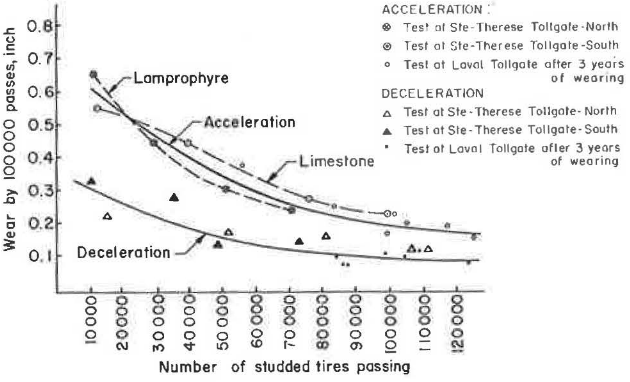

Figure 8. Relation between number of studded tires passing and wear of concrete slabs.

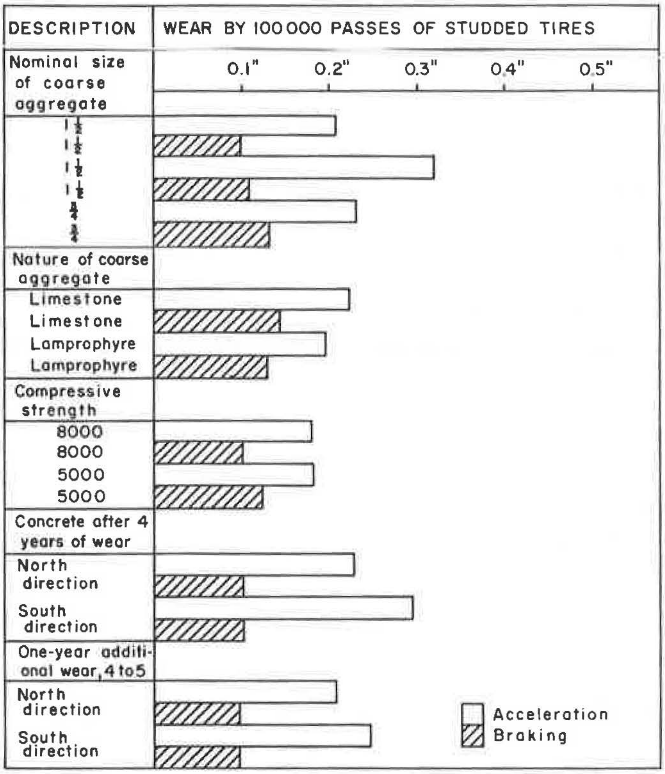

Figure 9. Resistance of various types of concrete mixtures to wear by studded tires.

principal variables studied were cement content; type, shape, and amount of coarse aggregate; and consistency of concrete.

As in the study described in this paper, Örbom shows that the wear rate of all pavements was relatively high in the prime phase of the tests but decreased later when the number of coarse aggregate pieces protruding above the abraded surface increased. Örbom's study also indicates that older cement mortar offers better resistance to wear and that resistance to wear is improved by minimizing the segregation during placement, which causes the accumulation of mortar in the surface layer.

Table 2 gives the effects of different factors on the resistance of concrete pavement to wear by studded tires. From Table 2 it is reasonable to conclude that the resistance of a portland cement concrete surface of wear by studded tires can be improved by using as great an amount as possible of sound, hard, and durable aggregate in a uniform concrete mix with very little mortar exposed on the surface.

It was also found in this study that the wear rate at places of acceleration is more than two times greater than at places of deceleration. This result is in opposition to Wehner's findings (5). This can be explained by the fact that, in the United States and in Canada, passenger cars are equipped with studded tires on rear wheels only, whereas in Germany most passenger cars are equipped with studded tires not only on the rear wheels but also on the front wheels, which bear about 70 percent of the load during braking.

EFFECT OF STUDDED TIRES ON WEAR OF ASPHALT PAVEMENTS

Various Types of Bituminous Mixtures

The purpose of this test was to determine the effects of various types of mixes, conventional and special, on the rate of wear of bituminous pavement by studded tires. The

TABLE 2

EFFECT OF FACTORS ON RESISTANCE OF CONCRETE PAVEMENT TO WEAR BY STUDDED TIRES

Factor	Influence on Wear	Ratio
Number of passes of studded tires[a]		
10,000 vs 100,000 passes	Very significant	3:1
Cement content[b]		
325, 350, and 400 kg/m^3	Not significant	–
Amount of coarse aggregate[b]		
55, 61.5, and 73.5 percent	Significant	1.6:1.1:1
Size of coarse aggregate[a]		
¾ vs 1½ in.	Not significant	–
Type of coarse aggregate		
Granite, gneiss, diabases, quartzite, and sandstone[b]	Not significant	–
Limestone vs lamprophyre[a]	Significant	1.3:1
Shape of coarse aggregate[b]	Not significant	–
Age of mortar[b]		
2 months vs 11 years	Very significant	2:1
Compressive strength of concrete		
502 vs 645 kg/cm^2[b]	Not significant	–
4,970 vs 8,135 psi[a]	Not significant	–

[a] Data taken from Keyser's work (1). [b] Data taken from Örbom's work (4).

properties of the bituminous mixtures used are given in Table 3. Twelve types of mixes were compared as follows:

1. Three conventional mixes—sheet, stone-filled, and bituminous concrete made with limestone aggregate and silica sand;
2. Three special gap-graded mixes composed of sheet containing respectively 30, 40, and 50 percent one-size coarse limestone aggregates passing the ¾-in. sieve and retained on the ⅜-in. sieve; and
3. Three conventional mixes and three gap-graded mixes that were the same as in 1 and 2 except made with lamprophyre of igneous origin instead of limestone.

The criteria on which the design of special mixes are based are given in the discussion of this section. All bituminous mixes were of good quality and complied with the

TABLE 3

ASPHALT CONCRETE MIXTURES USED IN STUDY OF RESISTANCE TO WEAR BY STUDDED TIRES

Section	Type of Grading	Type of Mixture	Type of Coarse Aggregate	Bitumen Content (percent)	Gradation (percent passing): Retained No. 4 Sieve	Gradation (percent passing): No. 4 to No. 200 Sieve	Gradation (percent passing): Passing No. 200 Sieve	Stability	Voids in Mixture (percent)
N1	Discontinued	AE[a], 50 percent	Limestone	6.0	31	61	8	2,240	3.9
N2	Discontinued	AE[a], 40 percent	Limestone	5.3	37	57	6	2,450	4.7
N3	Discontinued	AE[a], 30 percent	Limestone	5.9	30	63	7	2,200	3.6
N4	Fine	Sheet	Limestone	7.6	0	90	10	1,665	5.1
N5	Stone sheet	Stone-filled	Limestone	5.8	20	70	10	2,245	3.2
N6	Dense	Bituminous concrete	Limestone	5.8	40	53	7	2,515	1.5
S6	Discontinued	Bituminous concrete	Lamprophyre	5.2	27	70	3	2,180	4.7
S5	Stone sheet	Stone-filled	Lamprophyre	5.9	11	79	10	2,100	3.8
S4	Fine	Sheet	Lamprophyre	8.2	0	87	13	1,300	4.0
S3	Discontinued	AE[a], 30 percent	Lamprophyre	6.2	26	66	8	1,870	4.5
S2	Discontinued	AE[a], 40 percent	Lamprophyre	4.8	45	47	8	2,120	4.1
S1	Discontinued	AE[a], 50 percent	Lamprophyre	4.6	50	44	6	2,810	2.8

[a] Elementary aggregate ½ in.

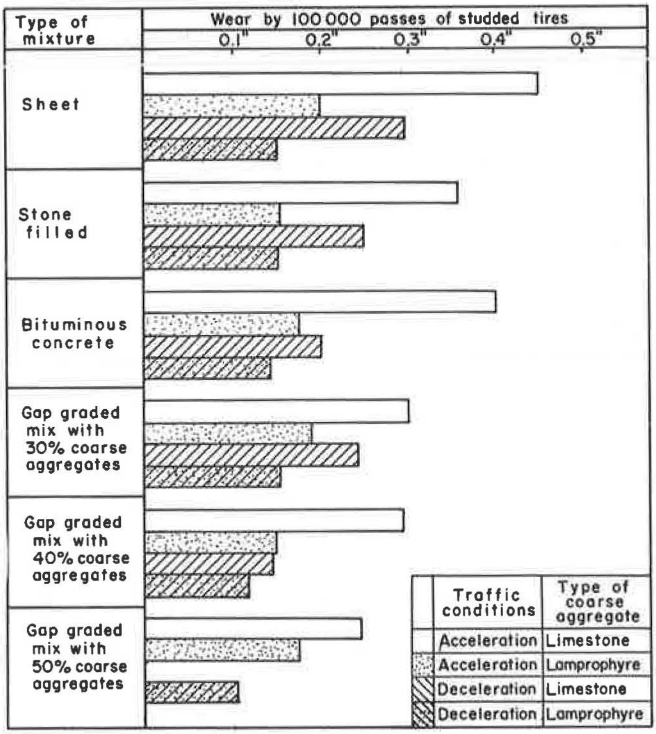

Figure 10. Resistance of various types of bituminous mixtures to wear by studded tires.

physical requirements of standard specifications for surface mixes. Figure 10 shows the results obtained with different mixes at places of acceleration and deceleration. The wear measurements were made at two locations along one of the two wheelpaths of each of the 12 lanes: 17 ft from the starting point of the rear tires where the cars accelerate and 15 ft from the stopping position of the front tire where the cars decelerate. In the calculation of the wear caused by 100,000 passes of studded tires, it was assumed that the wear profile follows the shape of a normal distribution curve. The following observations are made based on data shown in Figure 10:

1. The mixes can be classified in the order of a decreasing rate of wear: sheet, stone-filled sheet, bituminous concrete, and gap-graded mixes with 30, 40, and 50 percent coarse aggregate. By considering the results obtained at the point of acceleration, we note that the wear caused by studded tires can be reduced from 150 to 200 percent through the use of special mixes.
2. Figure 11 shows the influence of the type of coarse aggregate on the resistance to wear and the variation of wear with the type of mix. There is a relationship between the type of coarse aggregate and the rate of wear. For example, lamprophyre, an igneous hard rock, offers a better resistance to wear than limestone, a sedimentary rock. In fact, the average ratio of the rate of wear of limestone mixes to that of lamprophyre mixes is 1.65 at the point of acceleration and 1.15 at the point of deceleration.
3. For special gap-graded mixes, there is a relationship between the coarse aggregate content and the wear resistance. The mixes containing the most coarse aggregates offer a better resistance to wear.

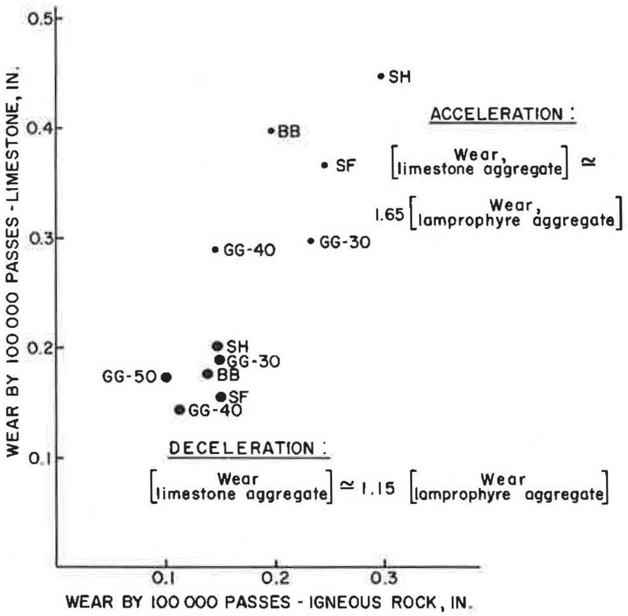

Figure 11. Effect of type of coarse aggregate on resistance to wear by studded tires.

Experimental Overlay

The purpose of this test was to determine the rate of wear of four types of conventional bituminous overlays under normal traffic conditions. Mix types tested were (a) stone-filled sheet with coarse limestone aggregate, (b) stone-filled sheet with coarse lamprophyre aggregate, (c) bituminous concrete with coarse limestone aggregate, and (d) bituminous concrete with coarse lamprophyre aggregate.

The characteristics of the stone-filled sheet mixes and the bituminous concrete mixes are given in Table 4. The characteristics of the stone-filled sheet comply with The Asphalt Institute Vb mix, and those of the bituminous concrete comply with The

TABLE 4

SUMMARY OF TESTS ON BITUMINOUS OVERLAYS

Designation	Lamprophyre		Limestone	
	Stone-Filled	Bituminous Concrete	Stone-Filled	Bituminous Concrete
Gradation, percent passing				
$^3/_4$ in. sieve	100	100	100	100
$^1/_2$ in. sieve	97	93	95	96
$^3/_8$ in. sieve	80	75	83	79
No. 4 sieve	72	54	75	60
No. 8 sieve	69	51	69	54
No. 16 sieve	52	37	55	41
No. 30 sieve	40	26	42	32
No. 50 sieve	30	19	31	24
No. 100 sieve	13	9	15	11
No. 200 sieve	4	4	6	4
Bitumen content, percent	5.8	5.3	5.9	5.0
Voids in mixture, percent	3.2	0.9	2.7	2.0
Voids between aggregate, percent	17.2	14.3	17.0	14.3
Degree of compaction	96.8	99.0	97.3	98.0

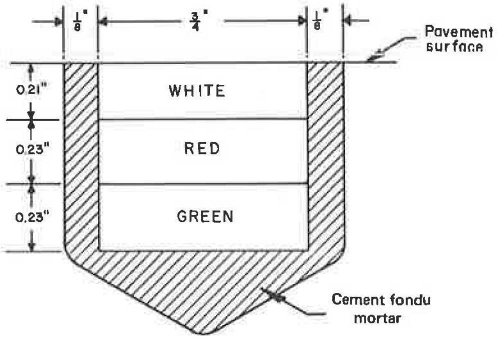

Figure 12. Cylinders of colored bituminous mixes used in overlay tests.

Asphalt Institute IVb mix. The degree of compaction of the overlay was higher than 95 percent in all cases.

Stations for measurement were installed along the Montreal Laurentian Autoroute: 11 on the curves, and 12 on the straight sections. Reference marks were set to measure the wear of pavement with the profilometer. Cylinders made of bituminous mixes consisting of three layers of a different color, each layer with a known thickness, were driven into the pavement 1 ft in front of each measurement station (Fig. 12). To ensure that at least one cylinder was in the wheelpath, three cylinders were obliquely placed at each measurement station along the wheel track: 1 ft, center to center, in the transverse direction; and 6 in., center to center, in the longitudinal direction.

After 1 year of wear, cross sections were taken at measurement stations. It was noted that, in most cases, the wear was spread over a much larger surface than the one predicted by the width of the profilometer (30 in.) because of the fact that traffic was not directed between the white traffic lines during the winter. This fact altered our measurements. On the other hand, it was noted that many cylinders inserted in the pavement were worn down to the next color (Table 5), indicating that the wear of the surfacing had exceeded 0.21 in. in certain spots.

The following observations are based on a comparison of the ratios of the number of stations where cylinders had worn from white to red (the wear of surfacing exceeding 0.21 in.) to the total number of stations:

1. Overlays with limestone aggregate on straight sections and those on curved sections were practically worn out at the same rate.

	Ratio of Red to Total	
Section	Stone-Filled	Bituminous Concrete
Straight	3:3	1:2
Curve	2:2	1:2

2. The bituminous concrete mix provided a better resistance to wear than the stone-filled sheet mix.

	Ratio of Red to Total	
Mix	Limestone	Lamprophyre
Bituminous concrete	2:4	0:2
Stone-filled sheet	5:5	1:2

3. Mixes made with lamprophyre aggregates provided a better resistance to wear than those produced with limestone.

	Ratio of Red to Total	
Aggregate	Stone-Filled	Bituminous Concrete
Coarse lamprophyre	1:2	0:2
Coarse limestone	5:5	2:4

TABLE 5

RELATIVE WEAR OF BITUMINOUS OVERLAYS AFTER ONE YEAR OF SERVICE

Mix	Aggregate	Straight Section			Curved Section		
		Ratio of Red to Total	Station	Color	Ratio of Red to Total	Station	Color
Stone-filled	Limestone	7:9	2	RRR	6:6	4	RRR
			3	RWW		14	RRR
			13	RRR			
	Lamprophyre	2:6	10	WRR			
				WWW			
Bituminous concrete	Limestone	3:6	6	RRR	3:6	5	WWW
			17	WWW		15	RRR
	Lamprophyre	0:9	8	WWW			
			9	WWW			

Table 6 gives an estimate of the average wear of the bituminous overlays in inches per 100,000 passes under normal traffic conditions. It shows that, assuming a minimum total wear of 0.21 in., the minimum wear rate is equal to approximately 0.11 in. per 100,000 passes.

Based on the comparison of results given in Table 6, the estimated value might be too low for stone-filled sheet with limestone aggregate and too high for bituminous concrete made with lamprophyre. It is likely to be realistic for stone-filled sheet with lamprophyre and bituminous concrete made with limestone aggregate. The wear rate for bituminous overlays of 0.11 in. per 100,000 studded tire passes is about 40 percent lower than the wear rate found for bituminous concrete and stone-filled sheet at the Laval tollgate at the point of deceleration.

	Wear per 100,000 Passes, in.			
	Tollbooth Deceleration		Experimental Resurfacing	
Type of Mix	Limestone	Lamprophyre	Limestone	Lamprophyre
Stone-filled sheet	0.16	0.15	>0.11	0.11
Bituminous	0.18	0.14	0.11	0.11

Discussion of Asphalt Wear

A literature survey reveals that several studies have been made on the rate of wear of bituminous concrete overlays by studded tires. An attempt will be made in the following discussion to (a) compare the rates of wear reported in the literature to those

TABLE 6

AVERAGE WEAR OF BITUMINOUS OVERLAYS UNDER NORMAL TRAFFIC CONDITIONS

Item	Northbound	Southbound
Number of vehicles equipped with studded tires (3 lanes)	3,297,019	3,533,300
Number of vehicles in the central lane (0.4 x total)	1,318,807	1,413,320
Number of studded tire passes		
36-in. wheelpath	217,603	233,198
48-in. wheelpath	171,445	183,732
Pavement wear, in. per 100,000 studded tire passes		
36-in. wheelpath	0.10	0.09
48-in. wheelpath	0.12	0.11

found in our study, (b) give relative wear of different types of bituminous mixes, (c) outline the factors influencing the resistance of bituminous mixes to wear, and (d) establish mix design criteria for wear-resistant bituminous mixtures.

In a report published by the National Road Research Institute (6), Rosengren states that "the maximum wear depth in the wheel-tracks in Finland and Norway has been computed at 20 mm per one million passes, in each direction, by stud-equipped vehicles.... In Germany, wear amounted to 28-35 mm per one million passes at constant speed on the straight-ahead section."

If we assume that the shape of wear follows a normal distribution curve along a wheelpath of 24 in. and that the cars are equipped with four studded tires 6 in. wide, the computed wear per 100,000 passes of studded tires is equal to about 0.07 in. for Finland and Norway and between 0.10 and 0.12 in. for Germany. These values are similar to the mean value of 0.11, with a possible range of ±0.03 in.

The studies made by Wehner in Germany (5) also give the ratios of wear for straight driving to wear for curves, acceleration point, and deceleration point. They are 1:1.1, 1:1.3, and 1:2.6 respectively. These figures are not in complete agreement with the results of our study. The corresponding figures in our investigation are approximately 1:1.1, 1:2.8, and 1:1.4.

The higher rate of wear at deceleration than at acceleration found in Europe and the reverse figures found in our study are attributable to the fact that in Europe nearly all passenger cars are equipped with four studded tires, whereas in America nearly all cars are equipped with studded tires on the rear wheels only.

Table 7 gives the relative resistance to wear of different types of bituminous mixes. Examination of the data allows the following observations:

1. The standard mixes conforming to The Asphalt Institute or the ASTM mixes are less resistant to wear than the mixes commonly used in Europe known under the name of mastic, gussasphalt, rolled asphalt, or Topeka;
2. As indicated by our study, it is possible to design bituminous mixes that will have considerably higher resistance to wear than conventional mixes.

Table 8 gives the effect of different factors contributing to the resistance to wear of asphalt pavement by studded tires. From Table 8, it is reasonable to conclude that the resistance of bituminous surfacing to wear can be improved by designing a mix with an optimum stone-to-mortar ratio. This will ensure that (a) the surface of the bituminous

TABLE 7

RELATIVE WEAR OF BITUMINOUS MIXTURES

Source	Asphalt Institute Formulas	Aggregate		Filler	Bitumen	Relative Wear	Notes
		Coarse	Fine				
Anderson et al. (7)	–	38	40	22	9.1	1	Mastic asphalt
	–	35	47	18	7.1	1.1	Topeka
	IVb	60	30	10	6.8	1.3	Asphaltic concrete
Huhtala (8)	VIa	38	50	12	7.6	1	Topeka
	IVb	64	28	8	5.4	1.2	Asphaltic concrete-gravel
	VIa	54	38	8	5.4	1.3	Asphaltic concrete
Keyser (1)	–	54	40	6	4.7	1	Skip-special
	–	47	46	7	5.0	1.2	Skip-special
	–	42	51	7	5.7	1.2	Skip-special
	IVa	50	47	3	5.2	1.6	Asphalt concrete $^0/_{12}$
	VIa	28	63	9	6.0	1.5	Stone filled
	VIIa	5	85	10	8.0	1.8	Sheet asphalt
Thurmann-Moe (9)	–	38	32	30	9	1	Gussasphalt
	IVa	57	35	8	6	1.5	Asphaltic concrete
	–	47	37	16	5.8	1.5	Rolled asphalt
Peffekoven (10)	–	49	43	8	7.2	1	Rolled asphalt
	–	46	32	22	7.4	1.1	Gussasphalt
	IVa	60	33	7	7.5	1.2	AC-$^0/_{12}$
	Va	51	39	10	6.6	1.4	AC-$^0/_8$
	Va	52	39	9	6.6	1.5	AC-$^0/_8$

TABLE 8

EFFECT OF FACTORS ON RESISTANCE OF ASPHALT PAVEMENT TO WEAR BY STUDDED TIRES

Factors	Influence on Wear	Wear Ratio
Penetration of bitumen[a]		
60 vs 300	Significant	1:1.3
Bitumen content[a]		
5 vs 7 percent (opt. at 7 percent)	Very significant	1:1.8
Type of aggregate[b]		
Lamprophyre vs limestone	Very significant	1:1.6
Mix type[b]		
Special mix vs sheet	Very significant	1:1.8
Voids in mix[a]		
3 vs 7 percent	Significant	1:1.4
Uniformity[a]		
Asphalt concrete variation	Variation	X ± 42 percent
Vehicle speed[a]		
60 to 80 km/hr	Not significant	—
Vehicle weight[a]		
Car vs truck	Very significant	1:1.9
Tire pressure[a]	Not significant	—
Temperature[c]		
37 ± vs 50 F	Very significant	1:1.5

[a] Data taken from Thurmann-Moe's work (9).
[b] Data taken from Keyser's work (1).
[c] Data taken from Huhtala's work (8).

layer is as rich as possible in durable stone (which can be achieved by proper gradation of the mix and the type of aggregate used); (b) the aggregate is solidly held in place by the mortar (which can be further improved by using a harder bitumen, an optimum asphalt content, and proper grading of fines); and (c) the mix can be uniformly laid and properly compacted.

In our study a successful trial was made to determine the optimum ratio between one size of stone and a high-quality sheet asphalt mortar. One size of stone was used to ensure a surface that was rich in coarse particles and solidly held into the matrix.

As shown by the values of the relative rate of wear given in the references, the resistance to wear of an asphalt wearing course can be very significantly improved by rolling coarse precoated chips into the surface. However, this practice may not be the best or the most economical solution for the following reasons:

1. Precoated chips will not provide a surface rich in coarse aggregates during the lifetime of the overlay. As Thurmann-Moe stated in his study (9), satisfactory results can be obtained with precoated chips if the stone content of the paving mixture does not exceed 35 percent. This means that poor performance of the overlay can be expected when the chips are worn out.
2. Treatment of pavement surface with precoated chips (which is practiced neither in the United States nor in Canada) will significantly increase the cost of the overlay pavement.

FURTHER STUDY

A laboratory test apparatus has been designed to measure the relative wear resistance of bituminous and concrete mixes. Preliminary tests on field samples show a good correlation between the relative wear obtained in the field and that obtained in the laboratory. A comprehensive study based on a statistical experimental design has been planned and is being carried out to evaluate the relative resistance to wear of different types of portland cement concrete and bituminous mixtures to wear by studded tires, all of which are designed according to the established criteria.

CONCLUSIONS

1. Rate of wear has been defined as the average depth of wear of a pavement caused by 100,000 studded-tire applications (in a 6-in. wide strip).
2. A simple and practical apparatus has been developed for measuring wear across the wheelpath.
3. The progress of pavement wear can be followed by inserting specially made colored cylinders into the pavement.
4. The wear profile of a narrow wheelpath follows the shape of a normal distribution pattern, whereas the wear pattern of a large wheelpath follows the shape of a platykurtic or a rectangular distribution.
5. The rate of wear of a new concrete pavement decreases with the number of passes of studded tires. The rate of wear after 10,000 passes is three times higher than the rate of wear after 100,000 passes.
6. The mean rate of wear of a concrete pavement stabilizes at the following values after 100,000 passes of a studded tire: acceleration, 0.26 in. per 100,000 passes; deceleration, 0.10 in. per 100,000 passes.
7. The resistance of a concrete pavement surface can be significantly improved by using the maximum possible amount of durable aggregate in a uniform concrete mix with a strong mortar matrix. As small an amount of mortar as possible should be exposed at the surface.
8. Bituminous mixes can be classified in the following order of decreasing rates of wear: sheet, stone-filled sheet, bituminous concrete, and gap-graded mixes with 30, 40, and 50 percent coarse aggregate.
9. The mean rate of wear of commonly used bituminous surfacings made with limestone aggregates expressed in inches of wear per 100,000 passes of a studded tire are as follows: acceleration, 0.36 to 0.44; deceleration, 0.18 to 0.20; and normal, 0.11.
10. The rate of wear can be reduced from 150 to 200 percent through the use of mixes made with hard and durable aggregates or by using special gradings.
11. In designing wear-resistant bituminous mixes, one must consider the following criteria: (a) the surface should be as rich in stone as possible; (b) the coarse aggregate should be durable and solidly held in place by the mortar; and (c) the produced mix should be uniformly laid and properly compacted. This can be achieved by ensuring a good balance between the quantity of sound, coarse aggregate of one size and the quantity of improved mortar in the mix.

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DISCUSSION

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Although Hode Keyser refers to laboratory studies in his paper, his study is essentially a field investigation, even though related laboratory studies are under way. It is particularly interesting for us in Minnesota to note that the results of our laboratory and field studies generally agree very well with his findings, even though there may be a few differences. There are several significant points covered in his paper that I would like to discuss in the following:

1. Rates of pavement wear—The initial rate of pavement wear is the most rapid, being about three times as rapid as the so-called terminal wear rate. The wear rate seems to stabilize at a depth of about 0.2 in. Our Minnesota tests agree remarkably well with these figures.

2. Concrete strength effect—It is stated that wear resistance of portland cement concrete pavement can be improved by using a strong mortar matrix along with the maximum possible amount of durable aggregate. However, it is also pointed out that there is no significant difference between the wear rate of one slab with a compressive strength of 5,000 psi and another with a strength of 8,000 psi. The Minnesota tests indicate that a stronger matrix (containing an additional 15 percent of cement) did not show much wear advantage. This also appears to be the case in our field tests, although this has not yet been fully established over an extended period of time. Although higher mortar strength may result in some slight wear improvement, the added cost is not yet fully justified.

3. Effect of kind of aggregate in concrete—The report indicates that there is less wear for concrete containing hard aggregate, such as igneous particles, than for concrete containing limestone aggregate. This is in agreement with the Minnesota findings that a gravel aggregate with a high proportion of igneous particles performs better with respect to wear than a limestone aggregate. The pavement containing limestone, which in our case had a Los Angeles rattler loss of 32, wore generally about 1.5 times as fast as the pavement containing gravel aggregate.

4. Effect of mortar at surface of portland cement concrete—Hode Keyser indicates that the amount of mortar at the surface of concrete should be as low as possible but should include an abundance of coarse aggregates. This is particularly pertinent to the initial wear rate on a new pavement, which is higher than the terminal rate that prevails as the wear progresses deeper. Again the Minnesota results confirm this finding. (Concrete of low slump design and placed with controlled vibration would probably help to prevent aggregate from settling excessively below the surface and thereby developing a thick layer of the less resistant mortar at the surface.)

5. Surface composition of asphaltic concrete—The results of this study indicate that in asphalt mixtures the surface layer should be as rich as possible in durable coarse aggregate particles with the least possible amount of mortar at the top. This is consistent with the Minnesota observations on asphaltic concrete having the lowest wear rate. In such a mixture the studs impinge more directly on the hard aggregate particles, which resist the abrasion more effectively than the mortar.

6. Effect of kind of aggregate in asphalt mixtures—The asphalt mixes containing the harder traprock wear less than mixes with the softer dolomitic limestone. The Minnesota tests agree with this finding. The average terminal rate for dolomite was 0.57 in. per million studded-tire passes. For traprock, the average terminal wear rate was 0.41 in. per million studded-tire passes.

7. Influence of aggregate size—according to Hode Keyser, the larger maximum aggregate size of $1\frac{1}{2}$ in. was no better than the $\frac{3}{4}$-in. size. In Minnesota we have no direct comparison with this, but fine-grained mixes (No. 4 maximum size) in the final laboratory test series were less wear resistant than the coarser asphaltic concrete.

8. In his conclusion Hode Keyser indicates that a good correlation was obtained between relative wear in the laboratory and in the field. The Minnesota results also substantiate this finding, notwithstanding the fact that other investigators previously reported that it was not possible to establish a good correlation between field and laboratory results.

Having compared the results of Hode Keyser's study with our results in Minnesota, I should like to present some information concerning Minnesota's recent research activities on the problem of studded-tire use in our state.

By way of background, the use of studded tires has been legal in Minnesota since the fall of 1965. We have, therefore, completed the sixth winter of exposure of pavements to studded tires. The percentage of automobiles equipped with studded tires during this time is shown in Figure 13. The decrease in 1970-71 may have been influenced by the possibility of a ban on studded tires. The 1965 legislature authorized a 2-year trial

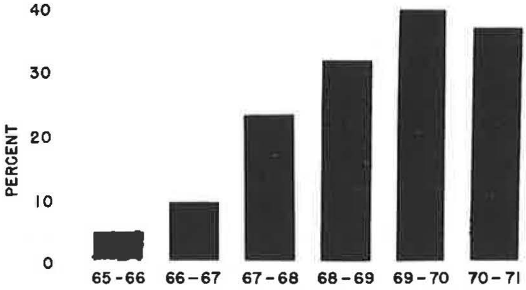


Figure 13. Automobiles in Minnesota equipped with studded tires.

period for the studs. Limited field tests were undertaken by the highway department, starting in the fall of 1964 with a car equipped with four studded tires, to observe particularly the effects of abrupt starting and stopping on both portland cement concrete and asphalt surfaces. Results of the field tests that had been continued in 1965 and 1966 demonstrated the potential for causing surface damage in areas of concentrated braking or acceleration, but it was thought that such wear, if localized, could be tolerated and could be repaired by special maintenance efforts. These tests did not, however, indicate strongly the type of extensive high-speed traffic wear that has been evident more recently.

The 1967 legislature consequently extended the use of studded tires for another 2-year period. Further field tests and observations again were considered to be insufficiently conclusive to justify the prohibiting of studs because, it was contended, any disadvantages or objections to studs were more than offset by the high safety benefits that were attributed to them. As a result, the 1969 legislature again authorized an additional 2-year extension and at the same time directed the department of highways to conduct an in-depth study of studded-tire effects.

Three specific objectives were outlined in the statute: (a) to determine the relative damage, if any, caused to Minnesota highways by metal studs, sand, and salt; (b) to determine if pavement surfaces could be made more resistant to stud damage by changing the aggregates or binder composing the pavements; and (c) to determine the effect on highway safety in Minnesota if studs were eliminated.

To pursue the first two objectives, the highway department expanded its field studies and initiated a laboratory pavement-wear study under a contract with the American Oil Company Research and Development Laboratory in Whiting, Indiana. The third objective was attained by contracting with Cornell Aeronautical Laboratory to conduct a study of the safety effectiveness of studded tires.

Notwithstanding the high estimated cost, approximately $300,000, the highway department, because of the urgency, undertook the projects independently to ensure obtaining the desired information in time to report to the 1971 legislature. Subsequently, we informed a number of other northern states of our program and invited their participation. In response, eight states joined with us, providing financial support in amounts ranging from $12,500 to $26,000 for a total of $161,000. The states are Illinois, Iowa, Michigan, New York, North Dakota, Pennsylvania, Utah, and Wisconsin.

The laboratory study at the American Oil Company was designed essentially to answer the four following questions:

1. How do the wear rates compare for various pavement types used in Minnesota?
2. What are the relative contributions to pavement wear of studs, salt, and sand?
3. Can surfacing courses be designed that economically will be capable of resisting stud-induced abrasion?
4. Can data obtained be used to estimate long-range wear rates caused by the use of studded tires?

The American Oil Company traffic simulator is a 14-ft diameter turntable type of machine with the capability of accommodating 12 pavement test slabs trapezoidal in shape and 2 ft wide (Fig. 14). The two cross-arm beams are each fitted with a regular size automobile wheel and tire at each end and are rotated by a central supporting drive post. In the test the wheels are loaded to 1,000 lb each, and the assembly is rotated with the wheels rolling freely at 35 mph while temperature is maintained at 25 F ±5 F. Special mechanisms permitted the application of sand or salt or both on the pavement surfaces in front of the rotating wheels to simulate conditions typical of those existing on Minnesota highways during the winter.

Figure 14. Test simulator test track of American Oil Company.

The tests were arranged in four series, three of which were made on both asphalt and portland cement concrete pavement types representative of those commonly used in Minnesota, and the fourth on a variety of specially designed surfacing courses to evaluate their relative capability of reducing the wear effects of studs. Each of the first three series was divided into two subseries: one in which studded tires were run over the test pavements, and one in which snow tires were run over the same slabs.

In the first three series, different deicing surface treatments were used: series 1 with sand and salt surface applications, series 2 with only salt applied, and series 3 with neither sand nor salt. From comparison of results of these three series, it was expected to be able to establish the relative wear contribution of each factor—studs, salt, or sand. For series 4, studs, sand, and salt were used and no tests were run without them, because the purpose was only to compare wear resistance under the most abrasive condition. The studded tires each contained 90 studs, with 15 in each of six circumferential rows. The protrusion of the studs beyond the surface of the tires was limited to between a minimum of 0.020 in. and a maximum of about 0.070 in. The studs used throughout the tests were all produced by one manufacturer. To obtain a uniform application of stud contacts on the test zone of the pavement surface, the machine had been modified so that each wheel was slowly moved radially a distance of 1.78 in. from its innermost to its outermost position. The full motion was very gradual, requiring 11 complete revolutions of the turntable. The overall stud contact width on the test slabs was 7.7 in. The resultant effect on the test slabs resembled the central portion of the approximately 36-in. width wheelpath on a typical roadway traffic lane.

Pavement mixtures used in the tests were composed of materials furnished by the Minnesota Department of Highways. The mixtures were designed, based on trial mixes made in the highway department laboratory. All materials were packaged in the Minnesota Department of Highways laboratory in exact proportions for each mix. The materials were then shipped to the American Oil Company where the mixtures and test slabs were produced under observation and with control tests by Minnesota personnel.

There were three asphalt test mixes, including the following:

1. Asphaltic concrete composed of dolomitic limestone coarse aggregate plus natural sand plus filler, with 85 to 100 penetration asphalt.
2. Modified asphaltic concrete consisting of crushed gravel coarse aggregate plus sand without filler and with 85 to 100 penetration asphalt.
3. An asphaltic mixture of intermediate type consisting of graded gravel and sand aggregate without filler and with 85 to 100 penetration asphalt.

Two of the mixes were replicated, making a total of five asphalt slabs. There were 5 portland cement concrete mixes:

1. Three gravel and sand mixes—two were with different gravels, one with 15 percent added cement;
2. One limestone with natural sand; and
3. One traprock with traprock sand.

A fourth test series was run, including a number of new and untried materials or mixtures that, based on a laboratory sandblast abrasion test, gave indications of possibly having improved wear resistance. These included eight bituminous mixes, three portland cement concrete mixes, and one epoxy and sand mix.

Figure 15. Four-inch portland cement concrete slab after test of 4 million tire passes (studded tires on right, tires without studs left of center, and original surface extreme left).

Each test was run up to a total of four million studded-tire passes or until the depth of the worn channel reached approximately 1.5 in. (Fig. 15). This maximum was fixed because of the mechanical limitation of the machine to operate to any greater depth. Operation of the test was continued around the clock with automatic controls to shut down operation in the event of any mechanical failure.

Most of the test runs were completed, although the series 3 tests of tires without studs were deleted from the schedule because the amount of wear produced by the tires without studs, even when salt was applied, was so insignificant as to not warrant running another test of tires without studs. Interpretation of the significance of the tests cannot be made until full analysis of the data and comparison of results of the several series are completed. A major consideration is the fact that the amount of wear is affected significantly by the length of protrusion of the studs beyond the tire surface. Therefore, wear rates must be adjusted to a common denominator of constant stud protrusion.

Test series 1 (conducted with sand and salt on road surface)—Test 1A used tires with studs. There were five specimens of asphalt with wear-rate depths that ranged from 0.54 to 0.75 in. per million studded-tire passes. There were also eight specimens of portland cement concrete with wear-rate depths ranging from 0.25 to 0.43 in. per million studded-tire passes. Test 1B used tires without studs. The average wear for all pavements was 0.0027 in. per million wheel passes. The studs produced more than 100 times as much wear as regular tires when sand and salt were applied.

Test series 2 (conducted with only salt on road)—Test 2A used tires with studs and with salt and no sand on road surface. This series generally corroborated the results of test 1A. Unexpectedly, the mixes containing 15 percent addition of cement with both

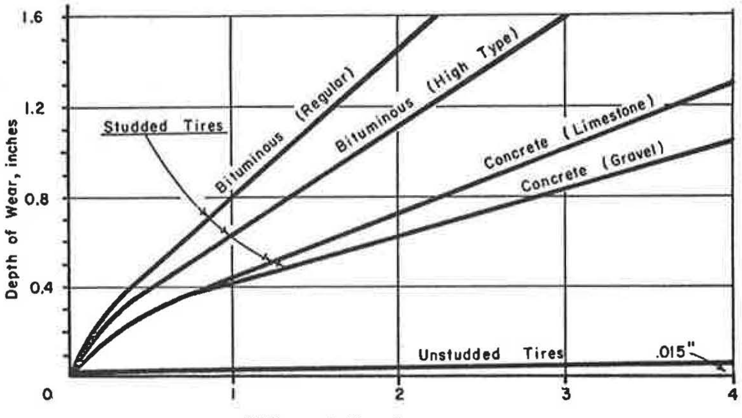


Figure 16. Wear rates of pavement specimens at test track.

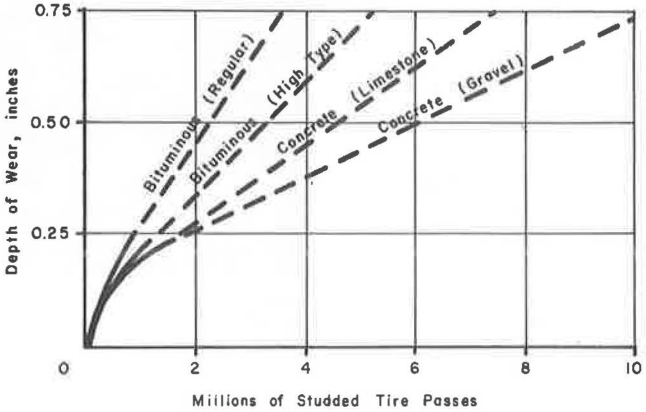


Figure 17. Wear rates of pavements of typical Minnesota highways.

types of aggregate—gravel and traprock—proved to be no better than the regular gravel mix. However, as mentioned previously, these results have not yet been adjusted for differences in stud protrusion. Test 2B, which used tires without studs on a road with salt, was postponed.

Test series 3 (conducted with no foreign material applied to road)—Test 3A used tires with studs. The results of this series were similar to test 2A that showed no significant effect of salt on the road. Test 3B used tires without studs. This series was deleted because plain tires show negligible wear on roads.

Test series 4—Of the three concretes, one with an application of a surface hardener and two with latex admixture showed no increase in wear resistance. One epoxy and sand mix was the most wear-resistant mixture, but the surface was extremely smooth and was so slippery as to be impractical for a road surface. Of the eight bituminous mixtures, four were the fine-graded type for thin overlays. Traprock and granite both performed quite well. Two were rubber and asbestos admixtures and showed a slight improvement. One with traprock instead of dolomite was somewhat improved. Traprock with rubber and asbestos reduced the wear by about 20 percent.

The wear rates of pavement at the test track and on typical Minnesota highways are shown in Figures 16 and 17. The relationships between test track wear and highway wear is shown in Figure 18.

Figures 19 through 22 show the pavement wear that has been experienced on Minnesota highways during the winters since the fall of 1965 when studded tires were first legalized in Minnesota. The photographs demonstrate the type of surface wear that has occurred on both asphaltic concrete and portland cement concrete pavements containing different aggregates, including gravel and crushed limestones.

The pavement wear developing on our high-traffic roads foretells the problems we may be expected to face in the future. Hazardous con-

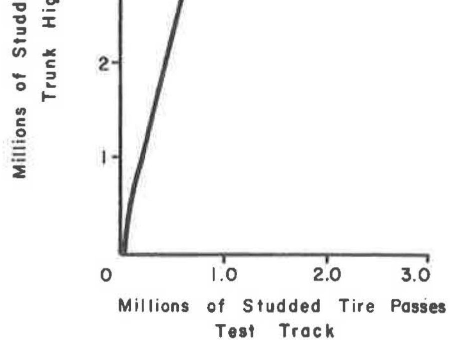
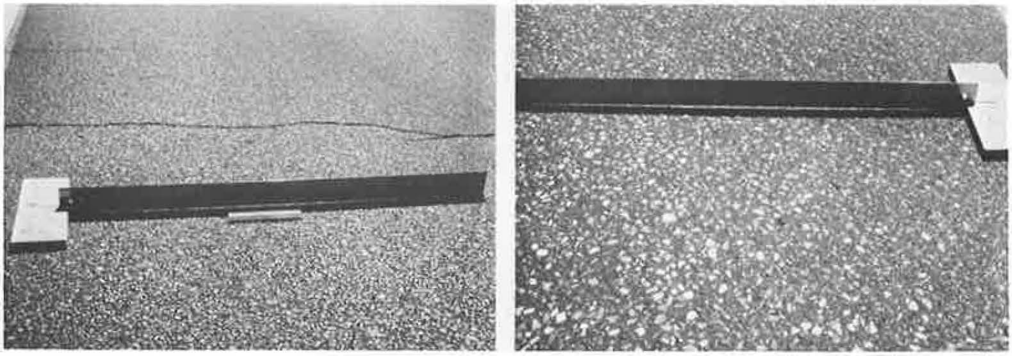


Figure 18. Relationship of wear between test track and highway surfaces.



after 215,000 studded tire passes during 1 winter

after 550,000 studded tire passes during 3 winters

Figure 19. Asphalt concrete surface with gravel aggregate.

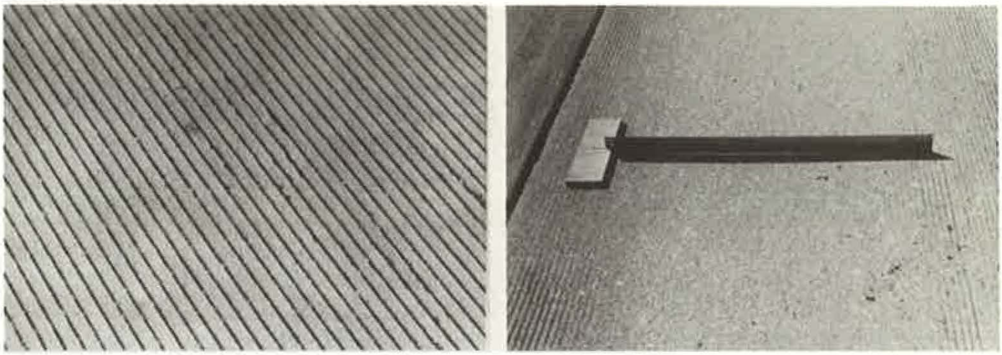
after 1,094,000 studded tire passes during 4 winters

after 1,700,000 studded tire passes during 5 winters

Figure 20. Portland cement concrete surface with hard gravel aggregate that wears less than mortar to produce rough, knobby texture.

after 213,000 studded tire passes during 3 winters

Figure 21. Portland cement concrete surface with limestone aggregate that wears same as mortar to produce smooth texture.



after 1 year and no traffic with studded tires

after 169,000 studded tire passes during 2 winters

Figure 22. Portland cement concrete surface with $\frac{1}{8}$ by $\frac{1}{8}$ in. safety groove on 1-in. centers.

ditions are being created that, we feel, will more than offset any advantages that could be ascribed to studded tires. Tremendous costs will be involved in repairing damage caused by the increasing use of studded tires. It would be far better for funds needed for repairing roads damaged by studded tires to be used instead for building new and safer roads and for making safety improvements on older existing roads.

AUTHOR'S CLOSURE

It is indeed interesting to note that our special field test results generally agree with those of the Minnesota laboratory and field studies. Based on the limited number of mixes tested (8 portland cement concrete mixes and 12 bituminous concrete mixtures) and the great number of factors affecting wear, it is not surprising to note a few differences between our two studies.

Preus indicates that higher mortar strength may result in some slight wear improvement. Studies made by the Swedish Road Research Institute have indeed indicated that old concrete pavement is, in fact, more resistant to wear than new pavement.

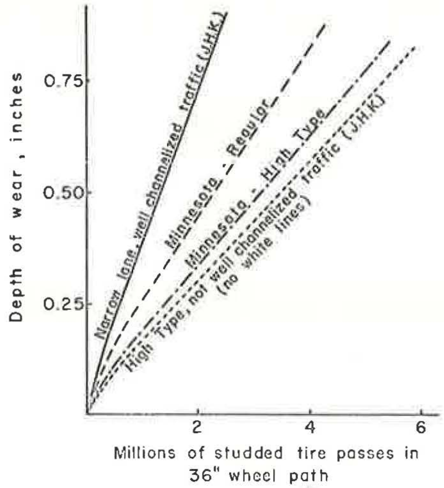


Figure 23. Estimated average wear rate of bituminous concrete pavement by studded tires.

As to the influence of aggregate size with portland cement concrete mixes, no difference was found between the 1½ and ¾ in. sizes. However, our laboratory test clearly shows, as the Minnesota study does, that with bituminous concrete mixture the resistance to wear is significantly influenced by the nominal size of coarse aggregate.

Figure 23 shows a comparison of the rate of wear obtained on typical bituminous pavements in Minnesota and the rate of wear obtained in our study. The curves were calculated for a 36-in. wide wheelpath. The steepest curve is calculated for a well-channeled traffic condition where the wear profile follows the pattern of a reversed bell-shaped curve of a normal distribution. The flattest curve is calculated for traffic that is uniformly distributed across the wheelpath. The 2 curves represent the extreme conditions that can prevail on a pavement.

EFFECTIVENESS OF STUDDED TIRES

Robert W. Smith and W. E. Ewens, Damas and Smith, Ltd.; and
Donald J. Clough, Department of Management Sciences, University of Waterloo

This paper describes the results of tests of the locked-wheel stopping distances of four tire combinations on glare ice, on wet and dry asphaltic concrete, and on wet and dry portland cement concrete pavements. Identical cars with highway tread tires on four wheels, with plain snow tires on the rear wheels, with studded snow tires on the rear wheels, and with studded snow tires on four wheels were tested at speeds up to 50 mph and at temperatures from -5 to 33 F. On glare ice, snow tires gave no consistent improvement in stopping distance, compared with standard highway tires. Studded tires on the rear wheels resulted in a significant reduction in stopping distance, and studded tires on all four wheels resulted in a reduction in stopping distance that was more than twice the reduction with studs in the rear tires only. The improvements were greatest at ice temperatures near the freezing point. While the improvements decreased with decreasing ice temperatures, these improvements did not disappear at temperatures near -5 F, as suggested by earlier research. On asphalt pavements, no significant differences in stopping distances were found on either wet or dry surfaces. On concrete pavements, studded tires were found to give small but significant increases in stopping distances on both wet and dry surfaces.

•STUDDED TIRES have now been in common use in Canada for a number of years, and research on both the advantages and the disadvantages of their use has been proceeding throughout this period. However, it was only with the publication of a report by Smith and Shonfeld (1) that there came into existence any general recognition of the costs to the public of damage done by studded tires to street and highway pavements. These costs for highways in southern Ontario alone were estimated at $127 million over the next 9 years.

Recognition of these costs and other disbenefits leads directly to the question of the value of the studded tires to the general public. This value may lie in convenience, resulting from an increased ability to start up on a slippery surface, or in enhanced safety, resulting from improvements in stopping distances, in cornering ability, or in tractive effort.

A review of technical literature revealed that tests of studded tires have been carried out by a number of agencies, mainly by those in other countries but also including significant work by the Royal Canadian Air Force (2) in 1965. The Highway Research Board has published a number of reports on studded tires. Perhaps the most important single document on the subject is a study by the National Cooperative Highway Research Program (3). The Committee on Winter Driving Hazards of the National Safety Council has carried out tests of studded tires on ice annually since 1964 (4) and has published reports of its test results (5).

The majority of identified test results was concerned with stopping distance tests on glare ice, almost all at low speeds (principally 20 mph). There seemed little reason to

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Sponsored by Task Force on Effect of Studded Tires and presented at the 50th Annual Meeting.

suppose that results arrived at elsewhere (particularly those of the National Safety Council, whose tests are conducted in northern Wisconsin) would not be valid in Canada. However, there did appear to be a question as to whether stopping distances derived at 20 mph could properly be considered as representative of stopping distances at other more typical speeds.

Some of the published research indicated, without establishing beyond question, that cars with studded tires may require greater stopping distances on some pavement surfaces than those required by cars with standard highway tires. As a result of this background, the Canada Safety Council in February 1970 engaged the firm of Damas and Smith to carry out the research reported in this paper. From other published test results, it was concluded that there were discrepancies between empirical test results and theoretical stopping distances on ice. A purely empirical approach was chosen for the research.

TESTING PROGRAM AND EQUIPMENT

The performance of any car in braking or traction is dependent on a multitude of factors, including tires, vehicle suspension system, surface conditions, driver action, and system action (the latter constituting the interaction of these and a variety of other identifiable and unidentifiable factors). In the case of studded tires, the relative importance of some of these factors may change, while others may be added—the number of studs, their size, their pattern of arrangement, the material of which they are made, and their shape and protrusion.

It was concluded that the effects of some of these factors are minor and that other variables might be fixed at average or representative values, thus enabling limited testing to produce meaningful results. At the opposite extreme, there are important variables whose values may be entirely fortuitous, such as ice and air temperatures. Between these two types, other variables are controllable, and their values and effects are, in some cases, of prime importance. Speed is outstanding among these.

In designing the research, we concluded that the stopping tests required measuring the important uncontrollable variables, controlling and measuring the more important controllable variables, and, so far as possible, fixing all other factors at single values. Thus, the tire characteristics were fixed at an average value by selecting tires of a single construction type and by frequent checking of tread wear and pressures. Similarly, the combined effects of the vehicle suspension system were nominally fixed by the use of identical vehicles. Driver actions could be fixed or their effects minimized by the use of highly disciplined drivers following very simple directions that would leave little room for the exercise of personal characteristics.

Four identical cars (new 1970 Chevrolet sedans) were fitted with the following tire combinations and were used to carry out stopping distance tests on glare ice, on wet and dry asphaltic concrete, and on wet and dry portland cement concrete pavements:

1. Standard highway tread tires on all four wheels;
2. Plain snow tires on rear wheels and standard highway tread tires on front wheels;
3. Studded snow tires on rear wheels and standard highway tread tires on front wheels; and
4. Studded snow tires on all four wheels.

The cars came equipped with belted bias tires. The snow tires selected for testing were also belted bias tires taking 122 studs. The only criteria used in selecting these tires were that they should have the same construction as the tires fitted to the cars by the manufacturer and that they should be readily available. It was hoped that they would, therefore, be representative of what the public might buy if seeking a good quality tire.

It was recognized that snow tires are not particularly suitable for use on front wheels and that, if studded tires were to be used on all four wheels, different tread patterns for front and rear wheels would be desirable. It was known at the time that one manufacturer was producing a special tire for use with studs on the front wheels, but this tire was not available in Canada. Consequently, it was necessary to settle for snow tires on all wheels in order to have studs on all wheels.

During the course of testing, the tires were checked daily for loss of studs and any excessive wear in either the studs or the tires. In addition, several daily checks were made to ensure correct tire pressures and the fitness of the vehicles and of the various testing devices. Replacement of most of the test tires became necessary following the first set of tests on dry pavement. Marking devices were used to mark the point of brake application. All of these were connected to the brake-light circuit.

Ice tests were conducted on Lake Vernon near Huntsville, Ontario. Pavement tests were conducted at three sites, all of which were provincial highways, selected on the basis of pavement type, level profile, and ease of detouring traffic. Two of the sites had pavements with HL1 asphalt mixes, 40 percent traprock, and 5.6 to 5.8 percent asphalt. These pavements were 1½ and 2½ years old, with annual average daily traffic (AADT) volumes of 3,500 and 4,800 vehicles. The third site was constituted of a concrete slab construction with a concrete surface, was 2½ years old, and had AADT volumes of 600 vehicles.

The stopping-distance tests were conducted at three speeds—20, 35, and 50 mph. The car was driven slightly above the test speed and then allowed to decelerate to the required speed. It was then brought to a skidding stop by locking the wheels and holding the steering wheel firmly in a straight-ahead position. Two Ontario Provincial Police drivers were used in rotation, with each driver completing at least four runs of each test series in each car.

A total of 599 observations of stopping distances on glare ice was recorded, with surface temperatures ranging from -5 to 33 F. A total of 581 observations of stopping distances on wet and dry pavements was also recorded.

ANALYSIS OF TEST RESULTS

Stopping Distance on Glare Ice

Mathematical Model—It was assumed that stopping distance is a function of two main factors—ice temperature and the speed when brakes are applied. It was assumed that the effects of all other factors could be adequately expressed as random error in which the standard deviation is proportional to the braking speed.

The first model for regression analysis purposes was specified as follows:

$$D_i = B_0 + B_1V_i + B_2V_i^2 + B_3T_i + B_4T_i^2 + B_5V_iT_i + V_ie_i \qquad (1)$$

where

i = 1, 2, . . . , n, the index number to identify sets of test factors;
D_i = distance to stop, ft;
T_i = temperature of ice, deg F;
V_i = velocity (speed) at which brakes are applied, mph; and
e_i = error, a random variable with a mean of zero and a standard deviation of σ.

The method of least-squares was used to fit the following regression equation to data for each of the four cars:

$$\overline{D_i} = b_0 + b_1V_i + b_2V_i^2 + b_3T_i + b_4T_i^2 + b_5V_iT_i \qquad (2)$$

where the b's are unbiased estimates of the unknown B's in Eq. 1.

After carrying out the standard regression analysis of variance and rejecting terms that were not statistically significant, we found that each of the four car types had a different set of statistically significant terms. It was also found that the signs of terms were such that negative values of D were obtained by extrapolation to the left of the ranges $0 \leq T \leq 32$ and $20 \leq V_i \leq 50$. Because of these inconsistencies, it was decided to eliminate the constant term and additive terms in T_i and T_i^2.

In the final analysis, the model was thus reduced to the following form:

$$D_i = B_1T_iV_i + B_2V_i^2 + V_ie_i \qquad (3)$$

For standard regression analysis purposes, this can be rewritten as follows:

$$(D_i/V_i) = B_1T_i + B_2V_i + e_i \tag{4}$$

The error term V_ie_i in Eq. 3 has a mean of zero and a standard deviation of $V_i\sigma$, while the error term in Eq. 4 has a mean of zero and a standard deviation of σ.

Estimation Equation—As a result of the preceding mathematical model analysis, the following regression equation was fitted to the data, using stepwise linear regression analysis, for each of the four cars:

$$D_i = b_1T_iV_i + b_2V_i^2 \tag{5}$$

where b_1 and b_2 are unbiased estimates of the unknown parameters B_1 and B_2 in Eq. 4. The following equations resulted.

1. Highway tire, four wheels (n = 99):

$$\overline{D}_i = 0.108\, T_iV_i + 0.250\, V_i^2 \tag{6}$$

2. Highway tire front, snow tire rear (n = 103):

$$\overline{D}_i = 0.090\, T_iV_i + 0.258\, V_i^2 \tag{7}$$

3. Highway tire front, studded snow tire rear (n = 91):

$$\overline{D}_i = 0.057\, T_iV_i + 0.232\, V_i^2 \tag{8}$$

4. Studded snow tire, four wheels (n = 98):

$$\overline{D}_i = 0.019\, T_iV_i + 0.202\, V_i^2 \tag{9}$$

The residual sum of squares for D_i/V_i in Eq. 6 was 100.54. Addition of a linear term V_i in Eq. 6 would reduce the residual sum of squares to 98.95. The reduction, 1.59, is not statistically significant because $F_{1,96} = 1.59/(98.95/96) = 1.54$.

The residual sum of squares for D_i/V_i in Eq. 7 was 146.84. Addition of a linear term V_i in Eq. 7 would reduce the residual sum of squares to 109.78. The reduction, 37.06, is statistically significant at the $\sigma = 0.01$ (99 percent) significance level, because $F_{1,98} = 37.06/(109.78/100) = 33.8$. However, the addition of the term V_i would yield a negative sign that is not acceptable when extrapolated.

The residual sum of squares for D_i/V_i in Eq. 8 was 45.46. Addition of a linear term V_i in Eq. 8 would reduce the residual sum of squares to 44.67. The difference, 0.79, is not statistically significant because $F_{1,86} = 0.79/(44.67/88) = 1.56$.

The residual sum of squares for D_i/V_i in Eq. 9 was 34.88. Addition of a linear term V_i in Eq. 9 would reduce the residual sum of squares by an insignificant amount.

Data Variations—In total, 599 tests were run on glare ice. However, the results of a number of tests were not used in the analysis. These were classified a priori as unsuitable because conditions changed during the tests (e. g., faults occurred in the ice) or because the accuracies of measurements were doubtful (e. g., thermometer readings of ice temperature were affected by local melting). The numbers of tests rejected and used for analysis were as follows:

Car	Total	Rejected	Used
Highway tire, four wheels	152	53	99
Snow tire, rear only	172	69	103
Studded snow tire, rear only	137	46	91
Studded snow tire, four wheels	138	40	98

After braking speed and ice temperature effects were accounted for, a good deal of variation in stopping distances remained. Such variations are the result of a multitude of factors not controlled in the tests and not included in the mathematical model. As noted in Eq. 1 or 2, the variations were described as values of a random variable $V_i e_i$, where e_i has a mean of zero and a standard deviation of σ. A sample standard deviation, s, was computed as an estimate of σ in each of the four cases, and the following results were compiled:

Car	s	$V_i s$	$2V_i s$
Highway tire, four wheels	1.018	$1.018V_i$	$2.036V_i$
Snow tire, rear only	1.206	$1.206V_i$	$2.412V_i$
Studded snow tire, rear only	0.716	$0.716V_i$	$1.432V_i$
Studded snow tire, four wheels	0.603	$0.603V_i$	$1.206V_i$

One would expect about 95 percent of all data points D to fall within the limits $D_i \pm 2V_i s$. About 95 percent of all the points used in the analysis did fall inside these two sigma limits. Plots of the data points and the upper and lower limits are shown in Figures 1, 2, 3, and 4.

Test Results—Equations 6, 7, 8, and 9 all have the same form. If ice temperature is fixed, the stopping distance is a parabolic function of braking speed. If braking speed is fixed, the stopping distance is a straight-line function of ice temperature. Plots of stopping distance versus ice temperature for cars traveling at fixed speeds of 20, 35, and 50 mph are shown in Figure 5. Plots of stopping distance versus speed for cars traveling on glare ice at fixed temperatures of 0 and 30 F are shown in Figure 6. Figure 5 shows that at 20 mph the stopping distance required for cars with the different tire combinations is almost the same at temperatures slightly below 0 F. This fact has also been reported in other research (4). However, at higher speeds, the stopping distances are still significantly different at temperatures below 0 F. It is evident that, at the three speeds tested and within the temperature range observed, the cars with studded snow tires required less distance to stop than those without. Also evident is the fact that the studded snow tires become more effective with increasing (higher)

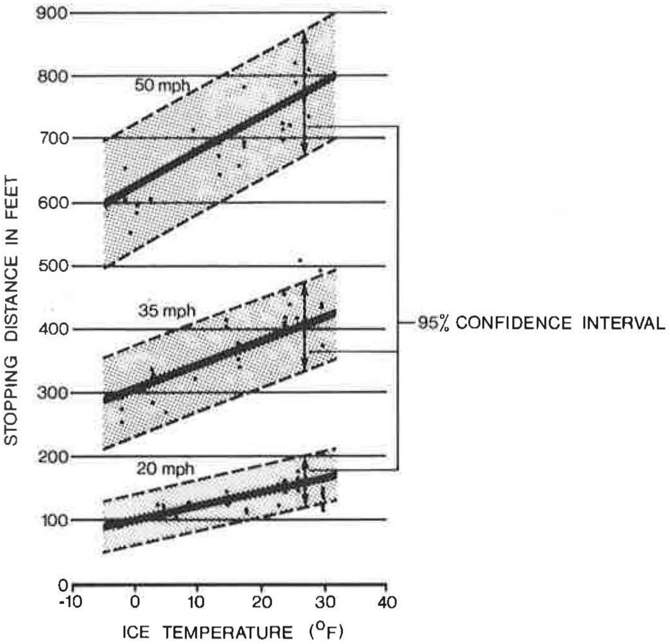

Figure 1. Stopping distance versus ice temperature for car with highway tires on four wheels.

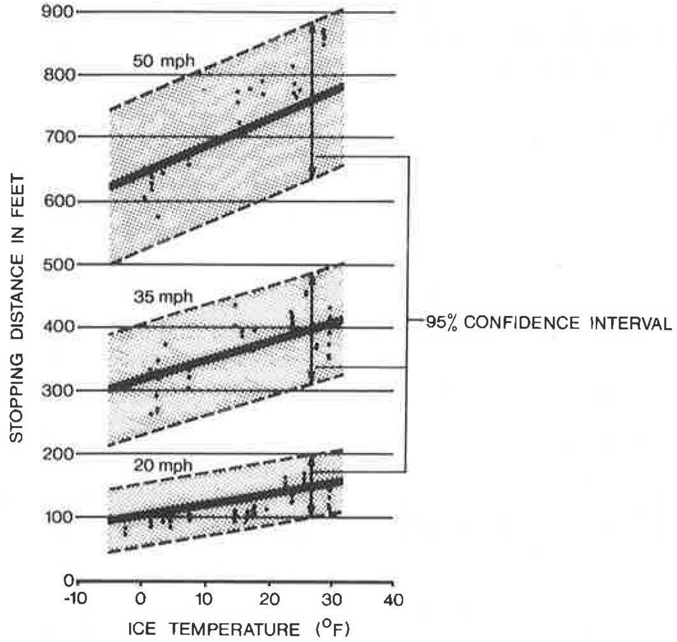

Figure 2. Stopping distance versus ice temperature for car with snow tires on rear wheels only.

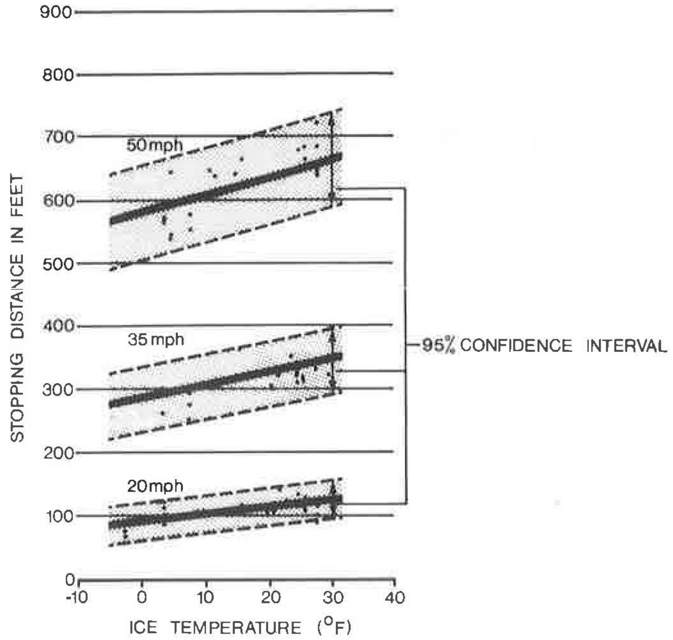

Figure 3. Stopping distance versus ice temperature for car with studded snow tires on rear wheels only.

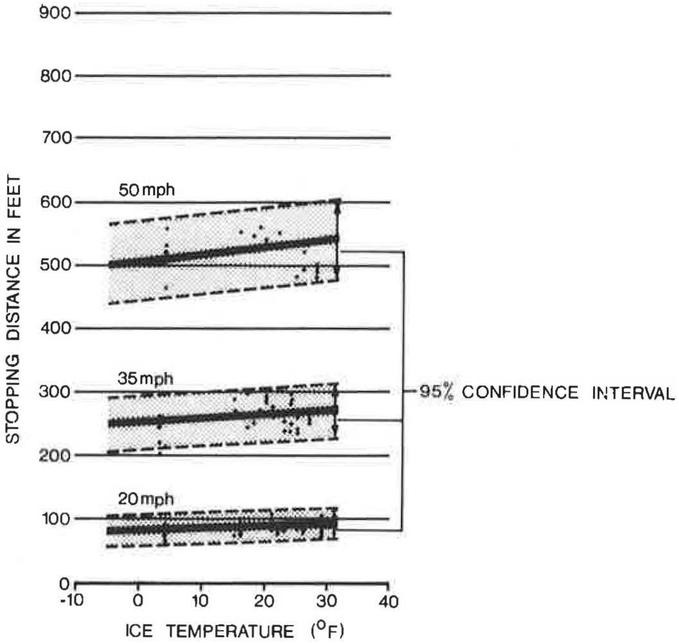

Figure 4. Stopping distance versus ice temperature for car with studded snow tires on four wheels.

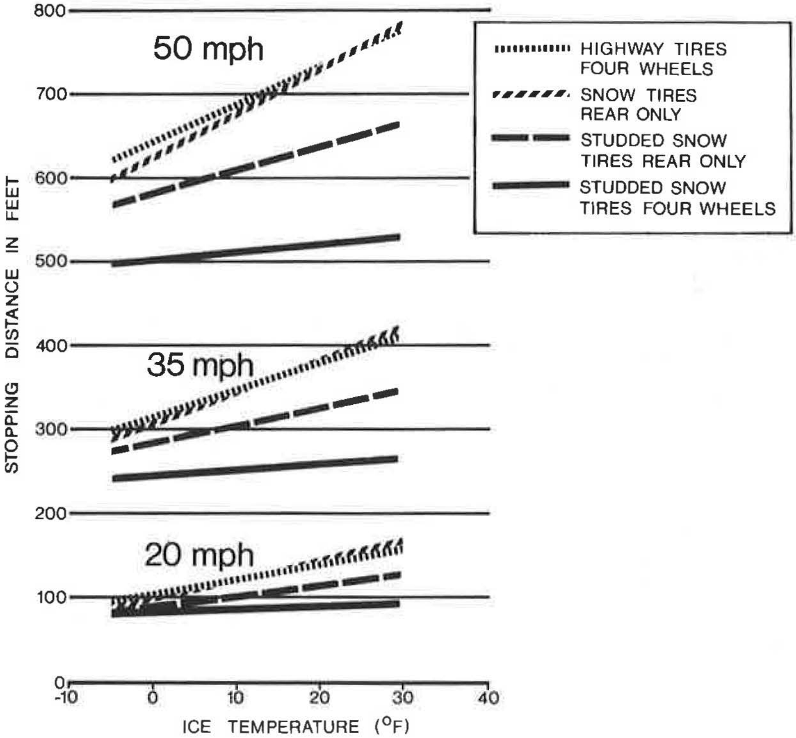

Figure 5. Stopping distance versus ice temperature for four cars traveling at 20, 35, and 50 mph.

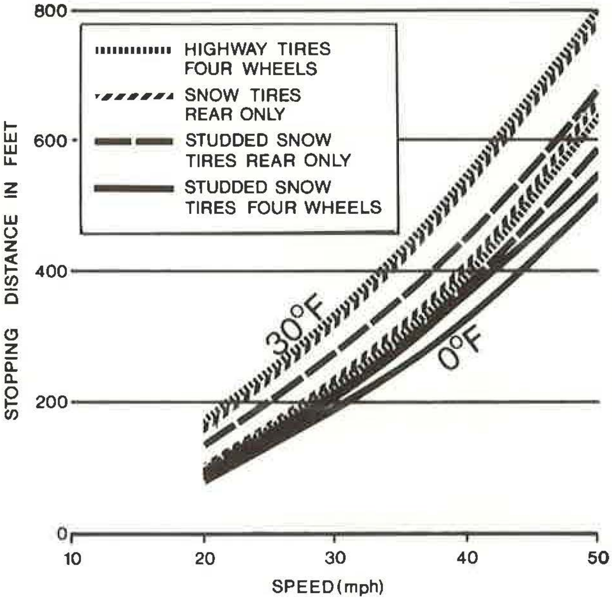

Figure 6. Stopping distance versus speed for cars traveling on glare ice.

temperature. It is also clear that the addition of studs in the front tires more than doubles the benefits from studs in the rear tires alone and that this enhanced benefit increases with speed. Figure 6 shows that the improvements in stopping distances with studded tires are materially greater at higher speeds.

Stopping Distance on Pavement

With few exceptions, at least eight test runs were completed for each test series. Initially all tests were conducted with the viewpoint that the variation in stopping distance would be different for each pavement surface. However, pairwise student t-tests at the 95 percent probability level showed that the two asphalt surfaces were from the same population of data. Therefore, the results of tests on the two asphalt surfaces were combined and are shown in Figure 7, while the results of the tests on the portland cement concrete surfaces are shown in Figure 8.

Figure 7 shows that, on the asphalt surfaces tested, the stopping distance does not materially depend on the type of tire. Figure 8, however, does show appreciable differences in stopping distances of the various cars under both wet and dry conditions of concrete. The ranking of the cars is in reverse order to that on the glare ice. It must be concluded, therefore, that, within the limits of the test conditions, studded tires increase the stopping distance on either wet or dry concrete surfaces and that this disadvantage increases with the use of studs on all four wheels.

The sample averages, $\overline{D}_i$, and variances, s_i, were computed for each test series. These are given in Table 1. The standard errors of estimated means, $s_{\overline{D}_i} = \sqrt{s_i^2/n}$, and the corresponding number of tests, n, are given in Table 2.

Significance tests were also made to determine whether the wet pavement tests differed from the dry pavement tests at the 95 percent probability level. This analysis showed that, while no significant difference could be determined at the lowest speed on the asphalt surface, the wet pavement test results were different from the dry pavement test results when all three speeds are taken into account.

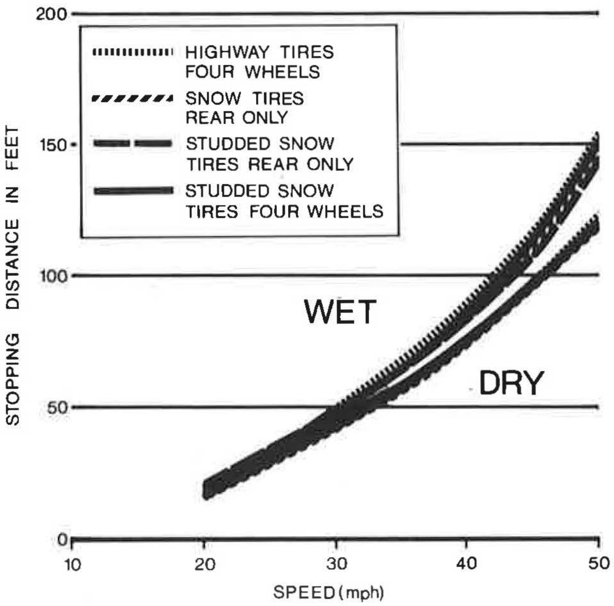

Figure 7. Stopping distance versus speed for cars traveling on asphalt pavement.

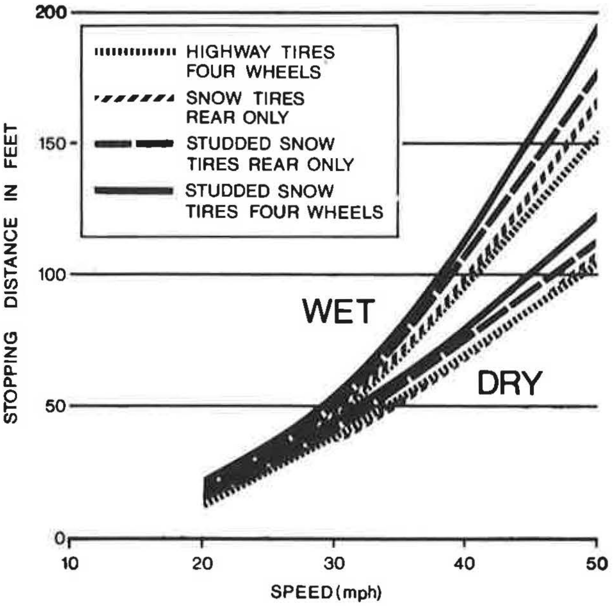

Figure 8. Stopping distance versus speed for cars traveling on concrete pavement.

TABLE 1

MEANS AND VARIANCES OF PAVEMENT TESTS

Pavement Type	Speed (mph)	Statistic	Highway Tires on Four Wheels	Snow Tires on Rear Wheels	Studded Snow Tires on Rear Wheels	Studded Snow Tires on Four Wheels
Dry asphalt	20	$\bar{D}_i$	17.50	15.20	17.60	17.50
		s^2	6.27	2.43	3.18	1.73
	35	$\bar{D}_i$	57.80	55.10	57.10	56.80
		s^2	42.16	20.73	15.05	20.33
	50	$\bar{D}_i$	121.10	117.70	117.10	116.10
		s^2	35.26	19.30	8.38	19.32
Wet asphalt	20	$\bar{D}_i$	17.80	15.70	18.50	17.40
		s^2	8.93	2.52	6.80	1.85
	35	$\bar{D}_i$	66.50	61.80	60.80	62.40
		s^2	62.00	13.00	20.16	5.72
	50	$\bar{D}_i$	150.90	148.00	141.80	148.60
		s^2	118.92	133.93	49.53	42.80
Dry concrete	20	$\bar{D}_i$	14.00	16.00	16.30	18.50
		s^2	12.28	1.42	1.00	2.00
	35	$\bar{D}_i$	53.00	50.30	56.80	58.30
		s^2	35.28	1.28	10.14	16.42
	50	$\bar{D}_i$	104.90	105.50	115.30	121.90
		s^2	45.00	29.71	8.71	9.57
Wet concrete	20	$\bar{D}_i$	14.70	17.50	18.60	22.80
		s^2	4.25	0.85	3.77	5.00
	35	$\bar{D}_i$	69.30	70.50	76.90	81.10
		s^2	139.50	23.71	33.66	152.42
	50	$\bar{D}_i$	153.50	165.60	177.10	195.00
		s^2	48.60	337.42	67.66	445.00

TABLE 2

NUMBER OF TESTS AND STANDARD ERRORS OF ESTIMATED MEANS

Pavement Type	Speed (mph)	Statistic	Highway Tires on Four Wheels	Snow Tires on Rear Wheels	Studded Snow Tires on Rear Wheels	Studded Snow Tires on Four Wheels
Dry asphalt	20	n	16	16	16	16
		$s_{\bar{D}_i}$	0.63	0.39	0.45	0.33
	35	n	16	16	16	16
		$s_{\bar{D}_i}$	1.62	1.14	0.97	1.13
	50	n	16	16	16	16
		$s_{\bar{D}_i}$	1.48	1.10	0.72	1.10
Wet asphalt	20	n	16	16	16	16
		$s_{\bar{D}_i}$	0.75	0.40	0.65	0.34
	35	n	16	16	16	16
		$s_{\bar{D}_i}$	1.97	0.90	1.12	0.60
	50	n	16	16	16	16
		$s_{\bar{D}_i}$	2.73	2.89	1.76	1.63
Dry concrete	20	n	8	8	8	8
		$s_{\bar{D}_i}$	1.24	0.42	0.35	0.50
	35	n	8	8	8	8
		$s_{\bar{D}_i}$	2.10	0.40	1.13	1.43
	50	n	8	8	8	8
		$s_{\bar{D}_i}$	2.37	1.93	1.04	1.09
Wet concrete	20	n	9	8	10	8
		$s_{\bar{D}_i}$	0.69	0.33	0.61	0.79
	35	n	9	8	10	8
		$s_{\bar{D}_i}$	3.94	1.72	1.84	4.36
	50	n	6	8	10	7
		$s_{\bar{D}_i}$	2.85	6.49	2.60	7.95

CONCLUSIONS

On the basis of the test procedures and conditions outlined in this report and to the extent that the tires and vehicles used in testing may be considered typical, the following conclusions may be reached:

1. On glare ice, snow tires give no consistent improvement in stopping distance, compared to standard highway tires. They appear to be slightly better at ice temperatures near the freezing point, slightly worse at ice temperatures near zero.
2. On glare ice, studded tires on only the rear wheels result in a significant reduction in stopping distance compared with standard highway and snow tires.
3. On glare ice, studded tires on all four wheels result in a reduction in stopping distance that is more than twice the reduction with studs on the rear tires only.
4. On glare ice, the improvements in stopping distance due to studs are greatest at ice temperatures near the freezing point.
5. On glare ice, the improvements in stopping distance due to studs, while decreasing with decreasing ice temperature, do not disappear at temperatures in the vicinity of -5 F, as suggested by earlier research. While the differences in stopping distance at 20 mph are very small, differences at higher speeds are still very significant at this temperature.
6. On dry asphalt surfaces, the type of tire and the presence or absence of studs make almost no difference in the stopping distance.
7. On wet asphalt surfaces, the type of tire and the presence or absence of studs make no significant difference in the stopping distance.
8. On both dry and wet concrete surfaces, studded tires on the rear wheels only result in a small but significant increase in stopping distance compared to that required with standard highway tires.
9. On both dry and wet concrete surfaces, studded tires on all four wheels result in an increase in stopping distance compared to that required with standard highway tires, but this increase is less than twice that resulting from studded tires on the rear wheels only.

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INFLUENCE OF STUDDED TIRES ON WINTER DRIVING SAFETY IN QUEBEC

Jean Normand, Department of Roads, Quebec

This paper summarizes winter accident data and winter driving conditions in Quebec and investigates the improvement in safety given by the use of studded tires. This investigation was conducted by comparing accident data in Quebec City for both the group using studded tires and the group not using studded tires. The general characteristics of these two groups were investigated by means of a questionnaire. Answers to the questions indicate that, for the purpose of the present study, both groups can be considered as identical. An analysis of the classification of the accidents shows that an improvement of safety related to the use of studded tires, if any, is inferior to the precision of the data. Answers to the questions also indicate that the use of studded tires does not seem to have improved the accident record of persons using studded tires.

•THE USE of studded tires in Quebec started during the winter of 1963-64. Because the publicity emphasized the security aspect, to which the public is very sensitive, studded tires soon became very popular as shown in Figure 1. This publicity has been substantiated since then by technical papers (1, 2, 3) reporting the ability of these tires to reduce braking distances on ice or hard-packed snow. The reduction of the braking distance on ice is approximately 20 percent when two studded tires are used and is approximately 35 percent when four studded tires are used. These figures are often used by marketing agencies and lead the general public to think that these reductions in braking distances are directly related to an increase in safety for the consumers. This obviously implies that the driver who has a car equipped with studded tires drives his car in the same manner as if he did not have any. The objective of this paper, therefore, is to investigate the true safety benefits of studded tires as used in Quebec.

The importance of the problem can be easily appreciated because studies conducted in Europe (4, 5, 6), in the United States (7, 8, 2), and in Canada (9, 10, 11) have indicated very clearly that studded tires do damage the pavements. The apparent scatter of the results is due solely to the number of variables involved in the wearing process of the pavement (10).

GENERAL CONDITIONS IN QUEBEC PROVINCE

All safety analyses are difficult, but, in the present case, an additional problem arises from the fact that winter driving conditions are modified from year to year by improvements of the roads, increased quantities of de-icing chemicals, and use of studded tires. The improvement of roads over the years can be neglected because the data are given as a percentage of the total number of accidents for each year. For the purposes of this study, a year is defined as the period starting on March 1 and ending on February 28. The winter is considered as starting on November 1 and ending on February 28.

Figures 2, 3, 4, and 5 show the variations over the years of the different types of winter accidents expressed as a percentage of the total number of accidents occurring during a year. The figures also show the percentage of yearly traffic occurring during

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Sponsored by Task Force on Effect of Studded Tires and presented at the 50th Annual Meeting.

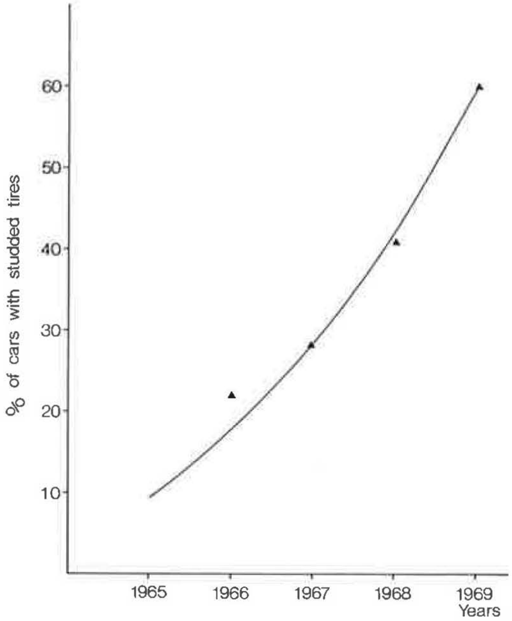

Figure 1. Increase of use of studded tires in metropolitan Quebec.

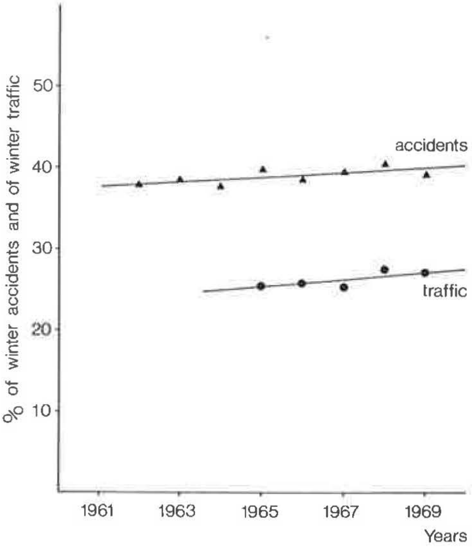

Figure 2. Increase of winter accidents and of winter traffic in Quebec Province.

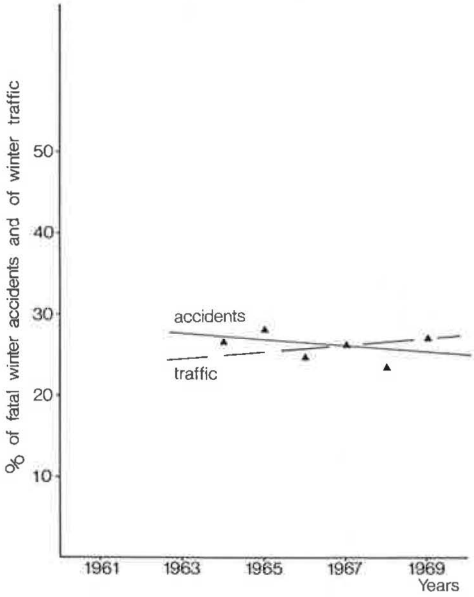

Figure 3. Decrease of fatal winter accidents in Quebec Province.

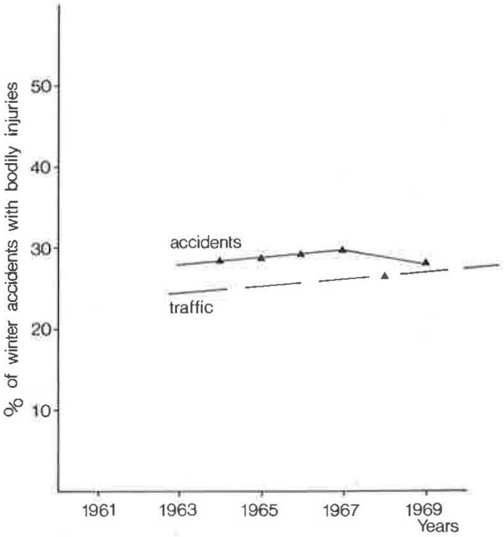

Figure 4. Increase of winter accidents with bodily injuries in Quebec Province.

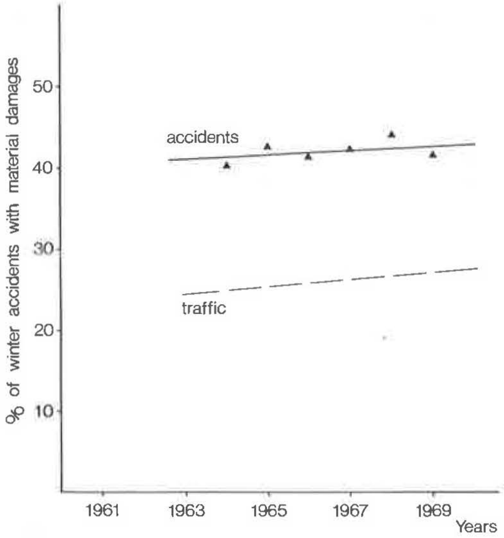

Figure 5. Increase of winter accidents with material damages in Quebec Province.

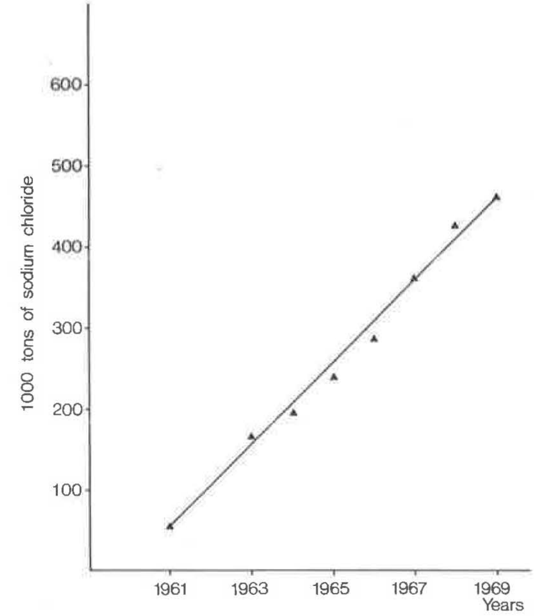

Figure 6. Winter use of sodium chloride in Quebec Province.

the winter. From these figures it can be seen that the annual increase in accidents is inferior to the growth of winter traffic. This is probably due to a general trend to artificial improvements, such as the use of studded tires (Fig. 1), and a wider use of de-icing chemicals (Fig. 6) that tend to eliminate the effects of winter and improve driving conditions. Although the individual effect of both variables is difficult to separate without an independent study, an attempt is made to determine, by analyzing for a period of years, the risk of being involved in an accident in slippery conditions during the winter compared with the risk of being involved in an accident in nonslippery conditions.

These values were based on a determination of the percentage of winter accidents reported as occurring in slippery conditions for 4 years. A pavement was considered to be in slippery condition when the pavement surface was reported as icy or partly to fully snow covered. The basic hypothesis of the investigation is to assume that traffic accidents on a highway network are directly related to the intensity of the traffic.

From this hypothesis, the percentage of vehicle-miles driven during the winter is the theoretical percentage of winter accidents. Because accidents occuring in nonslippery conditions are not related to the winter accidents when their number is deducted from the total number of expected accidents, the remainder is the theoretical number of winter accidents that would occur if the roads were not slippery when in fact they are slippery. Therefore, this remainder divided by the theoretical number of winter accidents represents the percentage of vehicle-miles driven in slippery conditions during the winter. It represents a winter serviceability index that is related both to the severity of the winter and to the efficiency of winter maintenance. The total number of accidents occurring in slippery conditions divided by the expected number of accidents is an index of the susceptibility to car accidents when the road is slippery. This index may be compared to nonslippery conditions, in which case the index is equal to 1.0 from the hypothesis mentioned previously. This index is given in Eq. 1, and the symbols are shown in Figure 7.

$$I = \frac{MA}{T - M(1 - A)} \qquad (1)$$

where

I = index of susceptibility to accidents in slippery conditions;
T = percentage of annual traffic occurring during the winter, which is also equal to the theoretical expected percentage of winter accidents;
M = percentage of annual accidents occurring during the winter; and
A = percentage of winter accidents occurring in slippery conditions.

Because the variable I is in some ways related to climatic conditions for a given region, observation of I over a longer period of time than that shown in Figure 8 could be more informative.

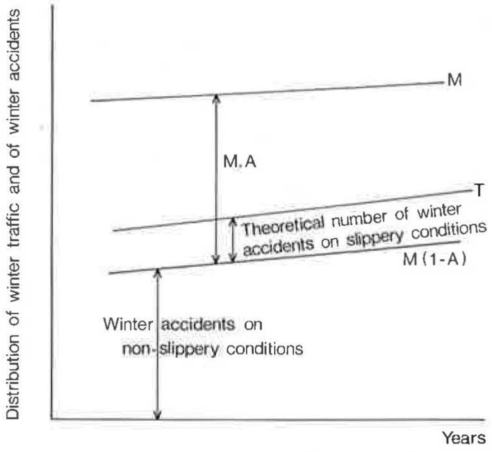

Figure 7. Determination of index of susceptibility to accidents in slippery conditions.

MODEL OF THE STUDY

Because an analysis of these statistics could not give a specific answer to the problem, a special investigation was carried out in Quebec City to determine the safety benefits of studded tires. The investigation consisted primarily of classifying all traffic accidents that occurred in Quebec City according to road conditions and to possession of studded tires. Assuming that both groups are identical, the distribution of accidents can be predicted when the size of both groups is known. By comparing the predictions with the observations, the advantages of studded tires can be determined.

VERIFICATION OF ASSUMPTIONS

The hypothesis of identical groups was checked by means of a questionnaire that contained the following questions: Do you own a car? Since when? Do you use your car during the winter? Does your car have studded tires? How many? Why did you buy studded tires: improved braking, improved traction, greater speed, improved security, other? Why did you not buy studded tires: too expensive, no need, inefficient, never thought of it, other? What is the average annual mileage of your car? How many miles are driven yearly within Quebec City? As a driver have you ever been involved in a car accident (damages greater than $100)? How many times in the last 10 years? As a driver have you ever been involved in a minor car accident (damages less than $100)? How many times in the last 10 years? When did you have your last and penultimate accidents? When did you have your last and penultimate minor accidents? Do you use your safety belt? To which age group do you belong: 17 to 25, 25 to 35, 35 to 45, 45 to 55, 55 and over?

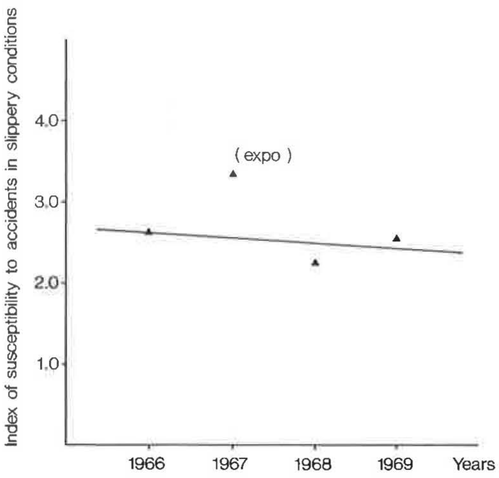

Figure 8. Annual variation of index of susceptibility to accidents in slippery conditions in Quebec Province.

The questionnaire was mailed to 786 persons chosen at random in metropolitan

Quebec. A letter enclosed with the questionnaire explained that answers would be obtained by a personal telephone call.

A total of 358 questionnaires were subjected to analysis after elimination of questionnaires for those persons who were not reached by telephone, those who did not own a car, those who did not use a car during the winter, those who refused to answer (6 people), and those who gave incomplete replies. Two groups were then made up of 218 car owners who had cars equipped with studded tires and 140 whose cars did not have studded tires. The questionnaire was designed to determine whether, during the time the interviewed person owned a car, his accident record was different according to whether his car was or was not equipped with studded tires. If a difference had been noted, it would have been attributed to the driver's attitude, because the questions concerning the driver's accident records applied to his entire driving life (which was an average of 13 years and, therefore, accorded little influence to the use of studded tires, because the existence of such tires was limited to recent years). The questionnaire was designed to determine whether the recent accident record of each group showed any improvement over the lifetime accident records of each group. The answers to the questions are given in Table 1. Group A is the group of 218 people owning cars equipped with studded tires, whereas group B is the group of 140 people owning cars not equipped with studded tires.

These results indicate that the experience of both groups is similar (Table 1, item 1). The exposure in Quebec City is identical although the yearly mileage of group B is lower because of the presence of a larger group driving less than 5,000 miles per year. The standard deviation of items 5, 6, and 7 should not be given too much emphasis, because the deviation may be influenced by the presence of two or three reckless drivers in group B. These drivers may also affect the average values to a certain degree.

Assuming that the individuals of both groups are not biased and give equally true answers, it can be concluded from these answers (Table 1, items 1, 2, 3, and 4) that both groups are identical as far as experience, age, and miles driven are concerned. It may also be noticed that the drivers of group A have a better driving record than those of group B (Table 1, items 9 and 12). This record may be ascribed to the fact that they use studded tires or to the fact that they are more safety conscious and for this reason buy safety devices. The last hypothesis is probably more reasonable, because most of them have had cars fitted with studded tires for only a very few years, and the improvement of their accident records (Table 1, items 15, 16, and 17) during the years is inferior to

TABLE 1

RESULTS OF QUESTIONNAIRE SURVEY

Item	Group A[a]		Group B[b]	
	$\bar{x}$	α	$\bar{x}$	α
1. Driver's experience, years	13.39	9.23	13.44	11.43
2. Driver's age	41.5		41.9	
3. Average yearly mileage	13,206	8,570	11,475	6,585
4. Average yearly mileage in city of Quebec	4,920	3,545	4,824	4,027
5. Percentage of mileage in city of Quebec	42.8	26.7	44.0	26.4
6. Number of major accidents per year	0.10	0.16	0.12	0.28
7. Number of minor accidents per year	0.08	0.15	0.09	0.19
8. Total number of accidents per year	0.19	0.24	0.22	0.40
9. Average mileage without major accident	66,633	77,020	61,898	65,637
10. Average mileage without minor accident	76,273	86,400	65,270	70,526
11. Average mileage without any accident	46,097	60,867	49,492	61,990
12. Mileage since last major accident	67,092	76,823	64,698	63,033
13. Mileage since last minor accident	77,604	85,829	68,427	69,723
14. Mileage since any accident	46,772	60,705	51,122	61,466
15. Recent improvement in driving without major accident, (item 12 - item 9)/item 9, percent	0.69		4.52	
16. Recent improvement in driving without minor accident, (item 13 - item 10)/item 10, percent	1.75		4.83	
17. Recent improvement in driving without any type of accident, (item 14 - item 11)/item 11, percent	1.46		3.30	

[a] Cars equipped with studded tires.

[b] Cars not equipped with studded tires.

TABLE 2

TWO-CAR ACCIDENT CLASSIFICATION

Date (1969-70)	Two Vehicles With Studded Tires		Two Vehicles Without Studded Tires		One Vehicle With and One Vehicle Without Studded Tires	
	Slippery	Nonslippery	Slippery	Nonslippery	Slippery	Nonslippery
Nov. 16 to Nov. 29	16	34	19	77	17	42
Nov. 30 to Dec. 13	17	60	20	67	19	63
Dec. 14 to Dec. 27	38	55	42	55	30	45
Dec. 28 to Jan. 10	56	49	79	39	50	30
Jan. 11 to Jan. 24	53	85	52	82	60	92
Jan. 25 to Feb. 7	60	39	38	32	52	31
Feb. 8 to Feb. 21	59	31	39	34	40	35
Feb. 22 to March 7	21	26	21	26	17	16
	320	379	310	412	285	354

those of group B. These values were computed by comparing the mileage since the most recent accident with the average mileage without accident during the driver's last 10 years of experience.

The validity of the answers given to the questionnaire was checked in two ways. The first way was to determine the number of miles a driver could expect to drive without an accident in Quebec in 1969. This figure was estimated at 68,000 miles based on the provincial vehicle-miles and the provincial annual number of accidents. This figure is in accordance with the findings of item 11 (Table 1), which excludes commercial drivers, and also with the fact that Quebec City has the highest of the provincial insurance premiums. The second verification on the validity of the answers was made by a second questionnaire. The results will be described later.

Accident Classification and Studded Tire Ownership

To achieve the objective of classifying accidents according to whether did vehicles or did not have studded tires, the Police and Traffic Department of the city of Quebec provided the needed data. All data of the accidents occurring in the city from November 16, 1969, until March 7, 1970, were classified according to road conditions and to the presence or absence of studded tires on vehicles involved in accidents. All accidents involving a bus or a truck were omitted, and incomplete reports were rejected. A total of 2,060 accidents of varying severity involving two cars in each case were classified. There were 46 percent of these accidents that occurred in slippery conditions.

The distribution of accidents is given in Table 2. While these data were collected, various ways of measuring the relative importance of each group were devised. The first method of measure was from the questionnaire, the second was from a sampling of cars parked in streets in the middle of November, and the third was from a sampling of 2,000 cars in movement in all areas of the city, with the importance of the sampling being related to the number of accidents in the different areas and streets of the city. The results of these classifications are given in Table 3.

TABLE 3

CLASSIFICATION OF ACCIDENTS ACCORDING TO TIRES ON VEHICLES

Source	Group A (percent)	Group B (percent)
Questionnaire survey	60.9	39.1
November survey	49.8	50.2
February survey	56.4	43.6
Day	54.7	45.3
Peak hours	58.8	41.2

It was noted in the February 1970 survey that 14.3 percent of those who owned cars equipped with studded tires had them on all four wheels. This represents 8.0 percent of the car traffic in Quebec City. The difference obtained between the November 1969 and the February 1970 surveys is attributed to the fact that in November 17 percent of the vehicles still had summer tires. The percentage of the February survey is used in this study because it takes into account the exposure that is a function of the mileage and of the possession.

Analysis of Accident Data

TABLE 4

DISTRIBUTION OF ACCIDENTS

Accident	Group A (percent)	Group B (percent)
In slippery conditions during winter	49.9	50.1
In nonslippery conditions during winter	47.6	52.4
During February survey	56.4	43.6

This classification of car accidents can be interpreted in several ways. The first method is to determine the number of single cars in each group that was involved in accidents during the winter and to compare the distribution with the results of the February survey (Table 4).

From these results one can note that the drivers of group B are more prone to accidents. This only confirms the results of the questionnaire (Table 1, items 8 and 11). It is however surprising to note that, in slippery conditions, the drivers of group A using a "safety device" are then more prone to accidents than in nonslippery conditions, in which studded tires are not useful and may even be a disadvantage (3).

A second method of interpreting the classification is to compare the percentage of accidents for each group according to road conditions and to compare these values with the expectancy of accidents based on the exposure of both groups. The results (Table 5) indicate that both groups had a higher rate of accidents than expected within their own group and a lower rate of accidents than expected between groups. This, in itself, is a strong indication of a bias in the data, because the advantage of one group over the other should be indicated in two categories. Because group A should be showing a better performance, it is somewhat surprising to note that the general performance of the group is not so good when the roads are reported as slippery, the condition in which studded tires should work the best.

Notwithstanding the bias, a close examination was made of 199 accidents out of 285 occurring in slippery conditions in which one car was equipped with studded tires and another was without. Out of these 199 cases, at least one car skidded in 99 cases or 48.7 percent of the time. In the other cases, the fact that the pavement was reported as slippery had no direct effect on the cause or the severity of the accident because no skid occurred. In all cases where skidding occurred, the accident was classified according to the responsibility and to the type of tires. The responsibility was determined from the driver's testimony, and only 6 cases were classified as unknown. Data are given in Table 6. The first observation is that the skidding vehicle is more likely to be responsible for the accident, which is an indication of overconfident driving in slippery conditions. A second observation is that both vehicles with studded tires and vehicles without studded tires are equally involved in skidding accidents with responsibility. An analysis of accidents where the skidding vehicle is not responsible for the accident is impossible to make because of the limited number of cases.

From this last analysis, studded tires do not seem to provide any advantage in safety even without correcting for accident susceptibility of the drivers of vehicles without studded tires as determined from the questionnaire (Table 1, items 8 and 11).

Analysis of Bias and Control Questionnaire

It had been assumed previously that both groups answered the questionnaire with equal honesty. Also pointed out was the possible bias introduced in the accident classi-

TABLE 5

OBSERVED AND THEORETICAL DISTRIBUTIONS OF TWO-CAR ACCIDENTS

Distribution	Two Vehicles With Studded Tires		Two Vehicles Without Studded Tires		One Vehicle With and One Vehicle Without Studded Tires	
	Slippery	Nonslippery	Slippery	Nonslippery	Slippery	Nonslippery
Observed	35.0	33.1	33.9	36.0	31.1	30.9
Theoretical	31.8	31.8	19.0	19.0	49.2	49.2

fication. In order to check these two points, a questionnaire was mailed on March 10, 1970, to 124 car owners living in metropolitan Quebec who were involved as drivers in at least one car accident during the third week of February 1970. Following the same procedure adopted for the main questionnaire, answers were obtained by telephone interviews. There were 46 persons in group A and 45 in group B who were interviewed, and there were 3 in each group who refused to answer.

TABLE 6

ACCIDENTS OCCURRING ON SLIPPERY CONDITIONS INVOLVING ONE VEHICLE WITH STUDDED TIRES AND ONE VEHICLE WITHOUT STUDDED TIRES

Accidents	Number	Percent
Accidents	199	100
With skidding	97	48.7[a]
Unknown responsibility	6	6.2[b]
Non-skidding vehicle responsible	16	16.5[b]
Skidding vehicle responsible	75	77.3[b]
Studded tire vehicle skids	38	50.6[c]
Unstudded tire vehicle skids	37	49.4[c]

[a] Of total accidents.
[b] Of accidents with skidding.
[c] Of accidents with skidding vehicle responsible.

The first point of interest was to determine whether the driver would admit that he had been recently involved in an accident. There were 26 persons, or 30 percent of each group, who failed to admit that they were recently involved in an accident. Most of them were responsible for the accident (16), or the accident in which they were involved was of minor importance (10). Because only 3 weeks had elapsed between the date of the accident and the date of the interview and because the responsibility for the accident had not yet been determined, it was felt that many drivers would be reluctant to talk about the accident. The credibility of the main questionnaire, therefore, might be expected to be greater. This fact is substantiated, as mentioned previously, by analysis of the average expected mileage without accident, which is close to the provincial average. The main conclusion from this control so far is that both groups are equally willing to admit that they have been involved in an accident.

The control questionnaire was also sent to verify whether the classification of the car noted by the police officer in the accident report form was correct. Having established that both groups answered the question with the same honesty, it is assumed that any difference of classification between the two groups would be due to a bias introduced by the police officer while writing his report.

Item	Group A	Group B
Agreement between driver's declaration and officer's report	31	25
Percentage of agreement	72.1	59.5
Introduced bias, percent	—	20.6

This bias was also noticed by grouping the accident reports and both drivers' declarations of their types of tires. This was possible for 13 accidents involving 26 cars. In 3 accidents, both drivers were in disagreement with the officer's classification. These 6 cars were reported as not being equipped with studded tires. Because numerous additional hypotheses would be required to correct the data, no attempt was made to do so.

In the analysis of accident data, the bias introduced by the police officer was not taken into account. This procedure seems justified because the bias should be least when both cars involved in an accident are classified differently. In view of the fact that the bias is introduced by the police officer, the officer is more likely to be correct when he makes a different classification for both cars. This is substantiated by the fact that only 31 percent of the car accidents were reported in that category, whereas 49 percent of the car accidents were expected to fall into this category.

CONCLUSIONS

The conclusions of this study are based on an analysis of the statistics concerning winter driving in Quebec Province, on the results of a questionnaire sent to the public, and on an analysis of accident data in Quebec City.

1. Because of the multiplicity of the variables and the limited number of statistics, it was impossible to determine from the statistics whether studded tires provided increased safety in driving.
2. It was found from the questionnaire that owners both of cars equipped with studded tires and of cars not equipped with studded tires formed comparable groups as far as accident records and honesty in answering the questionnaire were concerned. It was also found that drivers using studded tires on their cars had shown less improvement over the years in their safety record than the other group.
3. The analysis of accident data shows that there was a bias in the data. Assuming the bias to be independent of road conditions, the use of studded tires did not improve the driving safety of those who used them in slippery conditions. Because of its nature, the bias should be least when the cars involved in an accident belong to different groups. In that particular case, the use of studded tires did not improve the safety driving record of the driver using these tires.

For all these reasons, the general conclusion of the study is that, in the Quebec area, the use of studded tires has not brought about any major improvement in winter accident statistics. In fact, the data taken at face value indicate that no improvement has occurred.

ACKNOWLEDGMENTS

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DISCUSSION

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I will confine my remarks to a description of the study that is somewhat parallel to Normand's study and that is being conducted by Cornell Aeronautical Laboratory (CAL) for the Minnesota Department of Highways and to a brief summary of tentative findings based on preliminary analyses of the data collected thus far.

In 1969 the Minnesota legislature extended legal use of studded tires for 2 years until May 1, 1971. At the same time it assigned to the Minnesota Commissioner of Highways the task of evaluating "the effects, if any, that discontinuing the use of studded tires will have on highway safety."

Essentially, we were asked to determine whether the use of studded tires had any measurable effect on highway safety and, if so, the degree of benefit or detriment.

Minnesota has nearly 100,000 reported traffic accidents each year. On the average, 22 percent occur on roads classed as snowy and icy. Studies of accident statistics indicate that ratios of the accident rate on snowy and icy roads to the total accident rate are as follows: all accidents, 1.8; fatal, 0.8; personal injury, 1.4; and property damage only, 2.2. One may infer that accidents are more likely to occur on snowy and icy roads but are generally less severe than normal.

Improvements in vehicle performance have been cited as the solution to the problem of how to achieve greater winter highway safety. However, highway safety can benefit from the use of any safety device only if the potential safety improvement is translated ultimately into real reductions in accident severity and occurrence.

Because there was a complete lack of information in 1969 on accident research with regard to studded tires, the department initiated a $70,000 study in December 1969. The Cornell Aeronautical Laboratory was selected to do the study because of its extensive experience in accident data analysis and background of knowledge of studded tires.

The ultimate objective of this study was to determine whether the performance of studded tires do, in fact, provide greater safety on the highways and streets, in mixed traffic, and under all conditions. This was done by comparing studded tires to other tire types in terms of the amount and type of use; the effect on accident precipitation; and the effect on accident characteristics, including damage costs, severity, and injury.

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

Questionnaires were sent to a statistically selected random sample of 84,000 of the 1,800,000 Minnesota-registered automobile owners. Specifically, the respondent was asked to describe his vehicle and his driving as experienced the day before filling out the questionnaire. Typical data obtained from the questionnaires included: driver characteristics such as age, sex, driving experience, and attitude toward studded tires; vehicle characteristics such as make, age, power assists, brake type, tire type and wear, and total mileage driven; and road conditions and driving exposure time on the day that was reported. Equal numbers of the questionnaires were mailed twice weekly to sample all days throughout the data-collection period. A cover letter signed by the governor requesting the respondent's cooperation accompanied each questionnaire.

Accident reports, together with a supplementary informational form designed by CAL, were received for each investigated and reported accident from the Minnesota Highway Patrol and 11 municipal police departments. The cities participating were Minneapolis, four suburbs, and five other cities. The Minnesota Highway Patrol furnished statewide coverage of most trunk highway accidents in rural and smaller urban areas. The cities furnished coverage of most accidents on city streets, except Minneapolis where the police normally investigate only those accidents involving injury and fatality.

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

Collection of data for this study was started in February 1970 and continued until May 1, 1970, which was the end of the period of legal use of studded tires. The second data-collection period resumed on October 15, 1970, and continued until January 4, 1971, when it was terminated under the contract agreement.

CAL conducted a preliminary analysis of data from the first collection period to get the "feel" of the data. At that point, only simple statistical summaries of information obtained from questionnaires and accident reports were available. These findings, however, were unverified and tentative. Primarily, the findings show relationships between tire type, tire user characteristics, vehicle characteristics, travel exposure, accident characteristics, and accident effects.

The preliminary findings of the first questionnaire survey covering data from February, March, and early April 1970 (50,000 questionnaires) are given in the following:

1. Forty-three percent of the automobiles in the survey used studded tires, 26 percent used standard tires, and 28 percent used snow tires. The percentage of studded tires corresponds quite well with the 40 percent figure determined by the Minnesota Department of Highways field survey.
2. The proportion of automobiles equipped with studded tires decreased from 47 percent in February to 44 percent in March and to 34 percent in early April. The proportion of snow tires also declined in these periods, but at a much slower rate.
3. The proportion of automobiles equipped with studded tires was highest in rural areas, followed by urban areas, and then suburban areas. The differences were small.
4. Use of studded tires varied with vehicle-owner characteristics. In terms of percentage, more females than males owned vehicles equipped with studded tires. Owners over 65 years of age used snow tires more often and studded tires less often. The proportion of studded-tire use tended to increase with annual mileage of the owner.
5. Use of studded tires varied with vehicle characteristics. Proportionately, more sedans and convertibles were equipped with studded tire than were station wagons. Use of studded tires was greater for vehicles equipped with power brakes or power steering. Use of studded tires increased with later model vehicles up to 1969-70 when a decline was noted.
6. Automobiles equipped with studded tires accounted for 47 percent of all driving time in the period studied. Although this percentage was higher for roads completely covered with ice, snow, or slush, such conditions prevailed for only 1 to 8 percent of all driving time in the period studied. Sixty-eight to 87 percent of all driving time in the period studied occurred on roads with little or no road cover.
7. Driving in the northern counties was more likely to occur on roads covered with ice, snow, or slush than was driving in the southern counties.
8. The reported incidence of skidding of any kind ranged between about one-fourth and one-half of the vehicles traveling on other than bare roads. The reported frequency of skidding increased as the degree of road cover increased. Skidding was reported least frequently with studded tires and most frequently with standard-tread tires. In general, the reported skidding experience with snow tires was more similar to that with studded tires than to that with standard tires. The reported nonskidding superiority of studded tires increased as the degree of road cover increased.
9. The majority of respondents expressed the opinion that studded tires allowed one to drive closer to the speed limit on slippery roads. This opinion was held most frequently by owners of studded tires. (This opinion may suggest that the driver who uses studded tires may utilize his traction advantage to drive at higher speeds on slippery surfaces, perhaps diminishing safety benefits.)
10. Only 0.4 percent of the respondents did not drive because of snowy or icy roads.
11. Analysis of 972 unsolicited comments appended to the questionnaires by respondents indicated that 50 percent favored continued use of studded tires, 37 percent favored banning studded tires, and 13 percent expressed no opinion or were undecided. As the questionnaires were returned, the percentage favoring continuation of studded-tire use remained about constant through the period but the percentage for banning increased, indicating increased polarization in attitudes.

The preliminary findings of the first accident report analyses covering data from February, March, and early April 1970 are given in the following:

1. The accident sample studied consisted of 2,756 automobiles in 1,810 accidents with 1,422 injuries of which 57 were fatal injuries.
2. Twenty-five percent of the accidents reported in the study period occurred on roads described as having at least a scattered cover of snow, ice, or frost; 61 percent were on dry roads with little or no cover; and 12 percent were on wet roads. Only 3 percent of the accidents occurred on roads where sand or cinders had been spread.
3. In the sample, for all road-surface conditions, the proportion of vehicles equipped with studded tires and involved in accidents was less than the proportion of travel by vehicles with studded tires. This implies, for the sample only, that the accident rate for automobiles equipped with studded tires is lower than the rate for all automobiles, but this implication is incompatible with the finding that 75 percent of the accidents in the sample occurred on bare roads. It is hoped that the apparent paradox will be resolved by more data and analyses.
4. For each type of tire, there was little difference in the proportion of accidents on roads with at least some scattered snow or ice cover and the proportion of accidents on bare pavements.
5. Vehicles equipped with studded tires showed some performance advantage in reduced involvement in accidents in which slippery roads were reported to be a contributing factor and in reduced incidence of uncontrolled vehicle rotation before the collision impact.
6. Reported impact speeds were sparsely distributed and showed no advantage for any of the tire types in reducing the impact speed of collision.
7. Overall, there was no consistent advantage for any tire type in terms of personal injury and vehicle damage.

CAL has been completing the data coding. Kenneth Perchonok, the project director, has been adjusting the analysis procedure to conform to the specific characteristics of the data as determined from the preliminary results just presented. A final summary report of the findings will have been submitted to the Minnesota legislature before the conclusion of its session in May 1971.