HIGHWAY RESEARCH RECORD

Number 418

New Tire Studs, Alternate Traction Aids, and Wear-Resistant Pavement

4 reports
prepared for the
51st Annual Meeting

Subject Areas

31	Bituminous Materials and Mixes
40	Maintenance, General

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CONTENTS

FOREWORD iv

EFFECTIVENESS OF TIRES UNDER WINTER DRIVING CONDITIONS
Robert W. Smith and Donald J. Clough. 1
Discussion
E. Southern. 9

NEW TIRE-STUD DEVELOPMENTS
Rolf Cantz 11

MIX DESIGN CRITERIA FOR WEAR-RESISTANT BITUMINOUS PAVEMENT SURFACES
J. Hode Keyser 26
Discussion
G. Kohler. 42
Author's Closure 43

STUDDED TIRE EFFECTS ON PAVEMENTS AND TRAFFIC SAFETY IN MINNESOTA
C. K. Preus 44

SPONSORSHIP OF THIS RECORD 55

FOREWORD

The 4 papers in this RECORD are concerned with the effectiveness of studded tires, new developments in studded tires, the construction of bituminous pavements that have a high resistance to studded tire wear, and the effects of studded tires on pavement wear and traffic safety in Minnesota.

The paper by Smith and Clough deals with the effectiveness under winter driving conditions of natural and synthetic rubber snow tires, with and without studs; snow tires with controlled protrusion studs; elastomeric tire attachments and reinforced steel tire chains; and standard bias-belted highway tires. On clear ice, the use of oil-extended natural rubber in the tread compound does not give a consistent decrease in the locked-wheel stopping distance, whether the tires are studded or not. Stopping distances are shorter with controlled protrusion studs on all 4 wheels than with non-studded tires, but these advantages diminish with reductions in temperature. Stopping distances are shorter with elastomeric tire attachments and steel tire chains than with highway tires, but these advantages disappear at 0 F. On sanded ice, the stopping distance for every tire combination is less than half that on clear ice down to 0 F, but the effectiveness of the sand is insignificant at temperatures below 10 F.

The paper by Cantz maintains that some recently developed tire-stud designs show promise that the safety and convenience factors of studded tires can be retained with a considerable reduction in the amount of road wear caused by their use. With the built-in capability for adjustment, the new tire studs are maintained at a nearly uniform protrusion throughout their lifetime. The coefficient of friction on smooth ice is 75 percent greater with tires with these new studs than with identical tires without studs.

Hode Keyser's paper deals with wear resistance of bituminous mixtures to studded tires and concludes that the most effective ways to improve wear resistance are to use hard aggregates, increase the size of aggregates, and increase stone content in the mix.

Preus points out that studded tires cause pavement rutting, destruction of grooving, rapid loss of paint strips, and extremely rough surfaces. He states that to avoid riding in the ruts drivers are prone to shift the course of their vehicles from the normal wheelpaths. Preus reports that on icy or snowy roads studded tires provide some observable, though slight, safety advantages over other tires in terms of accident precipitation, vehicle behavior in emergencies, and driver injury. Results reflecting sliding accident rates, when corrected for extraneous effects, showed studded tires to have a mild advantage over snow tires on snowy or icy roads during the winter months.

—David C. Mahone

EFFECTIVENESS OF TIRES UNDER WINTER DRIVING CONDITIONS

Robert W. Smith, Damas and Smith Limited; and
Donald J. Clough, Department of Management Science,
University of Waterloo, Ontario

This paper compares the effectiveness in winter of snow tires with studs, without studs, and with controlled protrusion studs; elastomeric tire attachments and reinforced steel tire chains; and standard bias-belted highway tires. Correlations between each wheel combination and temperature variation were obtained for each set of tests for the following conditions: locked-wheel stopping from 35 mph on clear ice, sanded ice, and wet asphalt; breakout speed on a course designed to simulate a lane-change manuever on clear ice; and starting traction on clear ice and packed snow.

•IN 1970, 352 tests were carried out to determine the effectiveness of studded tires at various speeds and on different surfaces (1). These tests were limited to locked-wheel stopping and showed that temperature was a critical factor in tire performance on ice. A further series of tests was conducted during the winter of 1971 to evaluate different types of tires (2, 3) and tire attachments in use under winter driving conditions and to assess performance under driving as well as stopping situations.

TEST PROGRAM AND EQUIPMENT

The 1971 test program was set up to measure the following:

1. Stopping distances at a typical speed, i.e., 35 mph, on clear ice at temperatures ranging from -5 to +32 F, on sanded ice at temperatures ranging from -5 to +32 F, and on wet asphalt;
2. Lane-change speeds on clear ice; and
3. Starting traction on clear ice at temperatures ranging from -5 to +32 F and on packed snow.

For each series of tests the following different tire types and attachments were used:

1. Standard highway tread F78 x 15 bias-belted tires;
2. Similar tires refinished with oil-extended synthetic rubber snow tread;
3. Similar tires refinished with oil-extended natural rubber snow tread;
4. Similar tires refinished with oil-extended natural rubber snow tread and fitted with 72 studs;
5. Similar tires refinished with oil-extended synthetic rubber snow tread and fitted with 72 studs;
6. Commercial bias-belted snow tires fitted with 122 controlled protrusion studs designed to reduce the dynamic force on the road and thus reduce wear (these have a special shape and project 33 percent less than normal studs);
7. Standard highway tread tires fitted with reinforced steel tire chains; and
8. Standard highway tread tires fitted with elastomeric tire attachments intended to provide the advantage of chains without requiring their removal in use on bare pavement.

Four 1970, 8-cylinder sedans of the same make equipped with automatic transmission were used as test vehicles. The different tires and attachments were fitted on wheels and tested in combinations given in Table 1. Before each series of tests, each vehicle was checked for mechanical fitness, brake pressure, alignment, wheel balance, speedometer accuracy, tire pressure, and loss of studs.

TEST PROCEDURES

Ice tests were carried out on Lake Temiskaming in northern Ontario and road tests on Highway 115 near Peterborough, Ontario. The vehicles were driven by experienced Ontario provincial police officers, and all tests were carried out in accordance with the following procedures.

For stopping-distance measurements, the vehicles were allowed to decelerate from a speed slightly above 35 mph; at 35 mph, the brakes were applied to lock the wheels while the vehicle was maintained in the straight-ahead position. The test surface was swept for the tests on clear ice. For tests on sanded ice, the swept surface was covered in 2 overlapping passes with a salt-free sand mixture. For tests on asphalt, the surface was kept uniformly wet by pumping water over the surface after every second test.

Lane-change speeds were determined by simulating the lane-change maneuver shown in Figure 1. Only one driver was used for this test. He entered the swept course at increasing entry speeds. The vehicle was allowed to decelerate from the point of entry where its speed was recorded by radar. The breakout speed was defined as that entry speed at which the driver just failed to keep the vehicle within the course.

Starting traction was determined by hitching the vehicle through a series of pulleys to a vertically moving platform on which weights were incrementally placed until the rear wheels would spin (Fig. 2). For tests on clear ice, the area was simply swept; for those on packed snow, the ice surface was first wet and then covered with approximately 8 in. of snow that was then compacted with a wobble roller to about 6 in. to give a density of between 0.59 and 0.62 gr/cm^3.

All test results were verified by repetition. Care was taken to ensure that they were not influenced by previous activity in the area, and, where surface polishing or wear was noted, the site was changed immediately. This was accomplished smoothly and without delay by having several identical test sites laid out on a 1,500- by 300-ft area of the lake surface.

ANALYSIS OF TEST RESULTS

It was recognized that, no matter what the pavement conditions, vehicle performance in braking, handling, or traction is dependent on many factors other than the tires. With different types of tires, or tire attachments, the relative importance of different factors may vary.

Stopping Distance on Clear Ice

A linear model was postulated in the following form:

$$\overline{D_t} = B_0 + B_1 T_t \pm 2S$$

where

$\overline{D_t}$ = statistically unbiased estimate of average stopping distance at temperature T_t;

B_0 and B_1 = statistically unbiased estimates of coefficients whose values depend on the tires or tire attachments used; and

2S = estimated statistical limit within which approximately 95 percent of the observations might be expected to occur.

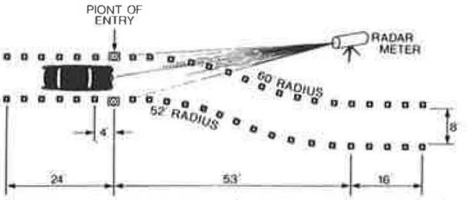
Field data from some 621 test runs were separately curve-fitted by linear regression to establish values of coefficients B_0 and B_1 for the various tires and tire attachments used (Table 2). The results were also plotted and are shown in Figure 3.

Table 1. Comparison of results of tests on highway tires and all other wheel combinations.

	Stopping Distance (ft)								Lane-Change Breakout Speed (mph)				Starting Traction (lb)			
	Clear Ice				Sanded Ice, 30 F		Wet Asphalt		0 F		30 F		Ice		Snow	
	0 F		30 F													
Wheel Combination	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1	312	—	466	—	187	—	62.7	—	16.4	—	11.7	—	177	—	659	—
2	-3	-1	+11	+2	-4	-2	+3	+5	+1	+6	0	0	+9	+5	+12	+2
3	+30	+10	0	0	-12	-6	+8	+13	0	0	+1	+9	+11	+6		
4	+12	+4	-45	-10	-50	-24	+7	+11	-2	-12	+2	+17	+51	+29	+28	+4
5	-15	-5	-127	-27	-24	-12	+1	+2	0	0	+4	+34	+33	+19		
6	+30	+10	-30	-6	-40	-20	+4	+6	-2	-12	+3	+26	+25	+14	+56	+8
7	+18	+6	+9	+2	-36	-18	+2	+3	0	0	+1	+9	+22	+12		
8	+12	+4	-65	-14	-26	-13	0	0	-3	-18	+2	+17	+45	+25	+55	+8
9	+6	+2	-102	-22	-29	-14	-1	-2	-1	-6	+4	+34	+21	+12		
10	+30	+10	-50	-11	-46	-22	+4	+6	+3	+18	+2	+17	+25	+14	+56	+8
11	0	0	-70	-15	-34	-17	+3	+5	+1	+6	+6	+51	+4	+2		
12	-8	-3	-93	-20	-34	-17	+6	+10	0	0	+5	+43	+65	+37	+67	+10
13	-27	-9	-53	-11	-35	-17	—	—	—	—	—	—	+7	+4	+160	+24

Note: Data for wheel combinations 2 through 13 represent increases or decreases in performance as compared with wheel combination 1.

Figure 1. Speed test course for lane-change breakout.



NOTE At point of entry the driver released the accelerator and coasted through the course. The speed was also recorded at this point.

Figure 2. Testing arrangement for starting traction.

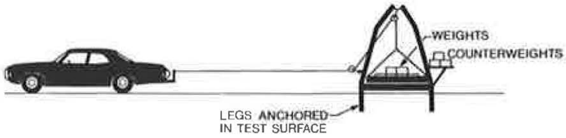


Table 2. Estimating formulas.

Wheel Combination		Stopping Distance		Lane-Change Breakout Speed
No.	Description	Clear Ice	Sanded Ice	
1	Highway tires, 4 wheels	$312 + 5.15\ T_1 \pm 74$	$288 + 5.15\ T_1 - 0.26\ T_1^2 \pm 72$	$16.4 - 0.157\ T_1 \pm 4.9$
2	Synthetic snow tires, rear wheels only	$309 + 5.63\ T_1 \pm 86$	$319 + 5.63\ T_1 - 0.32\ T_1^2 \pm 68$	$17.4 - 0.183\ T_1 \pm 5.0$
3	Synthetic snow tires, 4 wheels	$342 + 4.17\ T_1 \pm 54$	$306 + 4.17\ T_1 - 0.27\ T_1^2 \pm 84$	$16.9 - 0.144\ T_1 \pm 4.3$
4	Studded synthetic snow tires, rear wheels only	$324 + 3.28\ T_1 \pm 56$	$306 + 3.28\ T_1 - 0.28\ T_1^2 \pm 77$	14 ± 3.5
5	Studded synthetic snow tires, 4 wheels	$297 + 1.44\ T_1 \pm 40$	$334 + 1.44\ T_1 - 0.22\ T_1^2 \pm 77$	16.1 ± 3.3
6	Natural rubber snow tires, rear wheels only	$342 + 3.15\ T_1 \pm 79$	$357 + 3.15\ T_1 - 0.32\ T_1^2 \pm 88$	14.4 ± 4.1
7	Natural rubber snow tires, 4 wheels	$330 + 4.86\ T_1 \pm 81$	$310 + 4.86\ T_1 - 0.32\ T_1^2 \pm 75$	$16.8 - 0.142\ T_1 \pm 5.5$
8	Studded natural rubber snow tires, rear wheels only	$324 + 2.60\ T_1 \pm 48$	$319 + 2.60\ T_1 - 0.24\ T_1^2 \pm 73$	13.5 ± 4.6
9	Studded natural rubber snow tires, 4 wheels	$318 + 1.56\ T_1 \pm 40$	$339 + 1.56\ T_1 - 0.23\ T_1^2 \pm 27$	15.4 ± 4.5
10	Controlled protrusion studded snow tires, rear wheels only	$342 + 2.51\ T_1 \pm 67$	$313 + 2.51\ T_1 - 0.26\ T_1^2 \pm 77$	$18.0 - 0.129\ T_1 \pm 3.0$
11	Controlled protrusion studded snow tires, 4 wheels	$312 + 2.84\ T_1 \pm 46$	$303 + 2.84\ T_1 - 0.24\ T_1^2 \pm 84$	17.6 ± 2.4
12	Elastomeric tire attachment, rear wheels only	$304 + 2.33\ T_1 \pm 64$	$317 + 2.33\ T_1 - 0.24\ T_1^2 \pm 86$	6.3 ± 5.2
13	Reinforced steel tire chains, rear wheels only	$285 + 0.98\ T_1 \pm 60$	$291 + 0.98\ T_1 - 0.17\ T_1^2 \pm 89$	—

Figure 3. Stopping distance versus ice temperature.

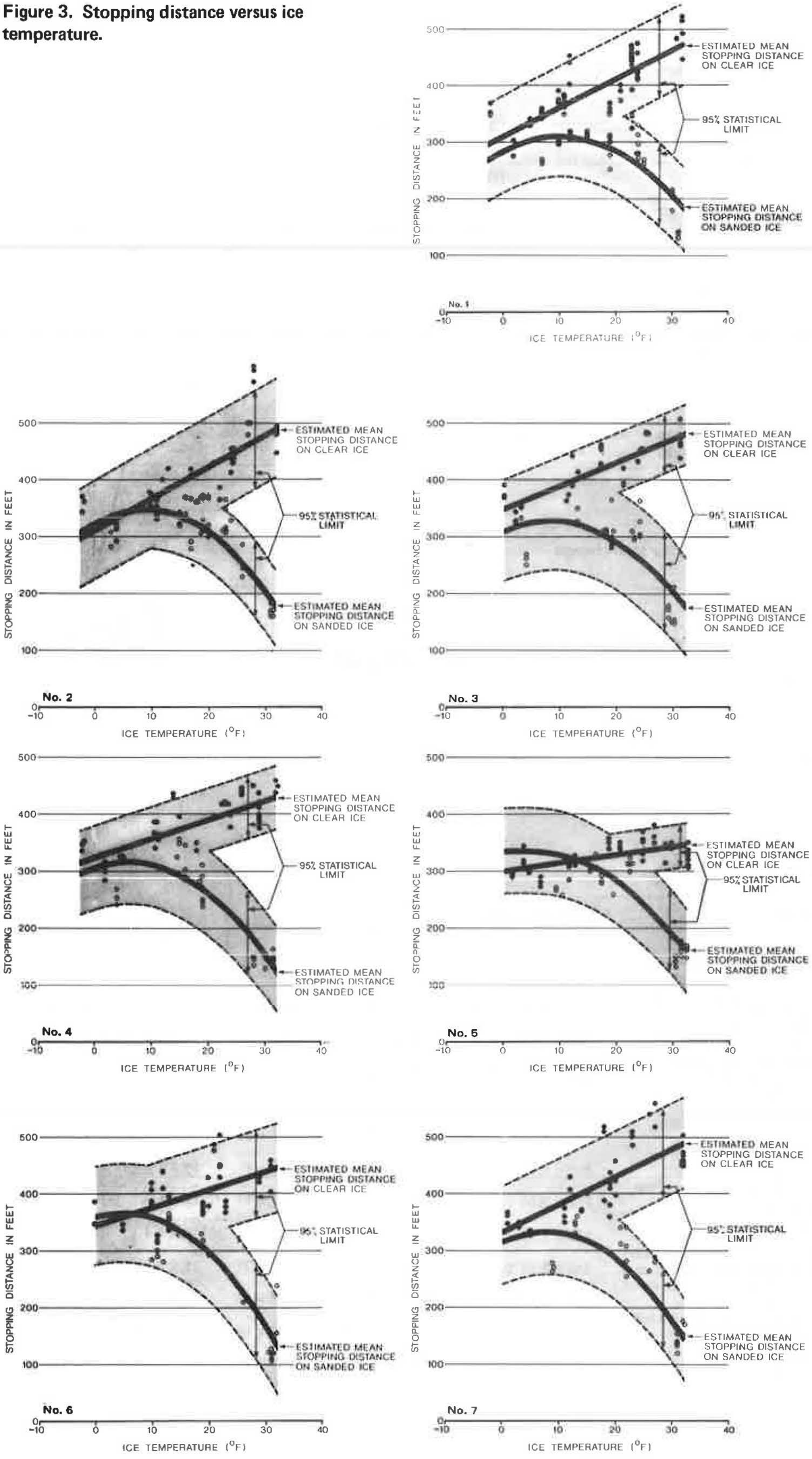


Figure 3. Continued.

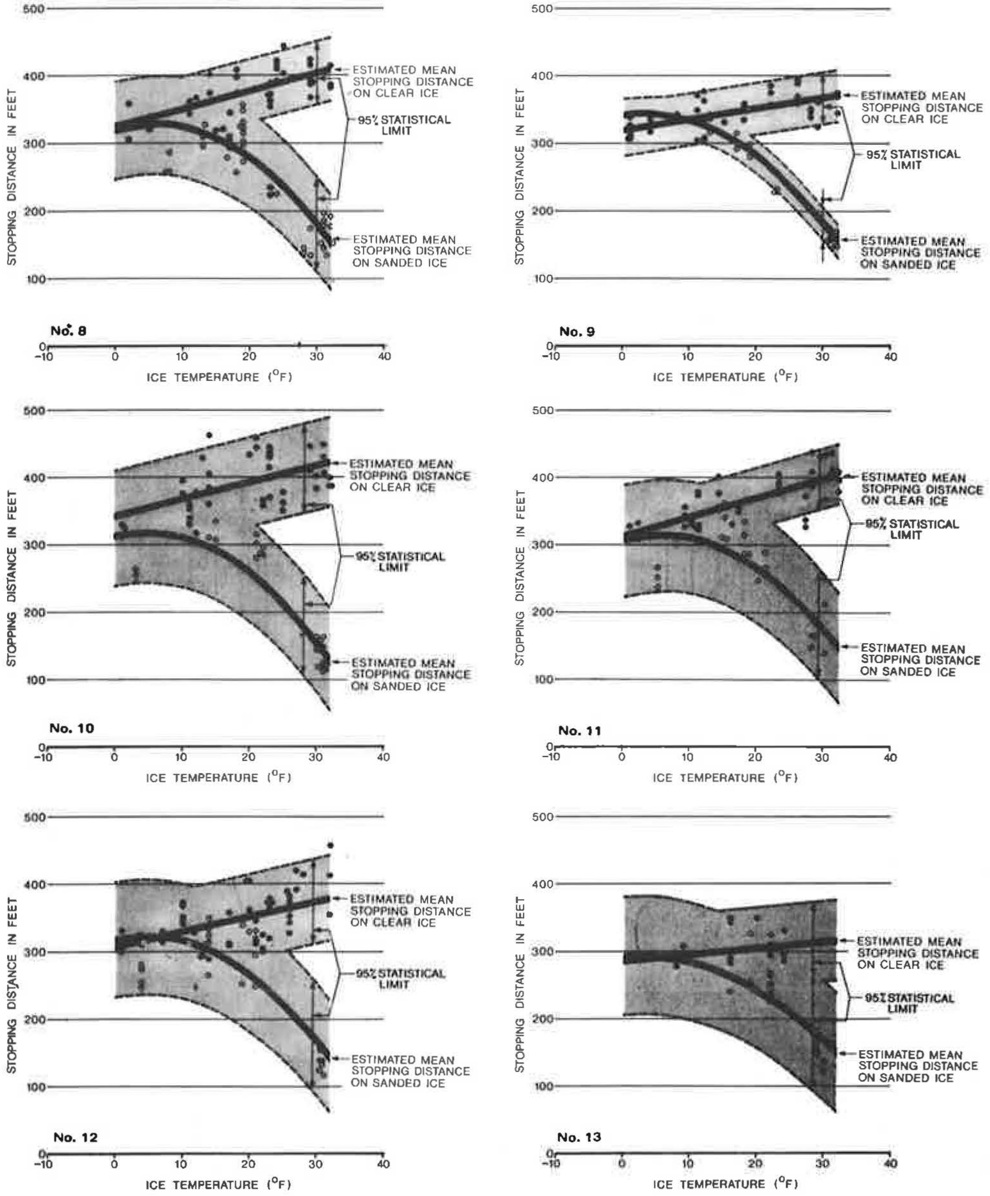
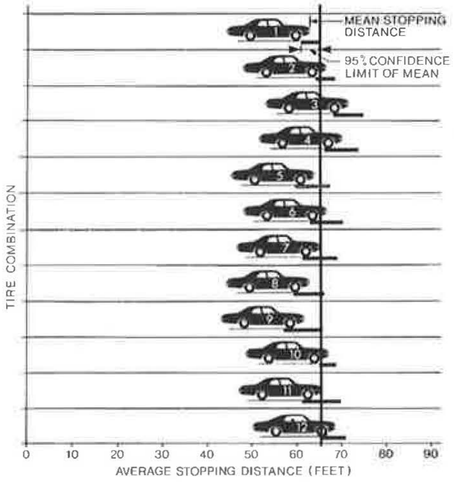


Figure 4. Stopping distance on wet asphalt.



Stopping Distance on Sanded Ice

On the basis of data point plots, a quadratic model was postulated in the following form:

$$\overline{D}_t = A_0 + B_1T_t + A_2T_t^2 \pm 2S$$

where

$\overline{D}_t$ = statistically unbiased estimate of average stopping distance at temperature T_t;

A_0 and A_2 = statistically unbiased estimates of coefficients whose values depend on the tires or tire attachments used;

B_1 = statistically unbiased estimate of the coefficient determined for the same tire or attachments in the clear ice stopping test; and

2S = estimated statistical limit within which approximately 99 percent of the observations might be expected to occur.

Field data from some 354 test runs were separately curve-fitted by linear regression to establish the values of coefficients A_0 and A_2 for the various tires and tire attachments used (Table 2). The results were also plotted and are also shown in Figure 3.

Stopping Distance on Wet Asphalt

Field data from some 312 test runs were analyzed by standard statistical methods to determine the estimated mean stopping distance and the confidence limits at the 95 percent t-distribution value for each tire or tire attachment combination used (Fig. 4).

Lane-Change Breakout Speed

On the basis of data point plots, a linear model was postulated similar to that for stopping distance on clear ice. After standard statistical tests were applied, it was found, however, that in some cases the effect of temperature was not significant at the $\alpha = 0.05$ level.

Field data from some 149 test runs were either separately curve-fitted by linear regression or simply averaged to establish the value of the coefficients or the estimated mean stopping distance for the tires and tire attachments used (Table 2). The results were also plotted and are shown in Figure 5.

Starting Traction on Clear Ice

Though a linear model similar to that for stopping distance was postulated, it was found, after standard statistical tests were applied, that the effects of temperature were not statistically significant. The field data from some 233 test runs were simply averaged to provide the results shown in Figure 6.

Starting Traction on Packed Snow

Field data from some 75 tests were analyzed by simple statistical methods to provide the results as shown in Figure 7. These results have been summarized for the tire type or attachment used on the rear wheels only because significance tests indicated that draw-bar pull depended entirely on the rear wheels and not on the front wheels.

CONCLUSIONS

On the basis of the test procedures and conditions outlined, and to the extent that the tires, attachments, and vehicles used may be considered typical, the following conclusions may be derived from the 1971 test results.

Figure 5. Lane-change breakout speed versus ice temperature.

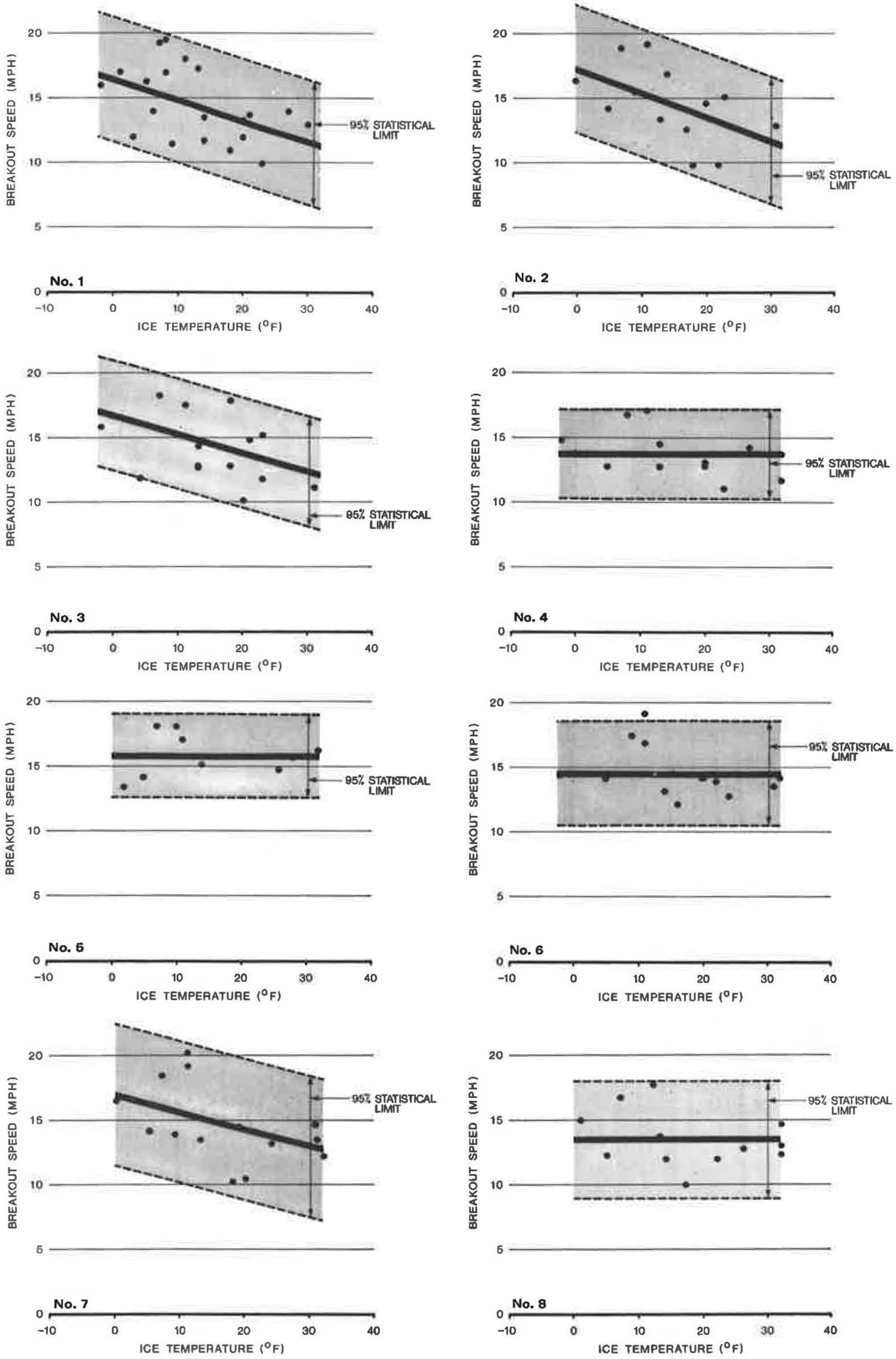


Figure 5. Continued.

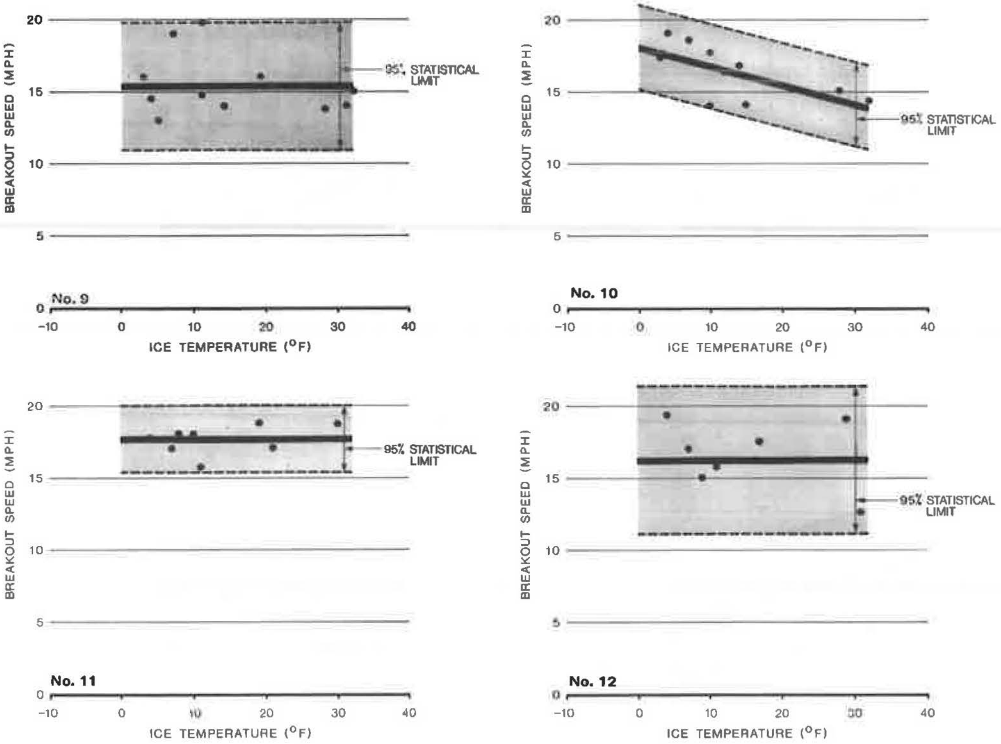


Figure 6. Starting traction on clear ice.

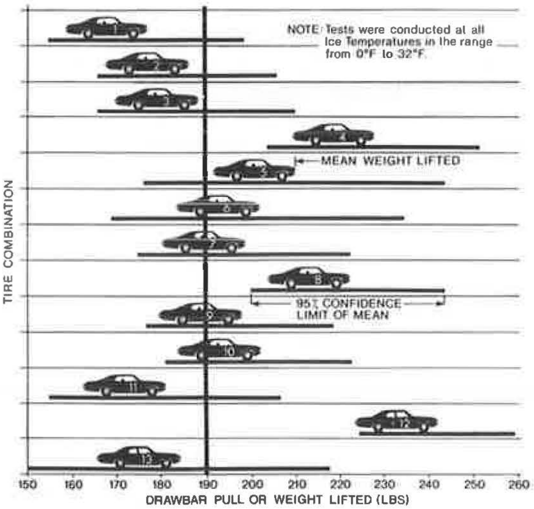


Figure 7. Starting traction on packed snow.

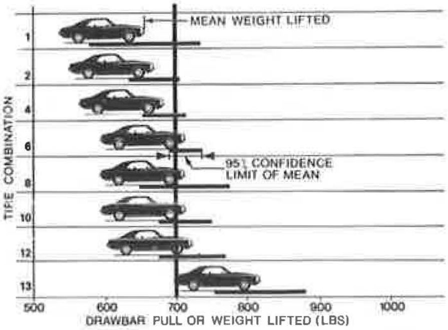
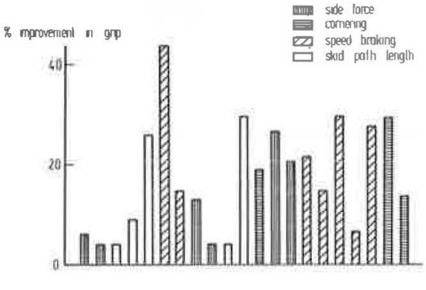


Figure 8. Improved grip of natural rubber tires over conventional synthetic tires.



Stopping Distance

Compared with standard highway tread tires, tire chains, studded snow tires on all 4 wheels, elastomeric attachment, and studded snow tires on the rear wheels only (in order of importance) significantly reduced the stopping distance on clear ice. This effect was most noticeable at temperatures near 32 F and diminished to become negligible at temperatures approaching 0 F. Controlled protrusion studs gave results similar to those obtained with the regular studs. Snow tires on the rear wheels had little effect on stopping distance, but, when used on all 4 wheels, they were less effective than regular highway tread tires.

On sanded ice, the effect of tire type or attachment was of much less importance, though for all combinations the stopping distance as compared to that on clear ice was reduced by more than half at 32 F. This effect diminished with decreasing temperature and became negligible at about 10 F.

On wet asphalt, the type of tire or attachment made little significant difference in stopping distance.

Lane-Change Breakout Speed

Compared with standard highway tires, studded snow tires and elastomeric attachments—either normal or controlled protrusion—on all 4 wheels (in order of importance) increased the speed at which a lane-change maneuver could be made on clear ice. This effect was greatest at about 32 F and diminished to negligible differences in speed at about 0 F.

Starting Traction

Compared with standard highway tread tires, elastomeric attachments and studded snow tires—either synthetic or natural rubber—on the rear wheels only (in order of importance) increased the starting traction on clear ice. The use of studded snow tires on all 4 wheels appeared to be a disadvantage. This effect was not significantly temperature-dependent.

On packed snow, starting traction was increased by reinforced steel chains and, to a lesser extent, by elastomeric tire attachments, controlled protrusion studded snow tires, and natural rubber snow tires (studded and unstudded). This effect was not significantly temperature-dependent.

ACKNOWLEDGMENTS

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DISCUSSION

E. Southern, Natural Rubber Producers' Research Association, Welwyn Garden City, Hertfordshire, England

The friction of rubber on ice is extremely variable, and it is necessary to carry out large numbers of measurements under a variety of conditions if meaningful results are to be obtained. Our own tests have shown that an oil-extended natural rubber compound has better grip than synthetic rubber on ice and hard-packed snow. The improvement ranges from 0 to more than 40 percent, and tests carried out under 1 set of conditions only could give a mean value anywhere within this range. An example of the variability of friction on ice is shown in Figure 8. Data shown are for separate tests on the same ice surface during a period of a few days. Each test is normally an average of at least 6 measurements. Different test methods have been used as shown, but the variation in the results is not confined to 1 test method. In these circumstances, it is obvious that large numbers of tests on different occasions are necessary to obtain a reliable estimate of the average improvement. The reason for this variability is not certain, but it may be due to variations in the ice itself. Extensive tests in 3 separate trials involving more than 2,000 measurements have shown that the average overall improvement is about 15 percent on hard-packed snow and ice. We feel, therefore, that data presented by Smith and Clough are not typical of the average improvement that can be expected in practice.

NEW TIRE-STUD DEVELOPMENTS

Rolf Cantz, Kennametal, Inc., Slippery Rock, Pennsylvania

Although they offer snowbelt motorists substantial improvement of vehicle control on icy roads, studded tires have been attacked with increasing vigor by highway officials for their contribution to road wear. Tests of some recently developed tire-stud designs show promise that the safety and convenience factors of studded tires can be retained—but with a considerable reduction in the amount of road wear caused by their use. In addition to a reduction in weight and minor dimensional changes, most of these new tire studs are designed in such a way that the carbide pin will move farther into the stud body if, at any time, the protrusion of the stud from the tire exceeds a critical limit. (The greater the protrusion is, the greater the impact force is; and it is high-impact force that causes the road wear.) With their built-in protrusion-adjustment capability, the new tire studs maintain nearly uniform protrusion throughout their lifetime. Their ability to do so is unaffected by differences in wear resistance of various rubber compounds, driving speeds, or road surfaces traveled. Tires fitted with these new studs show an increase of 75 percent in coefficient of friction on smooth ice as compared to identical tires without studs. Coefficient of friction decreases only about 5 percent with such studded tires on bare concrete (cement) roads. No difference at all in performance between studded and unstudded tires has been found on bare bituminous pavement, dry or wet.

•USE of studded tires during the winter season has become increasingly popular in areas where roads are frequently covered with ice or snow. Based on sales figures and local surveys, studded tires were used last winter on approximately 40 percent of all passenger cars in Canada, the northern part of the United States, and central Europe. It has been reported that in the winter of 1970-1971 more than 70 percent of all vehicles in Scandinavia were equipped with 4 studded tires.

Use of studded tires on trucks, for the most part, has been limited to Scandinavia and France. In most other countries, the use of studded truck tires has been restricted by law or has not been promoted by the tire-stud industry because of accelerated road wear. It has become evident, especially in areas with high traffic volume, that studded tires are an additional road-wear factor. This was confirmed in field measurements, road tests with controlled driving programs, and laboratory tests (1 through 34).

Most of the research clearly indicates that additional maintenance is required on roads that have a heavy traffic volume and a great number of cars equipped with studded tires. However, on roads that have a relatively light traffic volume, resurfacing is not required any earlier than would otherwise be necessary. It is significant that by far the majority of U.S. highways carry a relatively light traffic volume. Our heavily traveled Interstate routes, expressways, and major arteries within cities represent only a small part of the total mileage in our road system. Most reports also show that the wear resistance of different pavement types varies substantially and that pavements can be improved to offer substantially more wear resistance.

Faced with a possible legal ban of its product, the tire-stud industry has intensified activities to develop new tire-stud designs that retain their benefits for the motorist but are less damaging to road surfaces. This report describes the development of some of these new tire-stud designs and provides a basis for future realization of further improvement.

HISTORY OF TIRE STUDS

Use of metallic cleats in pneumatic tires is not new and can be traced back to the 1890's. They were at that time used to increase the wear resistance of tires and to provide better protection against damage on rough gravel roads. Better roads and improved tires made these cleats unnecessary. However, especially in Scandinavia, a variety of these traction devices are still used for ice races and winter rallies to increase friction on ice- or on snow-covered road surfaces. The effectiveness of these cleats is very limited because, on bare pavements, they are by far less wear resistant than the tread rubber and wear out rapidly.

The first studs with tungsten carbide cores (to achieve a wear performance comparable to tire-tread rubber) appeared in Scandinavia in the late 1950's (Fig. 1).

Fundamental research (36) generated the single-flange tire-stud design (Fig. 2), which has since been adopted by most of the world's tire-stud manufacturers. The only substantial change between the first single-flange design and those in use today has been the use of somewhat softer carbide, which resulted in a slight reduction of the average tire-stud protrusion, as follows:

Year	Protrusion (in.)	Year	Protrusion (in.)
1966	0.087	1969	0.074
1967	0.081	1970	0.068
1968	0.076	1971	0.065

PAVEMENT WEAR TESTS

Preliminary Laboratory Studies

Initial attempts to determine a wear ratio between a tungsten carbide tire-stud pin and a road surface were a failure. The method employed was to press a spring-loaded tire stud against a soft, low-speed grinding wheel (Fig. 3). The results of this test, which was primarily set up to determine differences in wear resistance of various carbide grades, did not correlate at all with actual road test findings.

The second approach was to use a device in which a spring-loaded (30 lb) tire stud slides over a pavement specimen with a velocity of 2.5 in./sec (Fig. 4). After each pass, the specimen is moved sideways to avoid having the stud slide more than once in the same groove. The results of this test gave a good indication of the wear resistance of different carbide grades but did not give a true indication of road wear under actual driving conditions. The specific wear (loss in weight of the pavement specimen, in grams, divided by the loss in weight of the carbide pin, in milligrams), ranged from 250 to 350 depending on the wear resistance of the pavement and the carbide grade used. However, these figures are valid only for driving conditions with 100 percent tire slip (acceleration with spinning wheels, braking with locked wheels, or 100 percent sideslip.)

To duplicate the pavement wear that would be caused by studs in a free rolling tire or a tire with limited slip required that a completely different test arrangement be developed (Fig. 5). A spring-loaded axially oscillating stud hits a slowly rotating pavement specimen with a frequency of 30 cps. The oscillating unit moves sideways across the centerline of the rotating pavement block. Wear of the pavement is not uniform across the test block because the number of impacts per surface area unit and the length of the gliding way between the stud and the specimen are functions of the specimen's radius (Fig. 6). The evaluation of the results had to be made individually for a number of concentric ring sections. Figures 7 and 8 show that the specific pavement wear increases with the force between the stud and pavement and with the sliding length of the stud on the pavement surface. This latter result explains why there is relatively more wear to road sections where slip between tires and pavement surface is more likely to occur. For example, intersections, curves, and tollgate lanes will usually show more wear than straight road sections carrying rolling traffic.

Tests With Road-Wear Simulator

To provide more practical results, a road-wear simulator was built, as shown in Figures 9, 10, and 11. Identical concrete pavement mixes (class A, Pennsylvania Department of Transportation specifications) were used. The minimum curing time was 60 days. The pavement specimen was slowly moved laterally so that uniform pavement wear would occur across the entire surface of the specimen (Fig. 12). The rather short length of the revolving arm of the machine once again resulted in abnormal longitudinal and lateral slip between the tire stud and the pavement surface. However, the results can be related to actual road wear by introduction of a constant correction factor. The following variables were tested.

1. Studs per tire—The number of studs per tire and road wear increase at a linear rate (Fig. 13).
2. Tire-stud protrusion—There is a linear increase in road wear with increasing protrustion (Fig. 14).
3. Tire-stud flange diameter—The diameter of the flange affects the force exerted by the stud on the road surface (Fig. 15). Studs having a small flange offer less resistance and are pushed back into the tire during their contact with the road.
4. Tire construction—Tests were made with radial, bias-belted, and 4-ply bias tires. No differences in road wear could be determined. It can be assumed that studded radial tires cause less road damage at higher speeds than bias ply tires because tires have less squirm on the road and consequently less slip between stud and pavement. However, this effect could not be proved on the road-wear simulator at a speed of only 15 mph.
5. Shape of carbide pin—The sharp edges of the tire studs with flat-tipped pins have a serious cutting effect on the pavement until the tip is worn off to a smooth radius (Fig. 16). This usually happens during the first 500 miles of normal driving, which is equivalent to approximately 50 hours of running time on the road-wear simulator. Figure 17 shows substantial wear differences between a stud with a sharp-edged flat carbide pin and a stud with a new domed pin. After about 50 hours of running time, both pins have the same shape and will have the same pavement wear effect.
6. Weight of studs—No differences in pavement wear could be found in similar studs of different weight. The reason again is the low speed on the simulator; there is negligible variation in the dynamic force of studs with different weight against the pavement at a speed of 15 mph.

Dynamic-Force Measurements

Special force-measuring tire studs (Figs. 18 and 19) made it possible to measure the dynamic axial forces of tire studs against the road surface. These measuring devices, identical in size to regular tire studs, contain 4 strain gauges wired in double bridge network. The protrusion of these measuring studs can be varied by changing the replaceable pins. The use of pins with various heavy metal inserts also allowed tests with different stud weights.

Figures 20 and 21 show a schematic of the test arrangement, description of the test car, and its equipment.

The test car was a 1970 Oldsmobile Cutlass S with the following options: 350 in.^{3}, 310 hp, turbo hydra-matic, extra heavy duty suspension (includes rear sway bar), power disc brakes, power steering, and air conditioning. The dimensions were as follows: front tread width, 59.0 in.; rear tread width, 59.0 in.; wheelbase, 112.0 in.; test weight (with equipment and personnel), 3,940 lb; and weight distribution front to rear, 55 to 45 percent.

Preliminary tests showed that the structure of the pavement surface does not affect the results. On smooth surfaces, however, the forces are more uniform, which makes it easier to evaluate the recordings. Tests on both front and rear wheels also resulted in no significant differences. This allowed us to eliminate most front-wheel tests.

The resolution of our measuring system allowed us to analyze the forces throughout the entire contact between stud and pavement surface. The highest forces occur the

Figure 1. First tire studs with tungsten carbide cores.

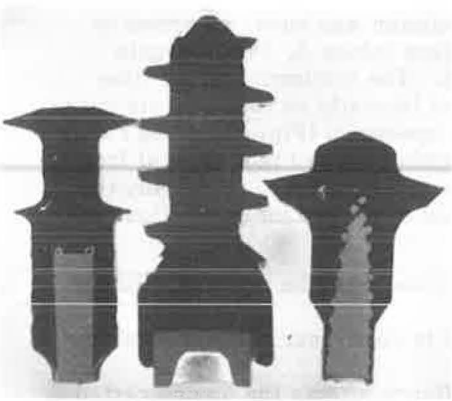


Figure 2. Cross section of single-flange tire stud.

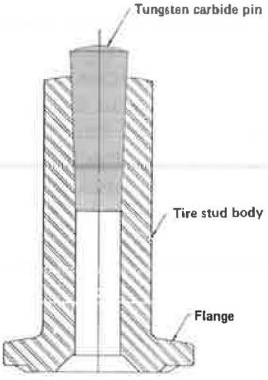


Figure 3. Early attempt to determine wear ratio between stud pin and road surface.

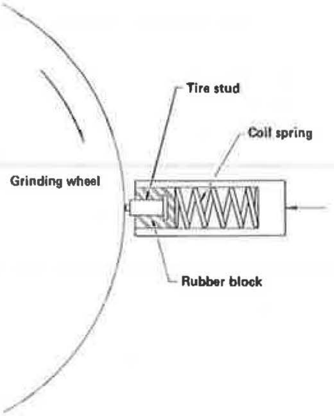


Figure 4. Second attempt to determine wear ratio between stud pin and road surface.

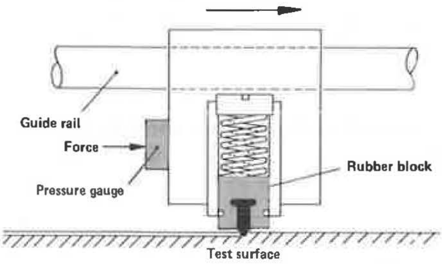


Figure 5. Later test arrangement for duplicating pavement wear.

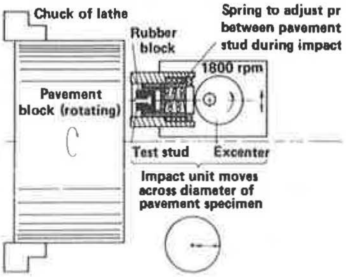


Figure 6. Detail of pavement-wear simulation.

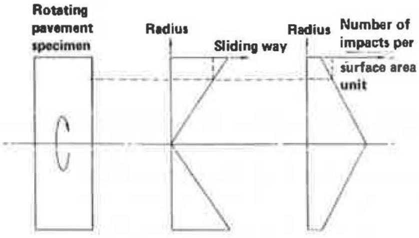


Figure 7. Pavement wear increases with increase of force.

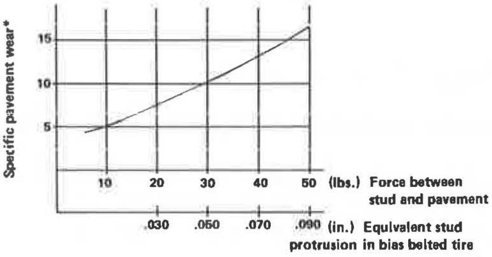
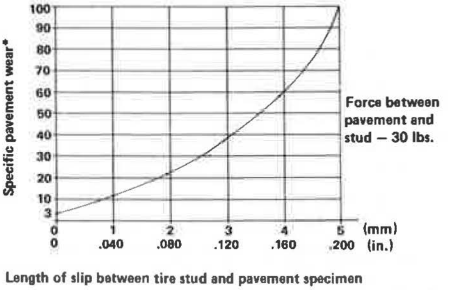


Figure 8. Pavement wear increases with increase of slip.



*Specific pavement wear = $\frac{\text{Loss in weight of road specimen (grams)}}{\text{Loss in weight of carbide pin (milligrams)}}$

Figure 9. Top view diagram of road-wear simulator.

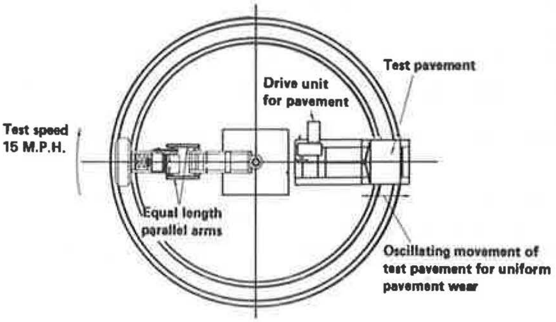


Figure 10. Side view diagram of road-wear simulator.

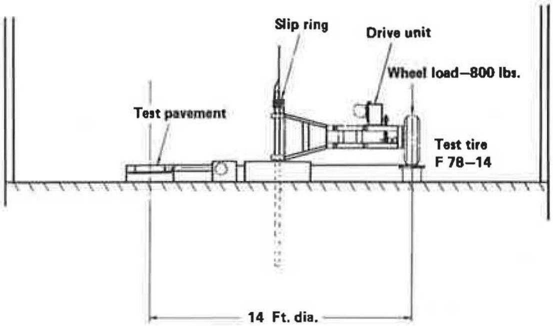


Figure 11. Road-wear simulator.

Figure 12. Closeup of pavement section in road-wear simulator.

Figure 13. Effect of number of studs per tire on pavement wear.

Protrusion: .060"
Flange diameter: .350"
Bias belted tire

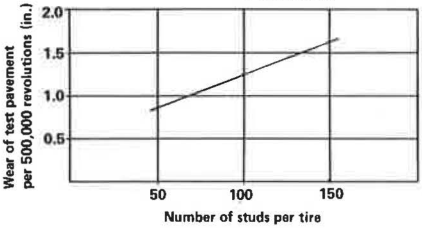


Figure 14. Effect of stud protrusion on pavement wear.

Bias belted tire
Flange diameter: .350"
108 studs per tire

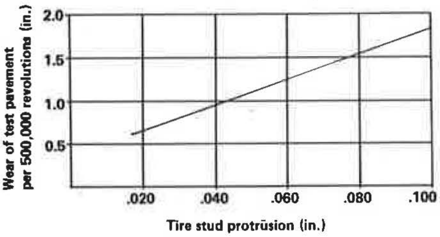


Figure 15. Effect of flange diameter of stud on pavement wear.

Bias belted tire
108 studs per tire
Tire stud protrusion: .060"

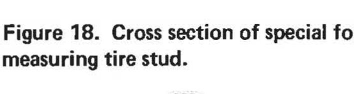


Figure 16. Pavement contact by 2 types of stud pins.

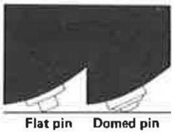
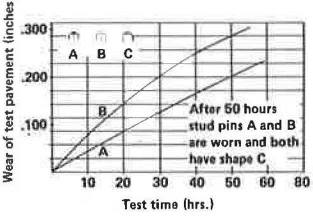


Figure 17. Relative pavement wear by 2 types of stud pins during first 50 hours of use.



After 50 hours stud pins A and B are worn and both have shape C

Figure 18. Cross section of special force-measuring tire stud.

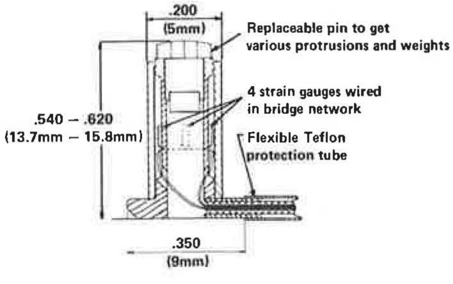
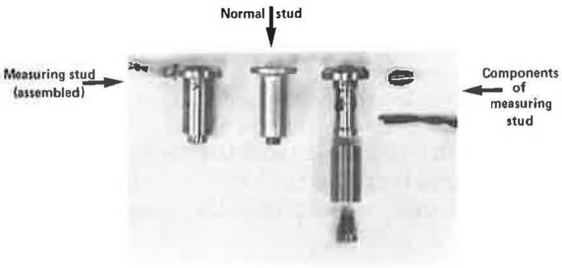


Figure 19. Comparison of special force-measuring stud with standard stud.



first moment the stud hits the road—inertial force required to push the stud back into the tire (Fig. 22). This initial impact is shown in the following figures as "dynamic force."

1. An increase of the force with higher vehicle speeds seems logical due to an increase in the inertial force (Fig. 23).
2. The relation between the dynamic force and the tire-stud protrusion is almost linear (Fig. 24)
3. It is quite obvious that the tire-stud weight becomes a very important influence on the dynamic forces, and it can be assumed that it affects pavement wear at a similar rate (Fig. 25).
4. Tire-inflation pressure and wheel load have no substantial effect on the tire-stud forces. Studs with larger flanges create higher forces (Fig. 26).
5. Thickness of the base rubber is the distance between the stud flange and the cord (Fig. 27). More "undertread," which acts like a rubber spring during the contact between the stud and the road, increases the resiliency and consequently reduces the dynamic forces. We could not find a reduction in force of 50 percent by doubling the undertread thickness (as reported by Scheuba, 37). Figure 28 shows, however, that the dynamic force is decreased by approximately 27 percent as the undertread thickness is doubled from 0.080 to 0.160 in.
6. Bias-belted and radial tires showed no significant difference in the dynamic force.
7. The dynamic force of tire studs with a center cavity and 4 symmetrically oriented pockets (Fig. 29) is, under all tested conditions, 4 percent lower than the forces of identical studs with flat flanges.

NEW TIRE-STUD DEVELOPMENTS

Road-wear test results and dynamic-force measurements show that the following changes in tire-stud or tire designs can reduce road wear: decreased tire-stud protrusion, reduced tire-stud weight, smaller flange diameter, increased undertread thickness, reduced number of studs per tire, increased resiliency of the undertread, and modified flange design. Several of these opportunities for road-wear reduction have been incorporated into the tire-stud designs described in the remainder of this report.

CP Stud

Basic changes are weight 18 percent lighter and flange 5 percent smaller. The new Kengrip controlled protrusion (CP) stud is designed in such a way that the tapered pin will move farther into the jacket as soon as a critical level of dynamic force is reached (Fig. 30). This dynamic force is determined primarily by the tire-stud protrusion and partially by the speed of the vehicle. This means that the studs maintain a certain protrusion level almost independent from the driving conditions and the wear resistance of the carbide pin and the tire.

The protrusion maintained by conventional studs during use is determined by the grade of carbide used for the pin, the wear resistance of the tire tread, and the driving conditions. The carbide grades in most of the tire studs in use today are the result of a great number of road tests. Generally they give uniform tire-stud protrusion for most drivers. Figure 31 shows a stud-tire combination that was developed for an average tire life of 16,000 miles, which is equivalent to a ratio of 0.028-in. tread wear per 1,000 miles. At this rate tire studs and the tire are wearing equally. If a driver has more tire wear because of more severe driving conditions, he may, for example, get a tire lifetime of only 10,000 miles with the same tire and stud combination. Under such conditions, it is probable that the tire will be wearing faster than the studs, which will result in an increase of protrusion. On the other hand, a driver who gets a higher tire mileage will experience a loss of tire-stud protrusion, for the tire studs will wear faster than the tread rubber. The new CP stud design reduces this problem.

The dimensions of the tapered pin and the shape and dimensions of the hole in the body determine the critical minimum force that is necessary to move the pin. This pin movement determines the tire-stud protrusion. The average protrusion with these CP

Figure 20. Test equipment used for dynamic-force measurements.

Figure 21. Equipment layout for force measurements.

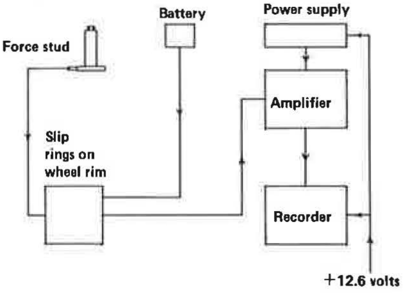


Figure 22. Dynamic force is greatest at moment of impact.

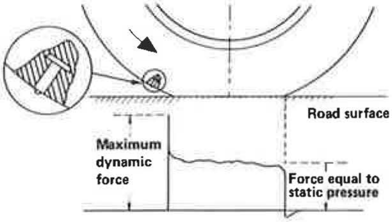


Figure 23. Dynamic force increases with vehicle-speed increase.

Protrusion: .050" Tire stud weight: 2.5 Grams
Flange diameter: .350" Undertread: .120"
Bias belted tire

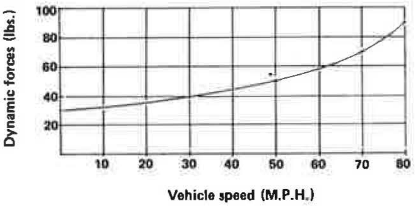


Figure 24. Dynamic force increases with protrusion increase.

Undertread: .120" Flange diameter: .350"
Vehicle speed: 50 M.P.H. Tire stud weight: 2.5 Grams
Bias belted tire

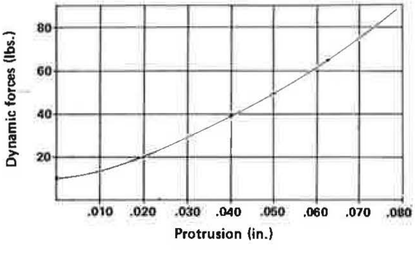


Figure 25. Dynamic force increases with stud-weight increase.

Protrusion: .050" Flange diameter: .350"
Vehicle speed: 50 M.P.H. Undertread: .120"
Bias belted tire

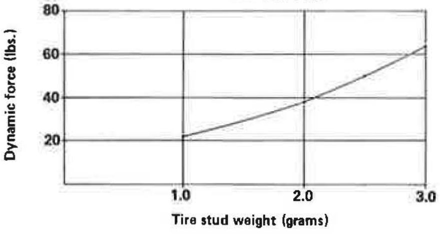


Figure 26. Dynamic force increases with flange-diameter increase.

Protrusion: .050" Tire stud weight: 2.5 Grams
Vehicle speed: 50 M.P.H. Undertread: .120"
Bias belted tire

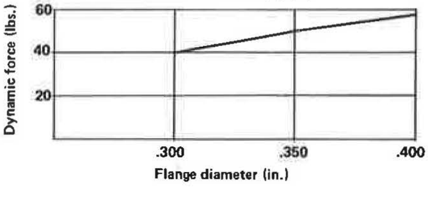
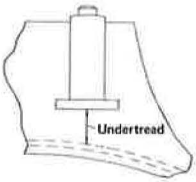


Figure 27. Undertread is distance between stud flange and tire cord.



studs is 0.040 to 0.050 in., approximately 30 percent less than the average tire-stud protrusion on vehicles in the winter season of 1970-1971. Tests show a reduction of 40 to 50 percent in road wear with this new CP stud.

Another advantage of the shortened protrusion is a reduction of the heat created during the impact of the tire stud on the road. Thus, the temperature between the stud and the tread rubber is lower. This in turn eliminates degeneration of the rubber around the stud, which is the main reason for undesired enlargement of the hole in the tire tread (Fig. 32). Manufacturing of this CP stud design is difficult because very close tolerances must be maintained.

CP Stud With Threaded Hole

The pin of this design (Fig. 33) is also able to move into the stud body. The movement is controlled by the force on the road and by the wearing of the body. The pin is basically locked in the body at its larger end by only 2 or 3 turns of the thread. If the stud starts to protrude too far, the end of the body breaks off (Fig. 34). This reduces the holding force, and the pin can move farther into the body. An advantage of this design is that the pin movement depends much less on the accurate dimensions of the body hole and the pin.

CP Stud With Wire Coil in Plastic Body

Figure 35 shows a cross section of the design of a tire-stud body that consists of a coil spring molded in plastic. The carbide pin is held in its position by only the 2 or 3 windings at the end of the coil spring. In case of excessive protrusion, the soft plastic material will be worn away on the pavement surface, and that causes the end of the coil to open up. This, in turn, reduces the holding force between body and pin, and the pin moves farther into the body. These studs have a weight of only 1 gram. Preliminary pavement wear tests show a reduction in road wear of as much as 65 percent compared to conventional steel studs.

FUTURE DEVELOPMENTS

A still newer approach, which could in the future reduce road wear even more is the attachment of a soft spring-like rubber cushion underneath the tire-stud flange (Fig. 36). Preliminary tests indicate that this could reduce the forces between the stud and the pavement surface as much as 40 percent. The forces remaining would still be sufficient to provide a grip on ice even at very low temperatures. This cushion could be made of a material that gets increasingly soft as temperatures go higher and stiffer as temperatures go down. This would increase the forces on ice surfaces when they are needed and would decrease them at higher speeds on bare pavements when the tire stud and the tires get hotter.

Research has been initiated, and results can be expected in the near future.

CHANGES IN TIRE DESIGNS

When tire studs were introduced, most tire manufacturers retained their existing tread designs and changed their molding procedures to simply add holes for tire stud installation. In most cases, there was not enough rubber around the stud to give adequate support. Too much flexibility allowed the stud to move away laterally, which caused irregular stud wear and irregular tire-stud protrusion. Generally, the studs had a tendency to "grow" out of the tire and, thus, increase road wear.

In new winter-tire designs (Fig. 37), the rubber area around the stud holes has been increased to provide sufficient support and eliminate lateral movement. Another tire design change being implemented is the molding of tire-stud holes with a configuration different from any previously made (Fig. 38). The new hole has a cavity at its end to receive the stud flange.

Tests have shown that with the previously used cylindrical hole the initial stud protrusion in new tires depends greatly on the pressure that is applied to the stud gun (Fig. 39). The new hole design eliminates most of the dependency on human skill (Fig. 40),

Figure 28. Dynamic force decreases with undertread increase.

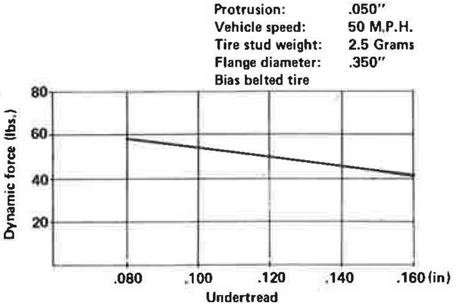


Figure 29. Stud with 4 symmetrically oriented pockets and center cavity (left) and flat flange (right).

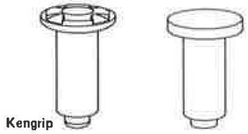


Figure 30. Stud currently used and new CP tire stud.

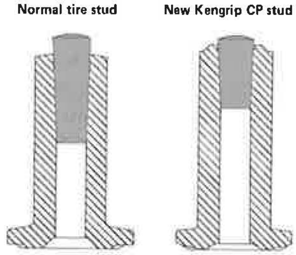


Figure 31. Relation of useful tire life to stud protrusion.

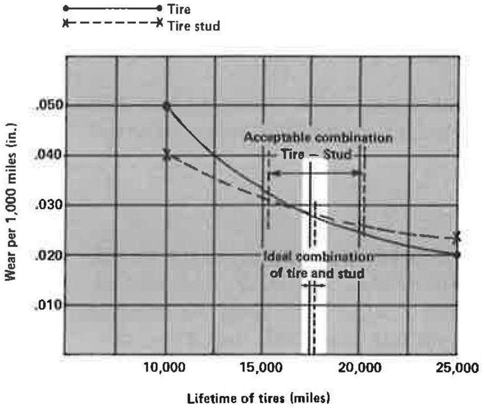


Figure 32. Effect of stud protrusion on heat generation.

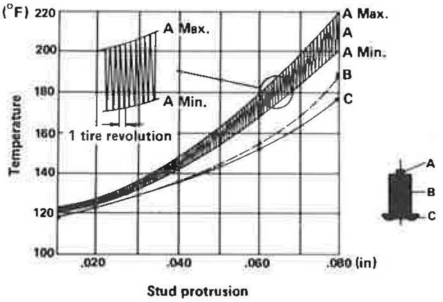


Figure 33. Experimental stud with threaded cavity for pin.

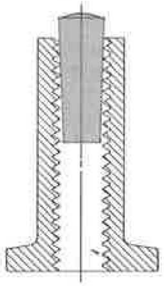


Figure 34. Characteristic wear of experimental stud.

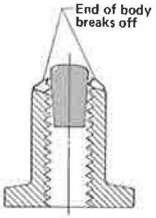


Figure 35. Experimental stud with wire coil embedded in plastic body.

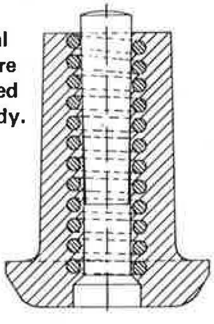


Figure 36. Experimental stud with rubber cushion beneath stud flange.

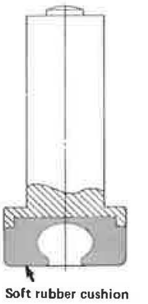


Figure 37. Old and new tread patterns.

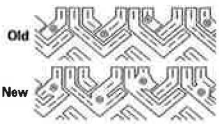


Figure 38. Old and new mold pins.

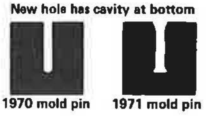
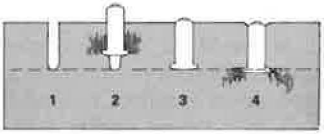
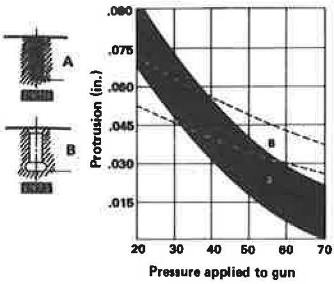


Figure 39. Stud installation.



(1) cylindrical hole (2) too little pressure and too much stud protrusion (3) correct position (4) too much pressure, no stud protrusion, and cracks in surrounding rubber caused by excessive elongation.

Figure 40. Effect of gun pressure.



and the stud will automatically adjust to its correct position during the first 100 miles of driving.

PERFORMANCE OF STUDDED SNOW TIRES

A great number of studies (5, 7, 9, 12, 14, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47) have been made to measure the effect of studded snow tires on ice-covered, snow-covered, and bare pavements. All reports agree that studded tires, as compared to identical unstudded tires, afford dramatic improvement in vehicle control on glare ice. However, reports concerning bare-pavement performance differ substantially. In some cases, the reason for the differences is that the use of nonstandard test equipment or comparisons between snow tires and highway tires or even the use of different brands of snow treads has produced varying results. Atmospheric temperatures, pavement construction, and surface finish are additional factors that can influence test results.

Figure 41 shows a comparison of some of these results. Both an increase and a decrease in the coefficient of friction have been found on asphalt and concrete, both wet and dry. The advantages and disadvantages on asphalt seem to be balanced. However, the presence of studs seems to have some negative effects on both wet and dry concrete surfaces.

We have conducted our own vehicle performance tests and used the test vehicle with the same options and dimensions as that used for the dynamic force measurements except that the test weight with equipment and personnel was 4,260 lb and the weight destribution front-rear was 54-46 percent. The test equipment is shown in Figure 42, and the equipment layout is shown in Figure 43.

The following sections discuss the result of winter tests that were conducted in 1969-1970 and 1970-1971. They conform with the results of earlier tests that were carried out between 1965 and 1969.

Coefficient of Friction on Glare Ice

Figure 44 shows the coefficient of friction evaluated in vehicle stopping tests at different speeds, ice-surface temperatures, and tire combinations. At 30 F, the use of 4 studded tires offers an increase in coefficient of friction of approximately 90 percent. As temperatures decrease, the advantages of studded tires are reduced, but even at -3 F there is still an increase in the coefficient of friction amounting to 25 percent. A test conducted in 1967 projected that all the effectiveness of studded tires would be lost at -10 F. Current testing, however, could not substantiate that proposition.

Effect of Number of Studs and Their Location

Friction increases with the number of studs per tire (Fig. 45). The tire design used for these tests made it possible to vary the number of rows in which the studs were positioned in the tire tread. Any given number of studs will be more effective on ice when they are located in a greater number of rows. This fact was taken into consideration in the design of most modern winter tires that have stud holes located across the tread in 6 or 8 rows.

Effect of Tire-Stud Protrusion

An excess protrusion of studs in a new tire raises the coefficient of friction (Fig. 46). However, the excessive protrusion, more than approximately 0.050 in., will cause excessive heat buildup in the studs. This in turn destroys the surrounding rubber and reduces the support strength of the stud. Then the studs no longer penetrate the ice so effectively. Thus, although excessive protrusion in a new tire will give a higher coefficient of friction, excessive protrusion in a used tire, with corresponding enlargement of the stud holes, will result in a lower coefficient of friction. Properly installed studs with correct protrusion, especially the CP design, will maintain their effectiveness on ice throughout the lifetime of the tire.

Figure 41. Comparison of stud performance tests.

		RESULTS									
		ASPHALT				CONCRETE					
		DRY		WET		DRY		WET			
TESTS MADE BY	KIND OF TESTS	FRICTION INCREASE WITH STUDS ←	FRICTION DECREASE WITH STUDS →	FRICTION INCREASE WITH STUDS ←	FRICTION DECREASE WITH STUDS →	FRICTION INCREASE WITH STUDS ←	FRICTION DECREASE WITH STUDS →	FRICTION INCREASE WITH STUDS ←	FRICTION DECREASE WITH STUDS →	REMARKS	REFERENCE
CANADA SAFETY COUNCIL	STOPPING TESTS 50 M.P.H.		- 0 %		- 0 %		-15 %		-19 %		1970 REPORT
ONTARIO PROVINCIAL POLICE	STOPPING TESTS 50 M.P.H.		- 7 %		-22 %						REPORT RR 165 DEPT. OF HIGHWAY ONT.
STATE OF NEW YORK	SKID TEST RESULTS	+ 1 %		+ 3.5%		+ 5 %		+ 3.5%			PHYSICAL RESEARCH REPORT RR 65-3
UNIVERSITY OF STUTTGART	STOPPING TEST 50 M.P.H.		- 0 %	+13 %			- 7 %		-10 %	TIRE-A	DEUTSCHE KRAFTFAHRT FORSCHUNG UND STRASSEN VERKEHRSTECHNIK 1967
			- 1 %	+ 3 %			-20 %		-20 %	TIRE-B	
TENNESSEE HIGHWAY RESEARCH PROGRAM	STOPPING TEST VARIOUS SPEEDS		- 5 %		- 1 %					PAVEMENT-1	CORNELL AERONAUTICAL LABORATORY REPORT NO. 159
		+ 4 %			- 3 %					PAVEMENT-2	
	SKID TRAILER TESTS	+ 2.5%		+ 1.6%						PAVEMENT-1	
		+ 2.4%		+ 1 %					- 2.6%	PAVEMENT-2	
STATE OF ILLINOIS	STOPPING TESTS 50 M.P.H.	+ 1.7%		+12 %		+ 5 %		+ 1.3%		NEW TIRES	RESEARCH & DEVELOPMENT REPORT NO. 13
		+ 1.7%		+ 3 %			- 8 %		- 3 %	OLD TIRES	
ROYAL CANADIAN AIR FORCE	STOPPING TESTS 40 M.P.H.		- 8 %				- 6 %			LIGHT TRUCK	

Figure 42. Test equipment used for stopping and acceleration tests.

Figure 43. Equipment layout for stopping distance and acceleration measurements.

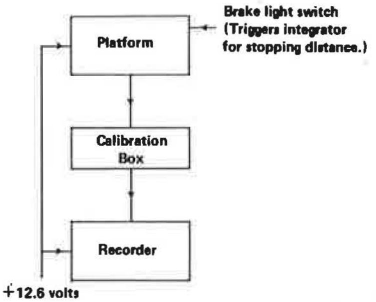


Figure 44. Effect of studded tires on coefficient of friction.

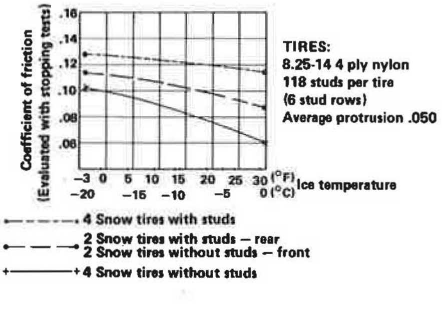


Figure 45. Effect of number of studs on coefficient of friction.

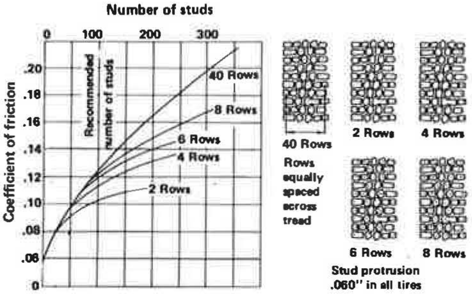


Figure 46. Effect of stud protrusion on coefficient of friction.

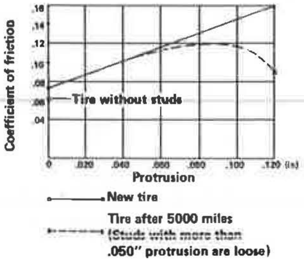


Figure 47. Effect of pin diameter on coefficient of friction.

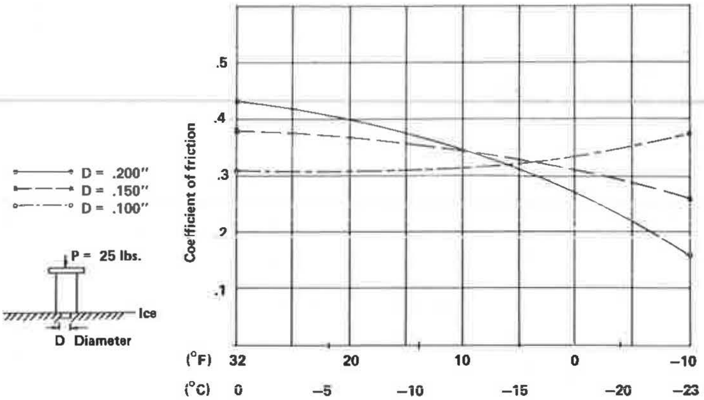


Figure 48. Stopping distances.

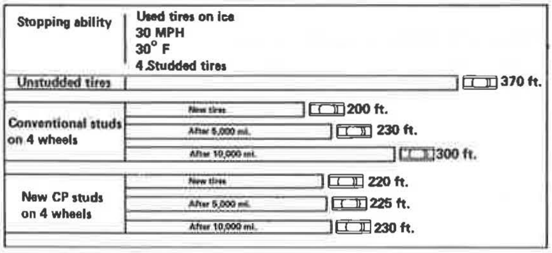


Figure 49. Climbing traction.

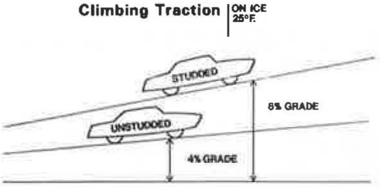


Figure 50. Starting traction.

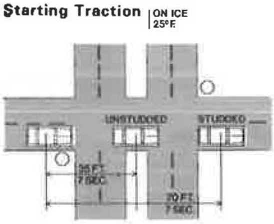


Figure 51. Cornering ability.

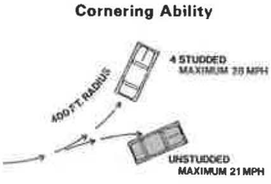
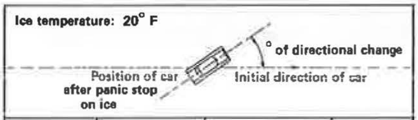


Figure 52. Directional stability.



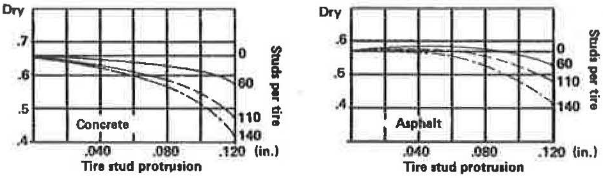
Initial speed of car (MPH)	4 Snow tires (without studs)	2 Snow tires front 2 Studded snow tires rear	4 Studded snow tires
	* Average	* Average	*Average
20	22°	14°	5°
40	90°	26°	12°
60	114°	36°	28°

* 20 Panic stops

Table 1. Percentage increase or decrease of friction compared with tire without studs.

Road Surface	Conventional Studs	CP Studs
Glare ice (30 F)	+85	+70
Packed snow	+11	+8
Loose snow	0	0
Dry concrete	-7.6	-4.5
Wet concrete	-8.8	-5.2
Dry asphalt	0	0
Wet asphalt	+1.9	0

Figure 53. Effect of protrusion and number of studs on coefficient of friction.



Effect of Carbide-Pin Diameter

Tests with 3 different pin diameters show that large pins lose some of their effectiveness at lower temperatures while smaller pins become more efficient (Fig. 47). This is due to their higher force per surface unit. This was taken into account with the CP stud design, which has a pin diameter of approximately 0.100 in.

Stopping Distances With Conventional and CP Studs

Figure 48 shows comparative stopping distances for a vehicle equipped with tires without studs, with conventional studs, and with CP studs. CP studs lose little of their effectiveness after 5,000 and even 10,000 miles of normal use.

Starting Traction, Cornering Ability, and Directional Stability

Figures 49, 50, 51, and 52 show comparisons in starting traction, cornering performance, and directional stability between vehicles with and without studded tires (CP studs).

Coefficient of Friction on Dry and Wet Asphalt and Concrete Surfaces

Test results with various tire and stud combinations are given in Table 1. The loss of friction on dry and wet concrete is less with CP studs than with conventional studs. The reason is the reduced force between CP studs and the pavement, which is caused by the shorter protrusion. Figure 53 shows the effect that protrusion and the number of studs per tire have onthe coefficient of friction, on dry concrete and asphalt pavements.

CONCLUSIONS

It may be impossible to eliminate all pavement wear due to the use of studded tires. However, new tire-stud designs, in combination with improved pavement compositions, can substantially reduce the problem. Indications are that the reduction in road wear thus achieved would be such that resurfacing would not be required any more frequently than normal.

Comparison testing of studded and unstudded tires indicates that studded tires do cause a slight loss of friction on dry and wet concrete pavements. The difference is relatively small when compared to other stopping distance factors such as vehicle weight, speed, and particularly the added distance required for snow-tread tires compared to regular treads. What is more significant is the substantial improvement in vehicle control on icy and snow-covered roads, as established by numerous tests by independent agencies.

Whether the use of studded tires contributes more to motoring safety or convenience is really an academic question. Traffic at horse-and-buggy speeds would surely be safer than traffic at the present legal speeds. But we do not design roads today for horse-and-buggy traffic. Today's highway system has been engineered and built to permit motorists to go where they want to go, with speed, convenience, and safety. Just as windshield wipers, 4-wheel brakes, and headlights serve that purpose, so do studded tires. We believe that a proper sense of values for safety and mobility, as well as convenience, will permit—indeed encourage—motorists to use studded tires for winter driving.

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MIX DESIGN CRITERIA FOR WEAR-RESISTANT BITUMINOUS PAVEMENT SURFACES

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This report presents the results of a laboratory study carried out to establish mix design criteria for wear-resistant bituminous mixtures. The relative wear resistance of various types of paving mixtures was measured by a laboratory test rig that consisted of 2 wheels driven by a central vertical shaft so that they turned freely on a circular runway made of 12 juxtaposed trapezoidal test specimens. Bituminous mixtures wear by pulverization, cutting, and attrition, and wear is accelerated by fragmentation, loosening, and dislodgment of aggregate particles. Rate of wear is lowest near freezing temperature and increases with increasing plasticity of the mix at higher temperature or with increasing stud force and brittleless of the mix at lower temperature. Rate of wear greatly increases when the pavement is wet. Factors affecting the resistance to wear were identified and their relative influence on wear determined. Mix design criteria for wear-resistant bituminous pavement surfaces were established, and performance of conventional and special bituminous mixtures are discussed.

•THIS REPORT is the third in continuing research on the wear of pavement surfaces by studded tires. The importance and complexity of the problem have been demonstrated in the first report, which was based on field observations and a comprehensive literature survey (1). The second report describes the results of a field test carried out to evaluate the wear resistance of different types of conventional and special portland cement concrete and bituminous concrete mixtures (2).

This report presents the results of a laboratory study carried out to establish mix design criteria for wear-resistant bituminous mixtures. It covers 5 main topics:

1. Development of a laboratory test method and procedure to evaluate the wear resistance of paving mixtures;
2. Identification and description of the mechanism of wear;
3. Determination of the effect of temperature and presence of salt water on the rate of wear;
4. Identification of factors affecting the wear resistance of bituminous pavement surfaces, including type, size, and amount of coarse aggregate, bitumen type and content, adhesion of asphalt cement to aggregate surface, film thickness, filler-bitumen (F-B) ratio, type and size of fine aggregate, and overall grading of the mix; and
5. Determination of mix design criteria for wear-resistant bituminous mixtures.

DEVELOPMENT OF LABORATORY TEST METHOD AND PROCEDURE

Description of Simulator

A traffic simulator was developed to measure the wear resistance of various types of paving mixtures. The apparatus consists of 2 wheels driven by a central vertical shaft at a constant speed of 5.28 mph. The wheels are made of solid rubber and turn freely on a 4-ft circular runway constructed of 12 juxtaposed trapezoidal test specimens made of a bituminous mixture. The traffic simulator, designed to measure relative wear, is not intended to and does not reproduce all rolling conditions that prevail on the pavement. A detailed plan of the traffic simulator is shown in Figure 1. It is composed of 4 main parts: the table and support, the driving unit, the running unit, and the test track.

The simulator is placed in a 10 by 8 ft (3 by 2.4 m) cold room, where the temperature can be controlled from 100 F (37.8 C) to -40 F (-40 C), with a precision of ±2 F (1.1 C). The test track rests on a mobile circular crown that can be rotated to change the position of the test specimens around the table. The crown is held in place by a circular guide fixed to the table. The runway is made of 12 trapezoidal test specimens that are butted together and held in place by 2 wooden curbs fixed on the mobile circular crown.

Wear Measurements

The wear or loss of bituminous material due to a given number of passes of studded tires can be expressed in terms of loss in weight, change in profile, or loss in volume. Although all 3 terms are used in this study, accurate results on the wear resistance of different types of bituminous mixtures can only be obtained from measurements of loss in volume. With low void mixes, the loss in volume can simply be determined from weights of test slabs, in both the air and water, before and after the test. The precision of this technique was found to be satisfactory (3).

Test Conditions

The rate of wear of a bituminous mixture is affected by many factors related to the testing conditions. The most important are wheel load, stud protrusion, temperature, and humidity.

A constant wheel load of 95 lb was used for all tests. When this load is applied, the unit pressure between the tire and the pavement surface is approximately 21 psi.

Figure 2 shows typical results of change in stud protrusion with the number of passes. Each histogram shows the variation in mean and range values of all of the 128 studs on the tire after a given number of passes. Results indicate that the decrease in protrusion is not directly proportional to the number of passes. Thus, to eliminate the effect of stud protrusion requires that different mixes be tested at the same time and that runs be alternated frequently among different series of tests. Control samples were also used to compare results from different series. The tires were changed as soon as the mean protrusion value reached 0.035 in. (0.09 mm).

The temperature for the test was standardized at 23 F (-5 C), which represents the weighted average temperature of a typical winter in Montreal, and the test track normally was kept wet during the test.

Precision of Test

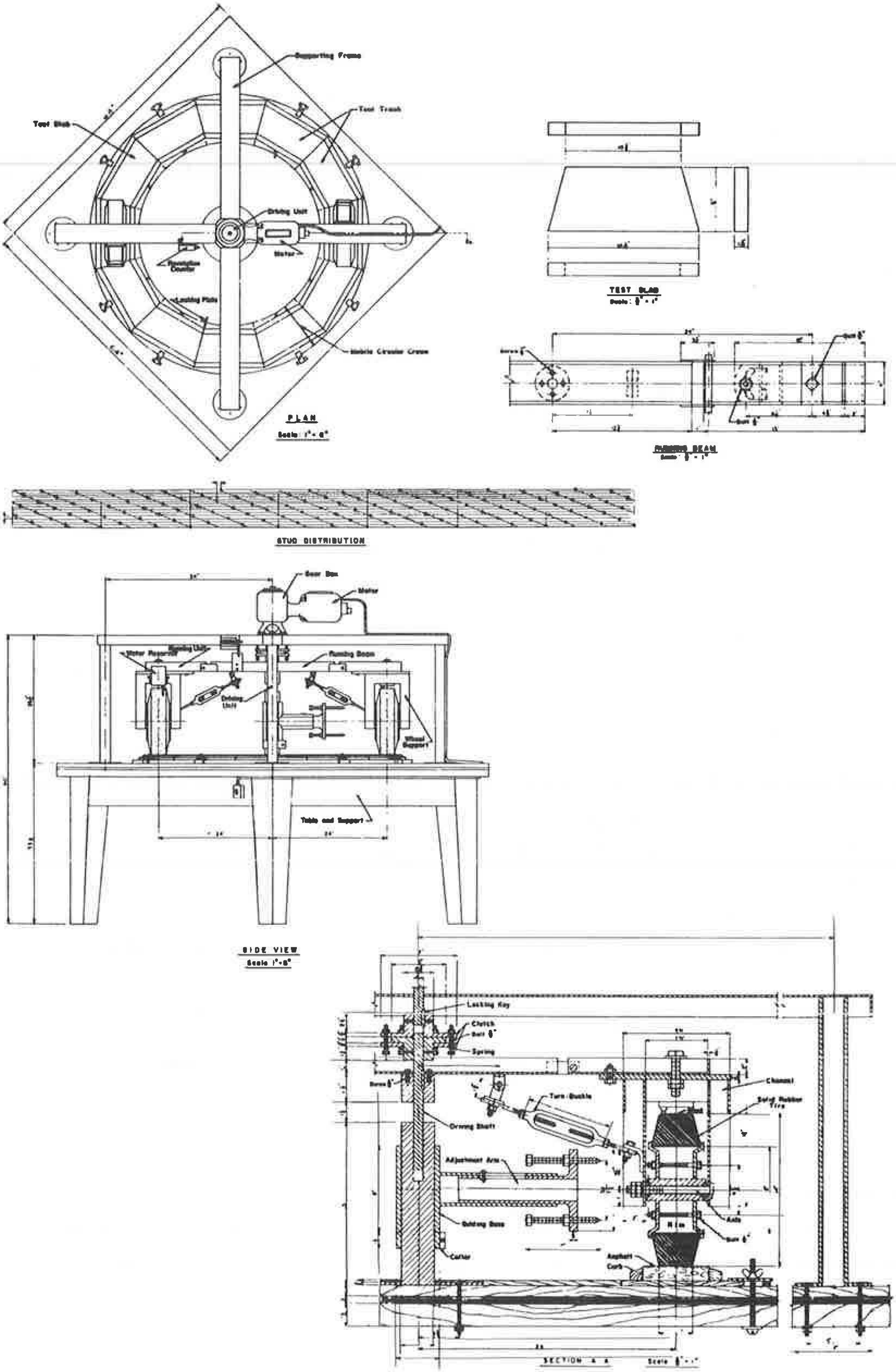
The repeatability of test varies with different types of bituminous surface as follows:

Mix Type	Size of Coarse Aggregate	Number of Samples	Coefficient of Variation (percent)
Gap-graded	No. 4-$^{3}/_{4}$ in.	18	7.6
Gap-graded	$^{1}/_{2}$-$^{3}/_{4}$ in.	12	4.8
Stone-filled sheet	No. 4-$^{3}/_{8}$ in.	12	3.0

Correlation With Field Test

A comparison between wear test results of skip-graded mixes obtained with the traffic simulator in the laboratory and those obtained during the field test (2) is shown in Figure 3. The results obtained during the field test agree fairly well with those obtained in the laboratory.

Figure 1. Traffic simulator.



ACTION OF STUDS ON PAVEMENT

The action of studs on pavement surfaces is a rather complicated phenomenon and depends on many factors related to the nature of vehicle tires and type of stud used, the geometry of the pavement, the contact area characteristics, the nature of the traffic, and the environmental conditions.

The pressure that a stud exerts on a pavement depends on the nature and the magnitude of stud forces and the effective contact area between the stud and the pavement. Lucas (4) and Carlstedt (5) have demonstrated that, when the whole area of a stud does not fully and uniformly come into contact with the pavement surface, a unit pressure several times greater than the compressive strength of most of the rock types develops.

A series of tests was made on skip-graded mixes to study the nature of wear of aggregate particles and the matrix exposed on the pavement surface. The test consists of making observations and measuring the average depth of wear of the matrix and that of the coarse aggregate after 30,000 passes of studded tires.. Sieve analysis was also made on the powder produced by the wear. The 12 specimens around the test track were made of the same mortar and 2 types of stone; only the percentage of the surface covered with stone was different.

Test results are shown in Figure 4. Examination of test results and observations during the test lead to the following conclusions:

1. The mixes are worn by a combination of three processes (Fig. 5): (a) pulverization, cutting, and attrition of the surface; (b) fragmentation and loosening of the aggregate mineral; and (c) loosening and dislodging of aggregate particles.
2. The mortar between the coarse aggregate particles wears rapidly at the beginning of the test. The rate of wear of the aggregate, which is much lower than the rate of wear of the mortar, is also higher at the beginning.
3. The rate of wear expressed in depth of wear and the nature of wear are different for the 2 types of aggregate used. With hard aggregate mixes (lamprophyre), the mortar and the sharp edge of the aggregate wear rapidly until the asperity of coarse aggregates is approximately equal to the stud protrusion. At that stage, the tire and studs are chiefly supported by the round-shaped protruding aggregate particles, and the rate of wear of the mortar is nearly constant and follows the rate of wear of the stone particles. With bituminous mixtures made with softer limestone aggregates, the nature of wear depends on the relative wear resistance of the constituent coarse aggregate and the matrix. If the aggregate is more resistant, the rate of wear stabilizes when the coarse aggregate has reached a constant average protrusion value that is less than the stud protrusion. At that stage, the tire and studs that are supported by the stone are also partly supported by the matrix, and the surface of the stone particles is much rougher than the one obtained with hard aggregate and is not rounded.
4. When the exposed aggregate on the pavement surface reaches a depth of embedment of about 0.05 in. (1.20 mm), the aggregate wears out rapidly by fragmentation, loosening, and dislodgment.
5. The powder produced by the wear of lamprophyre mix has a uniform grading, with particles ranging between 0.03 and 0.09 mm, whereas the grading of powder produced by limestone mix is continuous and lies principally between 0.02 and 0.15 mm. The difference in grading is attributed to the difference in the hardness and the structure of the 2 aggregates used. Limestone, being a soft crystalline aggregate, is pulverized and fragmented more easily than the hard amorphous lamprophyre aggregate.

EFFECT OF ENVIRONMENTAL CONDITIONS ON WEAR

Effect of Temperature

A series of tests was carried out to determine the effect of temperature on the rate of wear of 12 different types of bituminous mixtures. The characteristics of each mix tested are given in Table 1. A total of 48 test slabs were made, 4 per mix. Uniformity among test slabs of the same mix was controlled by the specific gravity. The ranges among the 4 test slabs were kept below 0.02 g/cm^3.

Figure 2. Stud protrusion and number of passes.

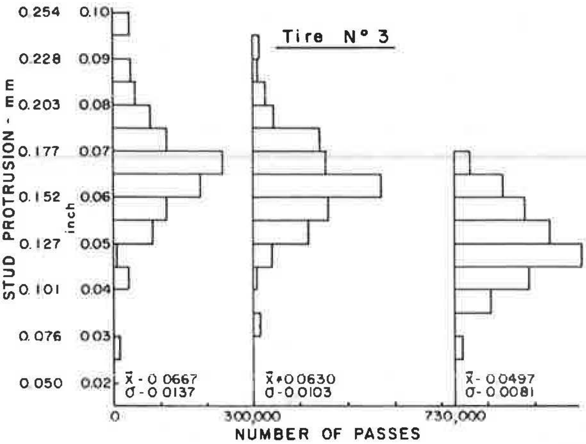


Figure 3. Comparison of field and laboratory tests.

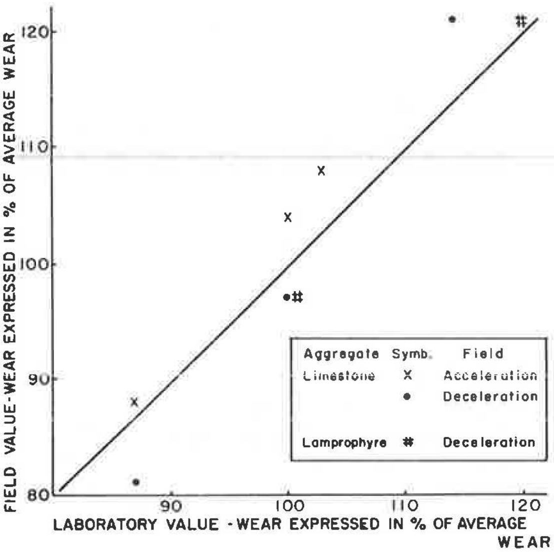
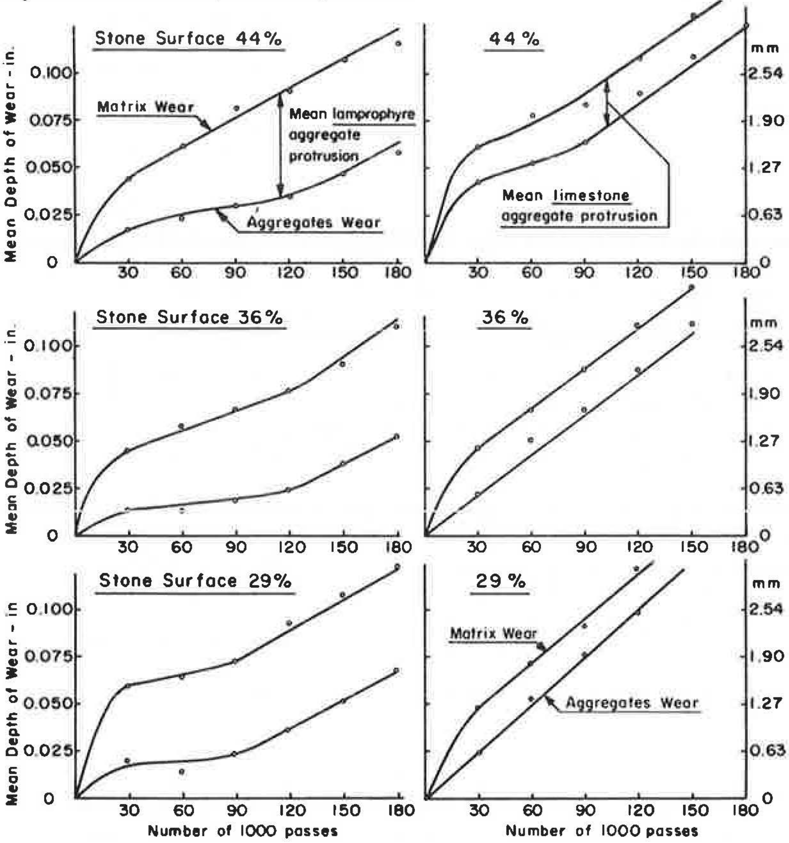


Figure 4. Stone surface and wear of matrix.



Test results obtained at 10, 30, 50, and 70 F (-12, -1, 10, and 20 C) are shown in Figure 6. For both limestone and lamprophyre mixes, a U-shaped curve is obtained, indicating that the wear is generally lowest near the freezing temperature and increases from this as temperature increases or decreases. The limited number of specimens tested causes the test results to be scattered, especially for mixtures made with limestone.

Increased wear at low and high temperatures is mainly caused by the change in both rigidity of the rubber tire supporting the studs and stiffness of the bituminous mixture. Figure 7 shows that the tire hardness varies with temperature: It increases under low temperature and decreases under high temperature. Thus, the force required to push the stud into the tire so that it is flush with the pavement surface depends on the temperature. At low temperature, the unit pressure is higher, and more wear results.

It is well known that the stiffness of asphalt varies with temperature. Asphalt cement is a viscoelastic, semisolid material with less cohesion at 70 F than at lower temperatures. Therefore, when the stud comes into contact with the mix, it penetrates deeper into it by displacing the aggregate particles and, thus, produces more wear by shear and dislodgment. Figure 8b shows that, when a stud comes into contact with a film of asphalt cement at 70 F, the asphalt cement is displaced through flowing, and the stud leaves a circular imprint. Figure 8c shows that at low temperatures the asphalt cement becomes brittle and, consequently, the indentation process causes the matrix of the mix to be partly crushed and chipped by fracture. This results in a higher rate of wear.

Influence of Wet-Dry Condition of Test

Another series of tests was carried out to determine the influence of the presence of water on the rate of wear of pavement surfaces. So that ice would not form at the testing temperature of 23 F, salt water was used to wet the runway. Water reservoirs were fixed on the wheel supports, and the rate of flow was adjusted to keep the track covered with a thin film of water.

Tests were carried out with 6 different skip-graded mixes made in duplicate with the same matrix, 2 different types of coarse aggregate, and different percentages of specimen area covered with coarse aggregate.

The mix characteristics and test results are given in Table 2. When the test track was kept wet, the rate of wear of mixes made with lamprophyre coarse aggregate was nearly doubled; however, with mixes made with limestone coarse aggregate, the ratio between the rate of wear obtained with wet and dry tracks varied between 1.3 and 1.7.

EFFECT OF COARSE AGGREGATE CHARACTERISTICS ON WEAR

Influence of Stone Type

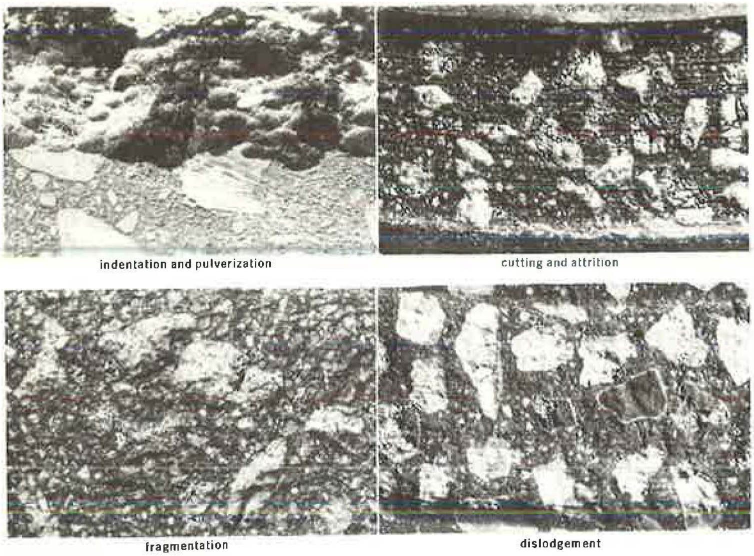
Several series of tests have been carried out to determine the influence of stone types on the wear resistance of bituminous mixtures. The performance of 2 types of stone was investigated: a common limestone and a hard lamprophyre. They represent the extremes among road-making aggregates that can be found in Montreal.

Petrographic analysis of the 2 types of stone revealed that the lamprophyre is a fine-grained, porphyritic, igneous rock with phenocrysts of amphibole and pyroxene in an intermixed fine-grained groundmass and a diabasic texture. It also contains a few phenocrysts of feldspar and opaque minerals. The matrix is composed of fine feldspar laths mixed with pyroxene and amphibole grains and some nepheline. The feldspar is altered to saussurite, and a small quantity of calcite is present. The Trenton limestone is a sedimentary rock made of successive irregular layers of fossil-bearing iron-silica minerals and of calcite of chemical origin.

A summary of the physical characteristics and chemical composition of the 2 types of rock is given in Table 3.

The relative wear resistance of the limestone and the lamprophyre was evaluated by the traffic simulator. The characteristics of the Chazy and Trenton limestones are similar, except that the Chazy limestone is less dense and contains about 1 or 2 percent less silicate.

Figure 5. Pavement wear processes.



indentation and pulverization

cutting and attrition

fragmentation

dislodgement

Table 1. Characteristics of asphalt concrete mixtures.

Section	Grading	Mixture[a]	Bitumen Content (percent)	Grading (percent) > No. 4	< No. 4 > No. 200	< No. 200	Stability	Voids in Mixture (percent)
N-1	Discontinued	AE 50 percent	6.0	31	61	8	2,240	3.9
N-2	Discontinued	AE 40 percent	5.3	37	57	6	2,450	4.7
N-3	Discontinued	AE 30 percent	5.9	30	63	7	2,200	3.6
N-4	Fine	Sheet	7.6	0	90	10	1,665	5.1
N-5	Stone sheet	Stone-filled	5.8	20	70	10	2,245	3.2
N-6	Dense	Bituminous concrete	5.8	40	53	7	2,515	1.5
S-6	Discontinued	Bituminous concrete	5.2	27	70	3	2,180	4.7
S-5	Stone sheet	Stone-filled	5.9	11	79	10	2,100	3.8
S-4	Fine	Sheet	8.2	0	87	13	1,300	4.0
S-3	Discontinued	AE 30 percent	6.2	26	66	8	1,870	4.5
S-2	Discontinued	AE 40 percent	4.8	45	47	8	2,120	4.1
S-1	Discontinued	AE 50 percent	4.6	50	44	6	2,810	2.8

Note: For the N-sections, limestone was the coarse aggregate used; for the S-sections, lamprophyre was used.

[a] AE = elementary aggregate ½ in.

Figure 6. Temperature and pavement wear processes.

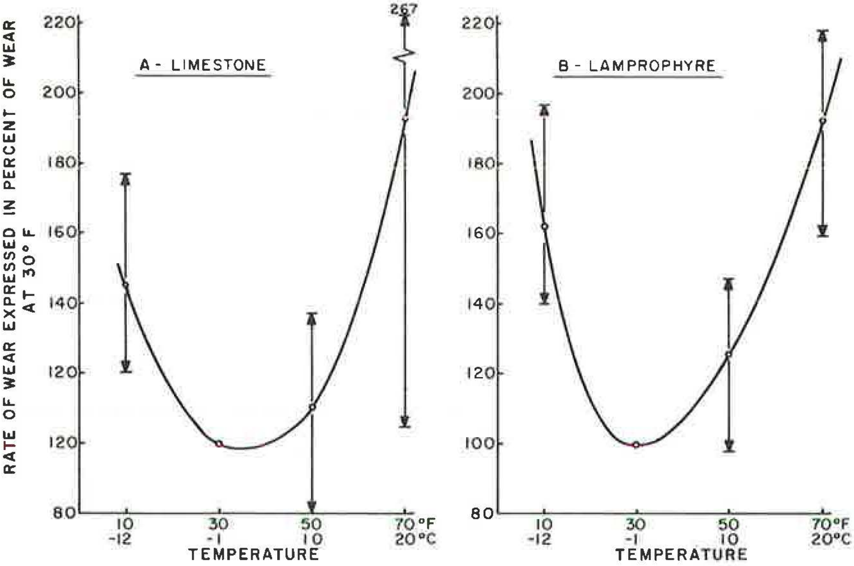


Figure 7. Temperature and hardness of tires.

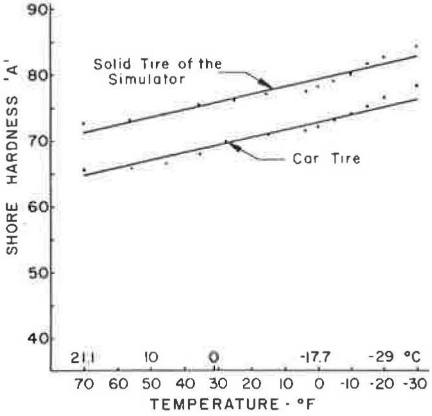
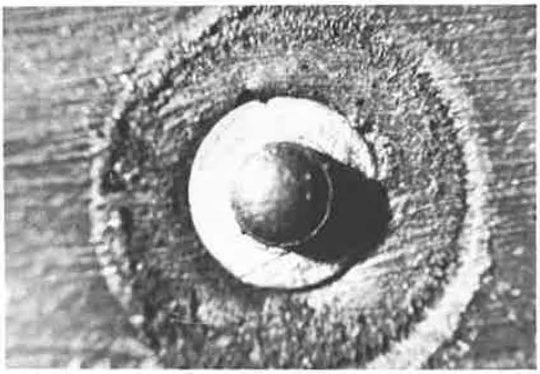


Table 2. Rates of wear under dry and wet conditions.

Aggregate	Surface Covered With Stone (percent)	Rate per 100,000 Passes[a]		
		Wet	Dry	Ratio
Lamprophyre	42	64	29	2.2
	38	49	25	2.0
	29	57	28	2.0
Limestone	47	76	46	1.7
	36	60	47	1.3
	29	75	52	1.4

[a] Mean of 2 specimens.

Figure 8. Temperature and asphalt stiffness.



(a) Stud

(b) 70 F Plastic Failure

(c) 10 F Brittle Failure

Table 3. Characteristics of coarse aggregate.

Characteristics	Lamprophyre	Limestone
Specific gravity, g/cm^3	2.77	2.72
Absorption, percent	0.2	0.5
Hardness		
Mohs	5 to 6	2.5 to 3
Knoop (equivalent)	266	173
Composition		
CaO	11.5	47.8
SiO_2	40.5	6.1
Al_2O_3	13.6	2.5
Fe_2O_3	11.4	1.1
MgO	3.1	1.7
Na_2O	6.8	0.2
K_2O	2.9	0.5
TiO_2	5.9	—
Soundness ($MgSO_4$), percent	1.8	4.3
Los Angeles abrasion, percent	13	28

Rockwell hardness tests were also made on the different stone samples. Because of significant differences in hardness of lamprophyre and limestone, 2 scales were used. Hardness is expressed in Knoop equivalent values for comparison. The Knoop values are approximate only, for the equivalency factors were originally established for iron and steel (6).

Figure 9 shows that there is a relation between the surface hardness of the stone and the relative rate of wear obtained with the traffic simulator. The harder the surface of the stone is, the lower is the rate of wear. The denser the limestone is, the higher the resistance is to indentation and wear. The resistance of a stone is often reduced by the absorption of water, which is usually related to the porosity. The greater the absorption is, the lower is the strength of the stone.

In the course of this study, several mixes of the same composition were prepared with the 2 types of aggregate (lamprophyre and limestone). Test results given in Table 4 show that the quality of aggregate is one of the most important parameters in the design of wear-resistant bituminous mixtures. However, the effectiveness of sound aggregates is closely related to their size and grading. A relative rate of wear of 1.3 is obtained for gap-graded mixes made with $^1/_4$ to $^5/_8$ in. graded coarse aggregate; a rate of more than 1.8 was obtained with mixes made with $^5/_8$ to $^3/_4$ in. coarse aggregate.

Influence of Coarse Aggregate Size

Tests were carried out to determine the effect of stone size on the wear resistance of bituminous mixtures. The test specimens were made with the same matrix but with coarse aggregate of different sizes. Test results are shown in Figure 10. The wear resistance of bituminous surfacing is slightly improved by increasing the size of coarse aggregate from $^1/_2$ in. (12.6 mm) to $^3/_4$ in. (18.9 mm) but greatly reduced by decreasing the size from $^1/_2$ to $^1/_4$ in. (6.3 mm).

The rapid wear of mixes made with smaller sized aggregate can be attributed to the following causes:

1. Aggregate particles are less resistant to wear near their exposed perimeter than in the center. For a given percentage of mix surface covered with coarse aggregate, the perimeter length increases proportionally with the increase in the number of particles and the decrease of the radius of the particles.
2. As demonstrated earlier, when an aggregate particle reaches a critical embedment depth of approximately 0.05 in., it fractures easily, becomes loose, and detaches from the pavement surface. Small particles are more rapidly worn to the critical depth because of their smaller size and more rapid rate of wear.

Influence of Stone Content

In this study, stone content means percentage of total surface of the specimen covered with stone and not percentage by weight. For a given stone content by weight of the mix, the area of stone exposed on the surface varies with the position of each particle. It is, therefore, more realistic to compare the rate of wear with the exposed surface area of the stone in contact with the tire and studs.

Four test runs were made with different mixes in an attempt to determine the relation between the quantity of exposed stone on the pavement surface and the rate of wear: (a) skip-graded mix as used in the field test, (b) skip-graded mix made with $^5/_8$ to $^3/_4$ in. limestone coarse aggregate, (c) skip-graded mix made with $^5/_8$ to $^3/_4$ in. lamprophyre coarse aggregate, and (d) skip-graded mix made with $^3/_8$ to $^1/_2$ in. lamprophyre coarse aggregate. The grading of the mortar was identical for all the mixes tested, and the uniformity between the triplicate compacted specimens was controlled by ensuring that the range in specific gravity between the test slabs did not exceed 0.02 g/cm^3. The test results, shown on Figure 11, allow the following conclusions:

1. A mix can hold a maximum amount of stone; the amount depends on the grading of stone particles and the nature of the surrounding matrix. If this amount is exceeded, stone particles are neither well embedded nor held together by the matrix. The laying and compaction of the mix by conventional methods may also become difficult. The

maximum amount of stone that a mix can hold increases with the increasing aggregate size.

2. The rate of wear decreases with increasing stone content until an optimum value is reached; beyond that value, the rate of wear increases again. With skip-graded mixes having 20 to 40 percent of the surface covered with No. 4 to $^{5}/_{8}$ in. coarse aggregate, there is a linear relation between the percentage of surface covered with stone and the rate ofwear.

3. An analysis of variance was carried out to determine the relative importance between stone types (lamprophyre versus limestone) and the percentage of surface covered with $^{3}/_{4}$ to $^{5}/_{8}$ in. stone (25 to 45 percent), as follows:

Stone	Surface Covered (percent)	Sample 1	Sample 2
Limestone	40	125	128
	36	78	109
	28	120	129
Lamprophyre	47	63	65
	36	45	53
	28	52.5	60

Test results given in Table 5 clearly indicate the importance of stone types over the percentage of exposed aggregate.

A further analysis indicates a close relation between the average free distance between particles and wear. For the $^{3}/_{4}$ to $^{3}/_{8}$ in. coarse aggregate and the prevailing test conditions, an optimum free distance of 0.32 in. was found.

INFLUENCE OF NATURE OF MATRIX ON WEAR

In this report, the matrix of a bituminous mixture is defined as a mixture of fine aggregate and binder. Fine aggregate is that fraction of aggregate passing the No. 4 sieve, and the binder is a filler-bitumen mixture.

In an earlier section, it was shown that the rate of wear of a stone-rich bituminous mixture is directly related to the rate of wear of the coarse aggregate, the mortar being protected by the protruding stone. This is true as long as the stone is sufficiently coarse and solidly held in the pavement surface by the binder of the matrix. As the stone content or stone size decreases, the protection offered to the matrix (by the stone) decreases, and the rate of wear increases accordingly until it is solely governed by the nature of the matrix material itself.

Adhesion of Bituminous Materials to Coarse and Fine Aggregates

As shown earlier, the rate of wear of mixes made with either lamprophyre or limestone aggregate is greatly increased if the test conditions are changed from dry to wet. The action of water in accelerating the wearing process may be attributed to 2 main causes: (a) the loss of adhesion between the aggregate particles and the bitumen and (b) the loss in hardness and strength of the aggregate and the matrix due to absorption of water.

Bituminous materials normally adhere well to all common types of road aggregates as long as the bituminous material is sufficiently fluid and the aggregate is dry and reasonably free from dust. However, if the aggregate surface possesses hydrophilic properties, it is possible for rainwater or melted snow to strip the binder from the aggregate particles. The rate of stripping depends on the ease with which water can penetrate and detach the film of bitumen and also on the traffic conditions. The speed with which water penetrates and detaches the film of binder generally decreases with (a) increased binder viscosity, (b) decreased amounts of hydrophilic aggregate and surface active agents, and (c) increased asphalt film thickness around the aggregate particles.

Figure 9. Surface hardness of stone and relative rate of wear.

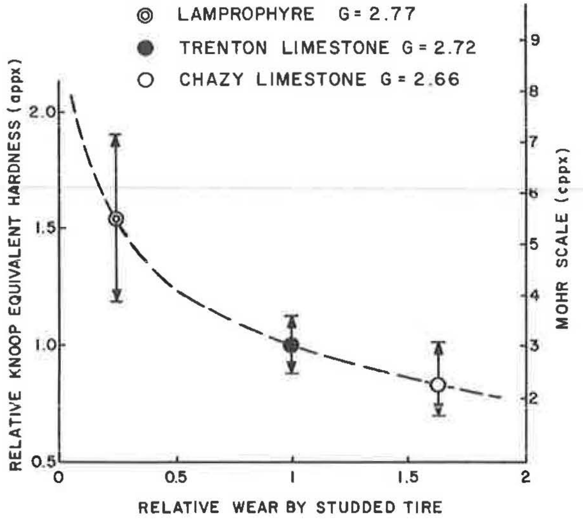


Table 4. Wear of gap-graded mixes made with limestone and lamprophyre aggregate.

Aggregate Size (in.)	Aggregate Surface (percent)	Test Condition	Wear Rate
1/4 to 5/8	21	Dry	1.3
1/4 to 5/8	32	Dry	1.4
1/4 to 5/8	38	Dry	1.3
5/8 to 3/4	45	Dry	1.7
5/8 to 3/4	38	Dry	1.9
5/8 to 3/4	28	Dry	1.8
5/8 to 3/4	43	Wet	1.9
5/8 to 3/4	36	Wet	1.9
5/8 to 3/4	28	Wet	2.0

Figure 10. Wear and total perimeter of coarse aggregate.

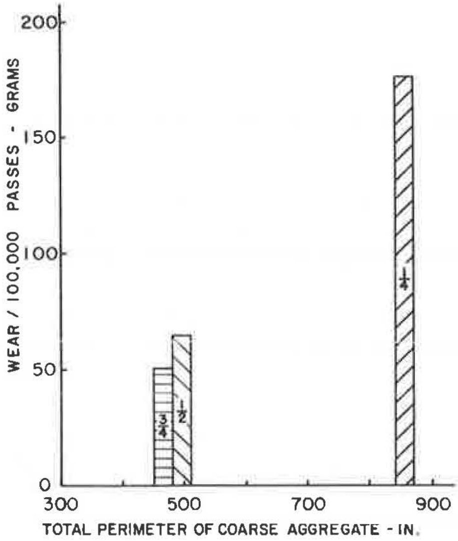


Figure 11. Wear and percentage of pavement surface covered with aggregate.

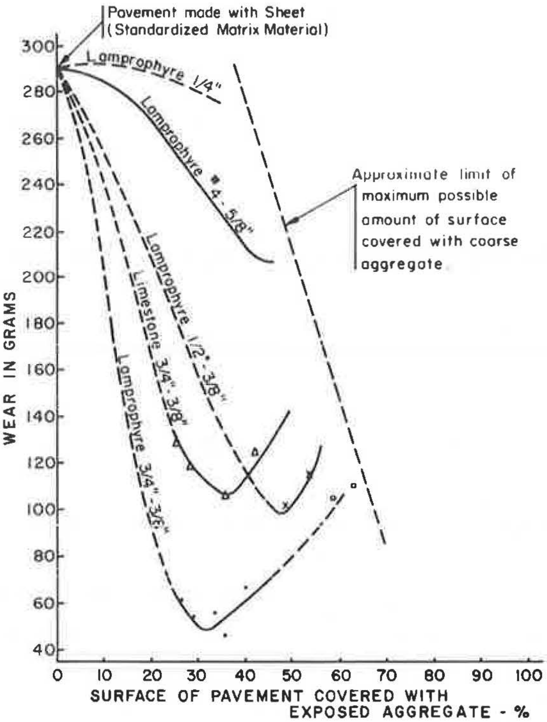


Table 5. Analysis of variance results.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio	Significance
Stone type	10,257.5	1	10,257.5	104.8	0.001
Percentage of surface covered with stone	1,594.4	4	398.6	4.1	None
Replicate measurement	587.6	6	97.9		

A study made in Sweden (7) showed that the wear resistance of ordinary hot-mixed asphalt concretes can be improved by the use of an aggregate precoated with coal tar. The wear resistance of cutback asphalt mixes can be improved by the addition of fatty amine to the binder.

Influence of Type of Bitumen and Bitumen Content

A literature review revealed that the grade of bitumen has little or no influence on the rate of wear of a bituminous concrete mixture. In his study, Peffekoven (8) shows that practically no improvement in abrasion resistance of fine bituminous concrete mixes can be obtained by the use of a 20 to 30 penetration grade instead of an 80 to 100 or even a 180 to 200 grade asphalt cement. In his study, Thurmann-Moe (9) indicates that the penetration of asphalt cement has a statistically significant influence on the rate of wear of bituminous concrete mixture. However, the increase in resistance to wear resulting from the use of a 50 penetration asphalt cement instead of 300 penetration is nearly insignificant compared to that resulting from mix type, hardness of the aggregate, or stone size.

Influence of Bitumen Content and Voids Content

An experimental design was carried out to determine the relative influence of bitumen content and voids content on the wear resistance of a sheet asphalt mix. The mixes were made with 45 percent manufactured limestone sand, 36 percent fine silica sand, and 19 percent limestone filler. The following grading was obtained:

Sieve	Percent Passing
No. 4	100
No. 8	97
No. 16	82
No. 30	70
No. 50	59
No. 100	35
No. 200	20

A variable amount of 85 to 100 penetration grade asphalt cement was used, and the desired voids content was obtained by variations in the degree of compaction. Triplicate samples of each mix were tested.

Wear test results are shown in Figure 12. Within the range of bitumen content normally specified (4 to 9 percent), there is a linear relation between the voids content and the rate of wear. The slope of the line depends on the bitumen content of the mix: A lean mix with an average film thickness of 3.6 microns is more influenced by the change in voids content (steeper slope) than a rich mix having a film thickness of 6.1 microns. This is attributed to the following: (a) The rate of decrease in cohesion with increase in voids content is much more rapid with a lean mix than with a rich one; and (b) if both mixes have the same grading and voids content, the lean mix contains more permeable pores than the rich one.

From the discussion given above, it follows that the resistance to wear can be improved by ensuring that the matrix contains a sufficient amount of asphalt and a low voids content. This can be achieved by proper mix design and adequate compaction. A bitumen content that yields a film thickness of 5 to 6 microns and a voids content below 6 percent appears to be adequate.

Influence of Filler Content and Filler-Bitumen Ratio

It is well known that the cohesion or tensile strength of a bituminous mixture is increased by the addition of filler, and there is an optimum filler-bitumen ratio at which a maximum tensile strength is obtained (10).

The influence of filler-bitumen ratio on wear of bituminous mixture is shown on Figure 13. The analysis of values by Thurmann-Moe (9) indicates that the wear resistance of bituminous concrete, Topeka, and mastic asphalt increases with the increasing filler-bitumen ratio of the mix. The analysis of data reported by Peffekoven (8) indicates that, for well-compacted bituminous concrete mixtures made with 40, 50, and 60 percent stone of ½-in. nominal size, the rate of wear decreases with increasing filler-bitumen ratio.

The relative influence of voids content and filler-bitumen ratio on the rate of wear of a sheet asphalt mix is shown in Figure 13c. Results indicate that the wear resistance of a bituminous mixture increases with the filler-bitumen ratio only if the mixture is well compacted. Otherwise, if the mix contains a high voids content, the wear resistance might decrease with increasing filler-bitumen ratio.

A minimum filler-bitumen ratio of 2 appears to be a desirable requirement for wear-resistant bituminous mixtures.

Influence of Type of Fine Aggregate

An experimental design was carried out to determine whether the type of fine aggregate of the matrix has an influence on the rate of wear. Two sheet asphalt mixes were compared; one was made with manufactured and silica sand identical to the one described earlier, and the other had the same grading and voids content and was made with silica sand only. A t-test revealed that there is no significant difference between the wear test results obtained with the 2 sheet asphalt mixes.

MIX DESIGN CRITERIA

Relative Influence of Different Factors on Wear

Figure 14 shows an overall idea of the relative importance of mix composition and other factors on wear of bituminous mixtures. It shows the results of this study and findings of other studies published in Europe. All pavement surfaces compared are high-quality surfaces. They possess good stability and durability and are properly compacted. Because wear is influenced by a great number of interrelated factors, it is understood that Figure 14 shows not absolute values but only the trend. It clearly illustrates the causes of wear and means of decreasing it.

Mix Design Criteria

The results of this study indicate that the design of wear-resistant bituminous mixtures should be based on the following criteria:

1. A sufficient portion of the pavement surface should be covered with coarse aggregate particles;
2. Coarse aggregate particles should be made from dense rock composed of hard minerals with strong interlocking and bonding among them, should be hydrophobic and free from fractures and cracks, and should be of cubical shape and be of the largest possible size;
3. The stone particles should be solidly held in the matrix;
4. In the presence of water, good adhesion should exist between the bituminous material and the aggregate surface; and
5. The matrix should be impervious, dense, stable, and durable.

Such a matrix can be ensured by the use of the smallest quantity of No. 16 to ⅜ in. particles possible, a sufficient amount of bitumen to yield a film thickness of at least 4.5 microns, enough filler to yield a filler-bitumen ratio higher than 2, and a bituminous pavement that is sufficiently compacted to produce a low voids content in the mixture.

A list of suggested special requirements for wear-resistant bituminous mixtures in relation to the causes of wear and the desirable characteristics is given in Table 6.

Performance of Conventional and Special Bituminous Mixtures

The discussion bears on 5 types of surface mixtures, 2 conventional ones that are currently used in the Montreal region and 3 special ones that have higher wear resis-

Figure 12. Wear and voids in given sheet asphalt.

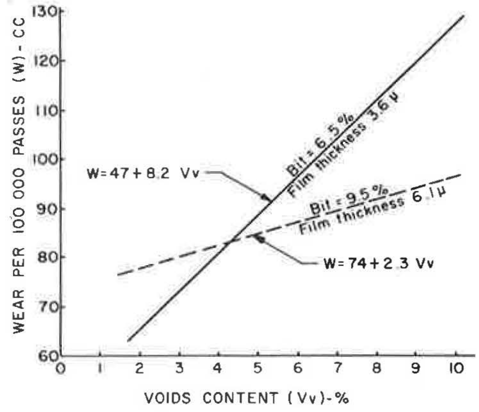


Figure 13. Wear and filler-bitumen ratio of matrix.

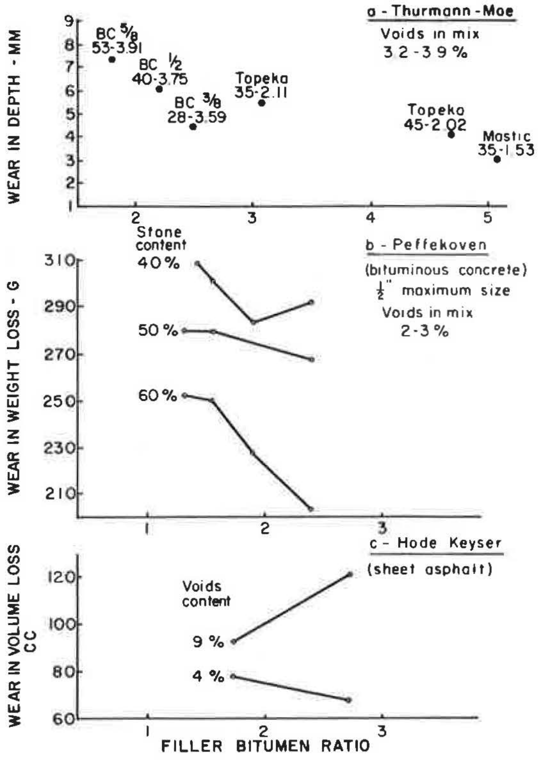
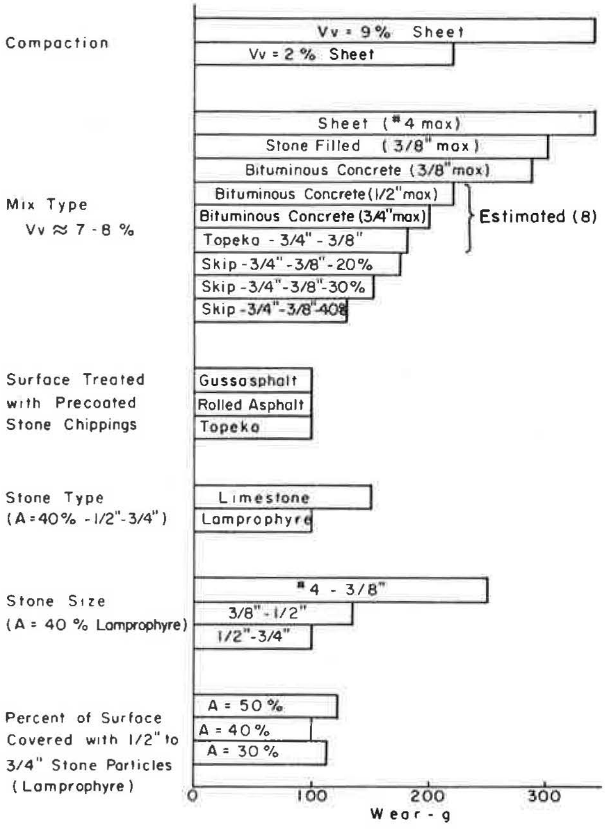


Figure 14. Influence of factors on wear.



tance. The grading and bitumen content of mixes are given in Table 7, and characteristics of the mixes that affect the wear resistance are given in Table 8. The following conclusions are based on established mix-design criteria:

1. The low wear resistance of stone-filled sheet mix is mainly due to the lack of hard stone particles of sufficient size, the presence of an appreciable quantity of $^3/_8$ in. to No. 8 material (28 percent), and the relatively high Hudson A number and low F-B ratio of the matrix.
2. The main weakness of asphalt concrete is the great amount of material ranging in size from $^3/_8$ in. to No. 8 (42 percent). This fraction is easily fragmented and dislodged as the matrix wears away.
3. The relatively good performance of Topeka mix compared with stone-filled sheet mix is mainly due to the presence of coarser particles, which are solidly held in an impervious matrix of high F-B ratio and high bitumen content.
4. The good performance of the Gussasphalt is mainly due to the presence of a high binder content (filler and bitumen) in the mix. This increases the stiffness and imperviousness of the matrix and reduces its brittleness.
5. The good performance of a specially designed skip-graded mix is mainly due to the continuous exposure of a sufficient amount of large stone particles on the surface of the pavement.

In general, the wear resistance increases each time steps are taken to improve adhesion between the stone particles and matrix, increase imperviousness and cohesion of the matrix, and increase the supporting value of hard coarse aggregate exposed on the surface.

CONCLUSIONS

1. Pavement surface wears by pulverization, cutting, attrition, fragmentation, and dislodgment.
2. With normal mixes made with conventional hard aggregates, the matrix between the aggregate particles wears rapidly when the pavement is new and stabilizes when the aggregate has reached a certain average asperity, which depends on the characteristics of both the matrix and the coarse aggregate.
3. When the aggregate particles exposed on the pavement surface have reached an embedment depth of about 0.05 in., the aggregate wears rapidly by fragmentation, loosening, and dislodgment. For this reason, aggregate particles ranging in size from No. 8 to $^1/_4$ in. wear rapidly.
4. An apparatus and procedure for evaluation of the wear resistance of different types of paving mixtures in the laboratory have been developed. Reasonably good correlation has been obtained between laboratory test results and field test results.
5. The initial rate of wear of bituminous pavement surface is on the average 1.5 to 3 times higher than the rate of wear in the long run.
6. The wear of bituminous mixture is lowest near the freezing temperatures. Above freezing point, wear increases with higher temperatures and plasticity of the mix increases. Below freezing, wear increases, for brittleness increases as temperature decreases.
7. The rate of wear of pavement surfaces is greatly increased when the pavement is wet; the action of water in accelerating the wearing process is attributed to the loss of adhesion between the aggregate particles and the bitumen and to the loss in hardness and strength of the aggregate and the matrix due to water absorption.
8. For good wear resistance, the aggregate particles must be composed of hard minerals with strong interlocking and bonding between the hard minerals. The particles must also be hydrophobic and free from fractures and cracks.
9. The rate of wear of bituminous surfacings is greatly increased with increasing perimeter of the stone particles exposed on the surface. Consequently, the wear resistance is slightly increased by increasing the size of the coarse aggregate from $^1/_2$ to $^3/_4$ in. and greatly reduced by decreasing the size from $^1/_2$ to $^1/_4$ in.

Table 6. Desirable characteristics of wear-resistant bituminous pavements.

Wear Process	Desirable Characteristics	Suggested Requirements
Indentation, pulverization, and attrition	Coarse aggregate—high resistance to indentation and smooth texture Matrix—good grading and high filler bitumen ratio Mix—sufficient portion of surface covered with coarse aggregate and good compaction	Coarse aggregate Mohs' hardness, minimum 6 Absorption, maximum 0.5 percent Filler bitumen ratio of matrix, minimum 2 Stone content of mix, minimum 40 percent Minimum degree of compaction of mix, 94 percent of voids less density
Fragmentation	Sound isotropic aggregate particles of cubical shape; coarse aggregate particles minimum size of 3/8 in.	Los Angeles abrasion, maximum 15 percent Soundness ($MgSO_4$), maximum 10 percent Aggregate particles of cubical shape Single size coarse aggregate particle, minimum 1/2 in.
Dislodgment	Good adhesion between aggregate and binder Great surface area of contact between coarse aggregate and mortar (good embedment)	Hydrophobic aggregate (no stripping) Aggregate particles of cubical shape Minimum film thickness, 5 microns
Cutting and shear (when slip)	Exceptionally hard aggregate	Aggregate resistant to scratching

Table 7. Grading and bitumen content of conventional and special mixes.

Mix Type	3/4 In.	1/2 In.	3/8 In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Bitumen Content
Stone sheet type 6a			100	90	72	61	49	39	22	10	5.9
Asphaltic concrete (8)		100	88	62	46	35	25	20	14	10	5.0
Topeka (7)	100	90	78	63	55	47	42	32	22	16	8.2
Gussasphalt (8)		100	84	65	63	60	54	46	38	30	9.0
Special skip-graded (2)	100	79	56	55	51	45	37	29	14	6	4.8

Table 8. Characteristics of conventional and special mixes.

	Coarse Aggregate				Matrix					
Mix Type	Type	Nominal Size	Percent Retained on 3/8 In.	Percent Between 3/8 In. and No. 8	Hudson A	Filler	F-B Ratio	Bitumen Content (percent)	Film Thickness (μ)	Resistance to Wear
Stone sheet type 6a	Lamprophyre	3/8[a]	0[a]	28[a]	3.2[a]	11	1.9	5.9	5.1	Poor
Asphaltic concrete	Diorite	1/2	12	42[a]	3.6[a]	16	3.2	5.0	6.0	Medium to poor
Topeka	Igneous	3/4	22	23[a]	2.6	25	3.0	8.2	6.7	Medium to poor
Gussasphalt	Igneous	1/2	16	21[a]	1.5	46	5.1	9.0	4.6	Medium
Special skip-graded	Lamprophyre	3/4	44	4	2.7	11	2.3	4.8	5.9	Good

[a] Principal weakness of the mix.

10. The rate of wear decreases with increasing stone content until an optimum value is reached. The optimum value varies for each type of mix.

11. The wear resistance of a bituminous mixture decreases with increasing voids content. Leaner mixes are more affected by the increase in voids content than are richer mixes.

12. When bituminous mixtures are well compacted, the wear resistance increases with increasing filler-bitumen ratio of the matrix.

13. Mix design criteria for wear-resistant bituminous mixtures have been established. Desirable characteristics for wear-resistant bituminous mixtures have been identified.

AKNOWLEDGMENTS

This continuing study is made possible by the support of the following organizations: Quebec Autoroute Authority, Quebec Department of Roads, National Research Council of Canada, City of Montreal, Department of Engineering Geology and Department of Civil Engineering of the Ecole Polytechnique, Miron Company Limited, and Kennametal Tools Limited. The author wishes to thank W. H. Goetz of Purdue University and N. W. McLeod for their useful comments. Acknowledgment is also made to J. E. Hurtubise and J. Granger, who made this publication possible, to the chairman, David G. Mahone, and to the members of the Highway Research Board Task Force on Studded Tires for their criticism and comments, and to A. Klein and L. Gottheil for reviewing the text.

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DISCUSSION

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At the Institute for Road Construction at the University of Aachen, West Germany, similar research programs were conducted (these were reported at the AAPT meeting, February 14-16, 1972, in Cleveland, Ohio). We found similar results. We also conducted tests with specimens that had undergone freeze-thaw changes before being worn and found that freeze-thaw has a great influence on mixtures with high content of voids, (5 and more percent voids). For asphalt with 45 to 65 penetration we found that with temperatures at about freezing (32 F) minimum wear is achieved. Asphalt mixtures with a penetration of 80 still showed a decrease of wear for temperatures below freezing (test temperature 14 F). Our conclusions about the influence of aggregate, gradation and binder content correspond to those of Hode Keyser. Our first practical experience with special mixes of high filler, bitumen, and coarse aggregate (larger than $\frac{1}{4}$ in.) content also showed a tendency to reduce wear. If certain limits of content of coarse aggregate are passed, the workability (laying and compaction) becomes a problem, which then will influence the wear resistance. We also found that the type of aggregate is of great importance especially with respect to relative open mixtures. The variations of type of aggregate, however, are not sufficient now for conclusions on criteria for use of special types of rocks. Therefore, comparative tests on test routes and with laboratory devices are now being conducted.

AUTHOR'S CLOSURE

I am pleased to see that there is good agreement between our results and those of Kohler. However, it should be noted that the conclusion here is valid only for the prevailing test conditions chosen for this study. A good correlation was found between results of laboratory tests and those collected from tests at the acceleration and deceleration segments of the pavement with passenger car traffic. For different traffic conditions, such as on other sections of the pavements or with vehicles with higher axle loads (e.g., trucks and trailers), different results would have been obtained.

One must also bear in mind that the results obtained and the conclusions reached are linked to the level of the contributing factors and their interaction. The particular factors for this project were those believed applicable to the climate and materials for the Montreal region.

With variations in the characteristics of the bituminous mixture or test conditions (e.g., temperature, track wetness, and amount of stud protrusion), quite different or even contradictory results could have been found according to the magnitude of the change or nature of the factors.

STUDDED TIRE EFFECTS ON PAVEMENTS AND TRAFFIC SAFETY IN MINNESOTA

C. K. Preus, Minnesota Department of Highways

•IN MINNESOTA, studded tires were legally permitted for 6 winters from 1965 to 1971. They are now banned for residents of the state since the 1971 legislature took no action to extend the previous permissive statute. However, nonresidents are permitted to drive with studded tires on Minnesota roads for up to 30 days in a calendar year, though enforcement of this latter limitation presents problems.

A year ago we reported (1) on the results obtained up to that time in Minnesota in the several studies of studded tire effects that had been undertaken in response to the 1969 legislature's directive that the commissioner of highways conduct an in-depth study of the subject. The studies included field observations and pavement wear measurements by the Minnesota Highway Department, laboratory pavement wear tests performed by the American Oil Company, and the studded tire safety effectiveness study conducted by Cornell Aeronautical Laboratory (CAL). The studies had not been completed by January 1971, and many of the results reported then were of a preliminary nature. This present report will supplement and update the information previously reported. A report was submitted to the legislature in May 1971 (2).

FIELD PAVEMENT WEAR

How highway surface wear continued to progress through the winter of 1970-71 is shown by a series of photographs of the condition of 2 high-traffic pavements after 5 or 6 winters of studded tire traffic.

Figure 1 shows a portland cement concrete pavement with gravel aggregate after 5 winters of studded tire traffic. There were an estimated 1.7 million total studded tire passes and approximately 10,450 ADT per lane. Pronounced wear in wheelpaths in each lane is clearly evident.

Figure 2 shows a closeup of the pavement at a measurement point on the same highway as shown in Figure 1 but at a slightly different location. Depth of wear in the wheelpath beneath the straightedge is 0.32 in.

Figure 3 shows the same concrete pavement but after 6 winters and an estimated 2.3 million total studded tire passes. The nearly full-width wear beneath the 10-ft straightedge illustrates how the wear pattern has gradually widened because of lateral shift of traffic to avoid driving in the roughened wheelpaths. The midpoint of the lane now shows 0.1-in. wear. The transverse profile reaches a wear depth of almost 0.4 in. in the right wheelpath.

Figure 4 shows another transverse profile of wheelpath wear in an Interstate concrete pavement containing limestone aggregate. Wear depth in the wheelpath has reached 0.4 in. beneath a 10-ft straightedge after $4\frac{1}{2}$ winters of studded tire traffic. The total number of studded tire passes is estimated at 1.9 million; ADT per lane is approximately 17,500.

Figure 5 shows an asphaltic-concrete pavement with gravel aggregate after 6 winters of studded tire traffic and an estimated total of 1.0 million studded tire passes. The ADT is approximately 9,800 per lane.

Figure 6 shows a closeup of the same pavement as that shown in Figure 5. Depth of wear beneath the straightedge is 0.41 in. Surface wear effect on texture is much the same as that for portland cement concrete.

Figure 7 shows the composite average wear rate curves developed for each of several different generalized pavement types. The curves illustrate that pavement composition definitely influences the rate of wear.

Figure 1. Wheelpath wear on PCC pavement with gravel aggregate.

Figure 2. Depth of wheelpath wear on PCC pavement.

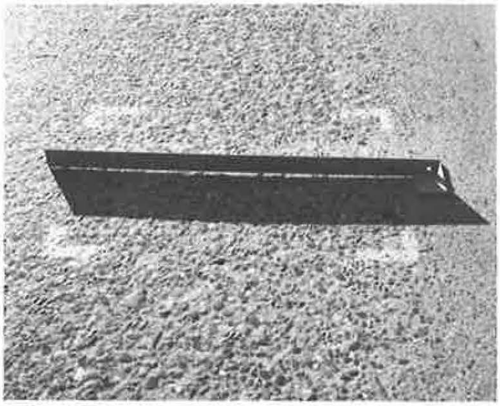


Figure 3. Transverse profile of wear on PCC pavement with gravel aggregate.

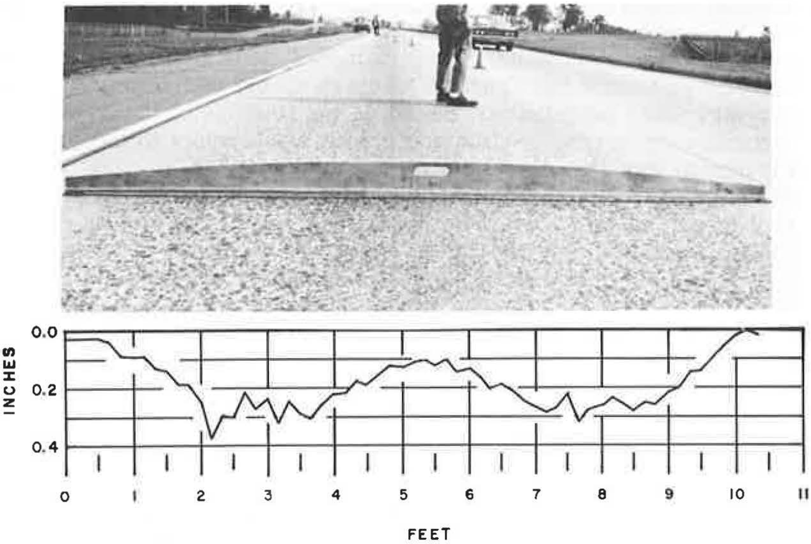
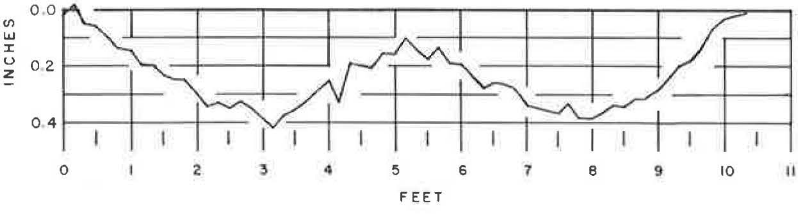


Figure 4. Transverse profile of wear on PCC pavement with limestone aggregate.



As a basis for estimating what the additional cost might be for future repair of studded tire damage to road surfaces, a judgment was made that the maximum depth of wheelpath ruts tolerable to traffic would be ¾ in. For bridges, the maximum depth considered allowable was set at ½ in. because of the possible detrimental effect that deeper wear might have on the corrosion of reinforcing steel and associated structural strength of the decks.

From the pavement wear rate curves, a determination was made of the number of studded tire passes that will produce the critical rut depth for each pavement type. This is given below.

Pavement Type	Millions of Passes
Concrete, igneous gravel	10.1
Concrete, limestone	7.4
Bituminous concrete	5.1
Bituminous, intermediate	3.8

Computations were made to determine when each segment of state trunk highways and bridge structures would have to be resurfaced if studded tires were continued in use. Resurfacing costs were based on the use of a bituminous overlay with a 1½-in. wearing course over a leveling course sufficient to fill the ruts on roadways. Bridge deck repair would generally require other techniques such as an inlay rather than an overlay and removal of damaged concrete and replacement with concrete patches.

In addition to the rehabilitation of existing worn pavements, it is likely that, if studs were to continue, new pavement construction would probably utilize more costly materials to achieve greater wear resistance. Based on the findings of the American Oil Company study, the increase in construction costs as it would apply to the project highway construction program was also calculated.

The combined additional costs attributable to studded tires were estimated at $2.8 million by 1973 when, it was expected, a start on resurfacing would have to be made. By 1979, the yearly added cost would be expected to reach $13.3 million. Through 1980, the cumulative total was estimated at $55.2 million. These costs do not include normal maintenance repairs associated with structural deterioration such as that normally caused by vehicle loads or climatic effects; they are only the added costs induced solely by studded tire effects.

LABORATORY PAVEMENT WEAR

In the American Oil Company laboratory study, a series of conventional pavement mixtures, both bituminous and portland cement concrete, and a number of special pavement mixtures were subjected to the abrasive action of rotating loaded automobile wheels to determine the damage caused individually by studded tires, salt, and abrasive sand. Forty-eight test slabs were included; 23 were bituminous, 24 were portland cement concrete, and 1 was an epoxy resin-sand mixture.

As each test run progressed, periodic precise wear depth measurements were taken transversely across the wheelpaths. Plots were made of the wear depth versus number of wheel passes, as shown in Figure 8. The upper curve is for a typical portland cement concrete test pavement, and the lower curve is for an asphalt test pavement. Differences in wear rates are obvious.

The wear rates indicated that the upper 0.1 in. of pavement wore most rapidly, being composed chiefly of portland cement mortar or fine sand-asphalt mixture. This is referred to as the initial wear rate. The wear rate for the second zone, from about 0.1- to 0.2-in. depth, was somewhat slower and is referred to as the intermediate rate. Beneath a depth of about 0.2 in., the wear rates, called terminal, diminished perceptibly, apparently because of the presence of the coarse aggregate particles.

Analysis of the data for different sets of test tires revealed that the amount of stud protrusion varied from one set to another and the rate of pavement wear increased with increase in stud protrusion. So that consistent data could be obtained, all wear

Figure 5. Wheelpath wear on asphaltic concrete with gravel aggregate.

Figure 6. Depth of wheelpath wear on asphaltic concrete.

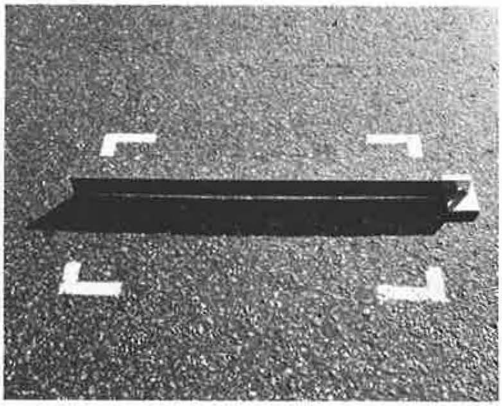


Figure 7. Average wear rate on different pavement types.

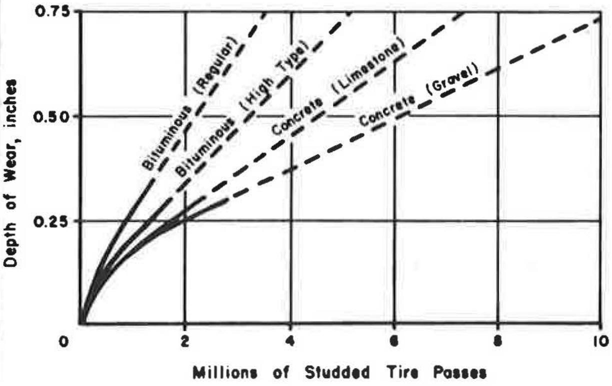
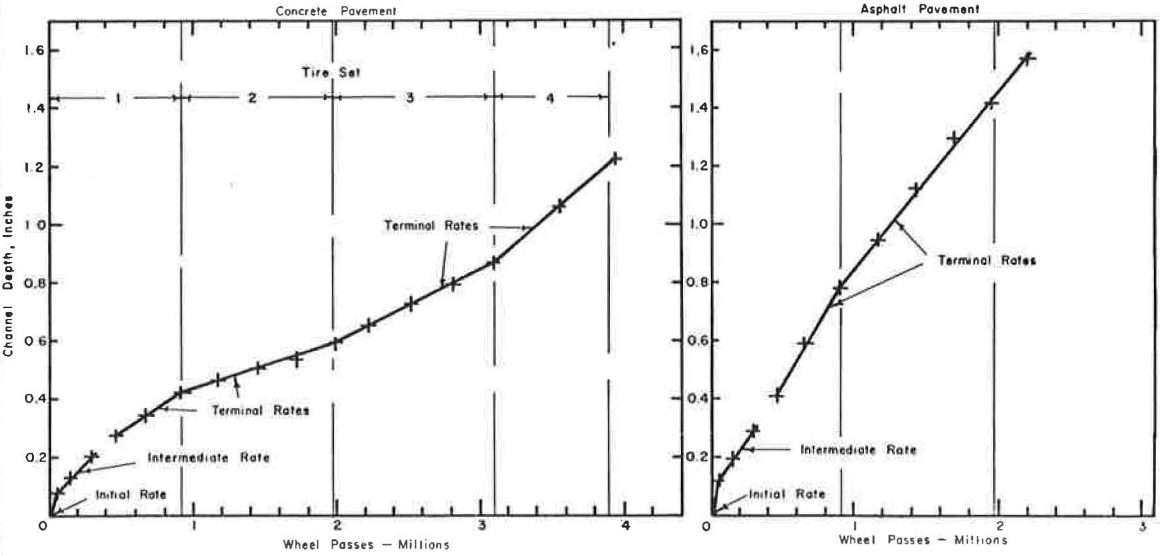


Figure 8. Individual laboratory wear rate curves.



rates were adjusted to a common base of 0.040-in. protrusion, which was selected because it represents the approximate average for the entire laboratory study.

The curves shown in Figure 9 represent the average laboratory wear rates for 4 different generalized categories of pavement surfaces with sand and salt applied. The wear data have been adjusted to the common base of 0.040-in. protrusion in contrast to the original unadjusted values, which had been plotted and shown in the 1971 report. For unstudded tires, the pavement wear was extremely slight, despite the sand and salt applications.

For the normal bituminous wearing courses, the average terminal wear rates ranged between 0.75 and 0.95 in./million studded tire passes. For conventional concrete pavements, the corresponding wear rates ranged from 0.30 to 0.47 in. The influence of different mix compositions, such as the kind of coarse aggregate, was reflected in different wear rates, as was also found to be true with road surface wear rates. Concrete made with good quality gravel aggregate composed predominantly of hard igneous pebbles experienced the lowest wear rate among the commonly used paving mixtures. Concrete produced with a limestone coarse aggregate suffered a faster wear rate. Conventional bituminous mixtures, both the higher type of asphaltic concrete and an intermediate or regular type, each in turn showed progressively more rapid wear.

Figure 10 shows sections removed from 2 representative pavement test slabs after termination of their laboratory test runs. Unstudded tires had operated over the left side of each slab, and studded tires had operated over the right side.

For unstudded tires and with sand and salt applied, the average wear depth on all conventional test pavements was only 0.011 in. for more than 4 million tire passes or an average rate of 0.0027 in./million passes. This was less than 1 percent of the wear rate caused by studded tires on even the best concrete pavements. Thus, the studded tires caused at least 100 times more abrasion damage than the wear increase produced by sand and salt and unstudded tires. Salt alone and unstudded tires produced no measurable pavement wear. The wear from sand and salt was scarcely measurable for unstudded tires after 4 million passes. The evidence seems inescapable that the studded tires are by far the prime cause of pavement abrasion, whereas sand and salt applied on good quality, air-entrained concrete or on asphalt pavements have little or no measurable wear effect when studded tires are not involved. When studs are involved, sand and salt do contribute to the rate of wear.

In the special mixtures tested to evaluate whether greater wear resistance could be developed, wear reductions from 10 percent to as much as 50 percent in one case were achieved by the use of traprock or granite aggregates, by an increase in the binder content, or, as in bituminous mixtures, by the addition of rubber and asbestos together with the better aggregate. However, the increase in cost of materials would generally correspond about proportionately with the wear reduction. A liquid surface hardener for concrete was ineffective. The most resistant surfacing was the epoxy resin-sand mixture; however, the resultant surface was too smooth and slippery for highways, and the cost would be 3 to 4 times that of conventional concrete. Based on these results, it appears that no cost advantage would be gained by efforts to modify the paving mixture composition. There could, however, be some potential advantage in using better though more costly mixtures, particularly on roads that would be subjected to high studded tire traffic. The more costly mixtures would reduce the frequency of repair and attendant inconvenience to traffic.

The relation between laboratory pavement wear and actual highway wear is shown in Figure 11, which is a revision of the figure included in the 1971 report (1), having been corrected for the adjusted test track wear rates based on 0.040-in. stud protrusion. The slope of the curve is about 5.5:1, indicating that, on the average, the same wear depth produced by 1 million studded tire passes on the test track would be produced by 5.5 million passes on a highway surface of the same type. It was found that this ratio, 5.5:1, was substantially valid for all of the conventional pavement types.

STUDDED TIRE INFLUENCE ON VEHICLE PERFORMANCE

The third phase of the 1969 legislative directive to the commissioner of highways required that he "evaluate the effects, if any, that discontinuing the use of studded tires will have on highway safety."

Studded tires can have an effect on the performance of a vehicle to some degree as long as they are on the vehicle and an effect on any pavement surface even though it may not be icy and slippery. Furthermore, the physical effects that studs have had on pavement surfaces can influence vehicle behavior the year round in ways not conducive to safe travel. Therefore, any evaluation of studded tires should encompass all vehicle travel under year-round conditions rather than under winter conditions only. Limitations on the performance of studded tires must also be recognized as well as the adverse effects they have created.

The advantages of studded tires have generally been ascribed to their ability to improve the stopping, cornering, and traction performance of a vehicle when operating on a smooth ice surface. It has been commonly considered that their greatest advantage is the ability to reduce the stopping distance on ice and that this is the most important element of vehicle safety. The extent of this stopping capability has been amply demonstrated by numerous driving tests such as those conducted and reported by the National Safety Council Committee on Winter Driving Hazards, the Canada Safety Council, and the Ontario Highway Department.

However, the ability to maintain control of the vehicle's direction of travel under all conditions is now indicated to be even more important to safe operation on the road than is the stopping capability. The CAL safety study, to be discussed later, indicates that vehicle pre-impact behavior that was most frequently noted in connection with the accidents in this study was loss of direction control and not a lack of stopping capability.

Improvement of starting traction on icy surfaces through use of studded tires has also been highly rated as a benefit by many motorists. But this is more often a matter of convenience rather than of safety, though some safety advantage may be ascribed to improved traction under certain conditions, such as when a busy street intersection is crossed on glare ice or when an icy hill is climbed and it becomes necessary to back down because of slippage.

Figure 12 shows the total annual number of reported traffic accidents in Minnesota. The numbers increased almost steadily from about 60,000 in 1958 to more than 100,000 in 1969 and 1970, except for 2 years, 1963 and 1970. In the latter case the decline followed a national trend for that year. Interestingly, the increase in total annual accidents continued at a fairly uniform rate even after 1964, the year when studded tires first appeared in Minnesota. It would be reasonable to expect that, if, indeed, the use of studded tires provides a distinct safety advantage, it should have had a noticeable effect in reducing the accident occurrences and severity. But such reduction is not evident from the records.

Figure 12 also shows between the upper 2 curves that the proportion of all reported accidents that occurred on snowy and icy roads during the 13-year period averaged about 22 percent, ranging between 16 and 29 percent.

The proportions of time in the winter of 1969-70 that different surface-cover conditions prevailed on various types of roads and streets are as follows:

Road Type	Bare	Icy	Snow
Freeways	96	2	2
State highways	90	4	6
County roads	74	11	15
Township roads	47	29	24

These data are based on about 18,000 observations made on representative thoroughfares in the Minneapolis-St. Paul urban area and surrounding rural areas. Icy conditions on freeways, where studded tires could potentially be of some help, existed only 2 percent of the wintertime. State highways were bare for 90 percent of the time in winter, and even on county roads the surface was bare 74 percent of the time.

Because the volume of traffic on the different types of roads varies widely, the following computations were made to show the proportion of winter travel for each of the general road-cover conditions during the winter of 1969-70.

Figure 9. Average laboratory wear rate curves.

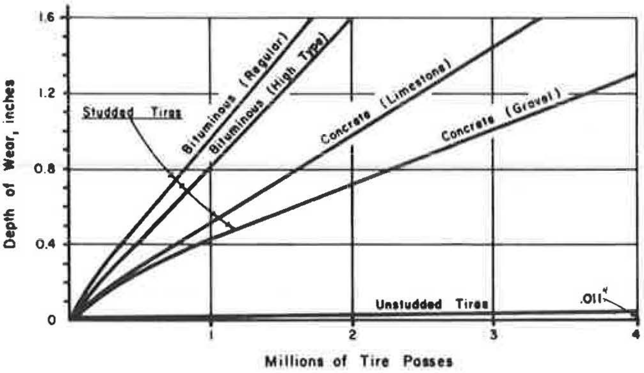


Figure 10. Pavement sections worn after laboratory test.

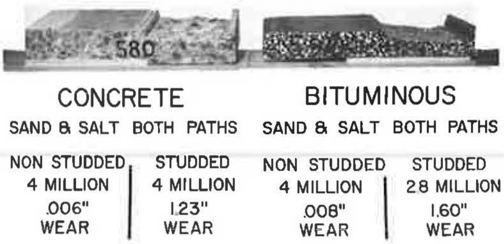


Figure 11. Wear by studded tires on roadway and on test track.

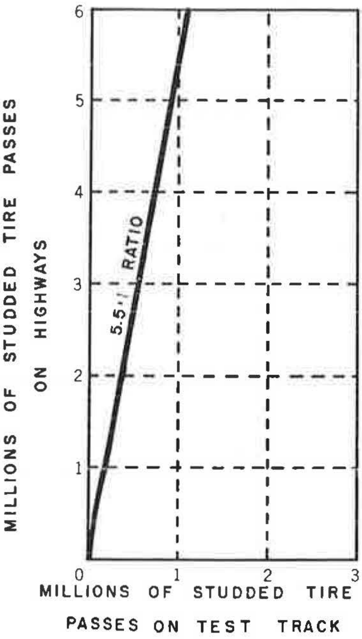
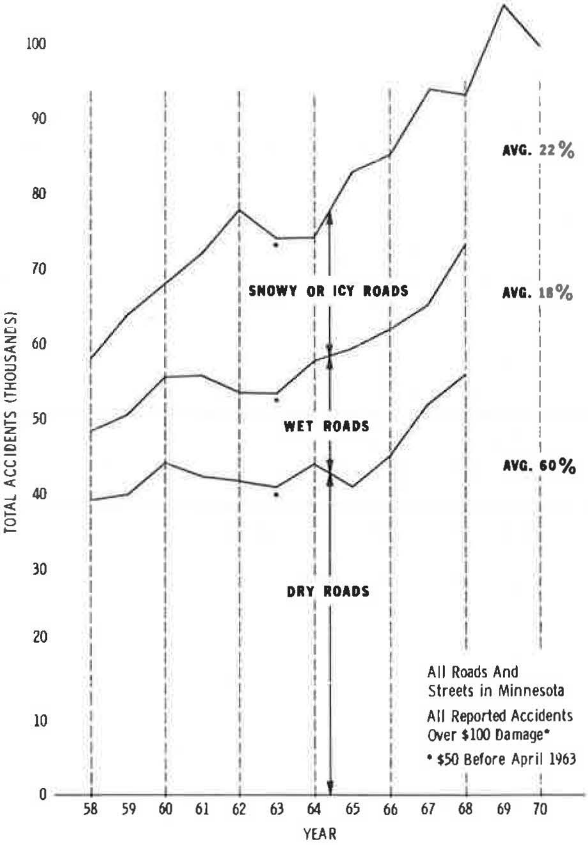


Figure 12. Minnesota traffic accidents.



All Roads And Streets in Minnesota

All Reported Accidents Over $100 Damage*

* $50 Before April 1963

Road Type	All	Bare	Icy	Snow
Freeways	11	10.6	0.2	0.2
State highways	37	33	2	2
Local roads and streets	52	31	11	10
Total	100	75	13	12

On the average, about 25 percent of the winter traffic was on snowy and icy roads. The winter traffic during the 6½-month studded tire season (October 15-May 1) amounted to 48 percent of the total annual travel. Therefore, the travel on snowy and icy roads was about 12 percent of the yearly total, and 88 percent was on bare pavements. Thirteen percent of the winter travel, or only about 6 to 7 percent of all the annual travel, was on surfaces that could be classed as icy, those surfaces where studded tires could be expected to be of potential aid. Conversely, for 93 to 94 percent of the yearly travel, studded tires would have provided no benefit.

The performance advantages of studded tires on icy surfaces have been noted. But on bare pavements the studded tires have no advantage and, indeed, may actually suffer by comparison with regular unstudded tires. When the advantages are viewed in light of the fact that 75 percent of all Minnesota winter travel in 1969-70 was on bare pavements and only about 13 percent of the winter travel was on icy roads where studs could potentially be beneficial, it is not unreasonable to surmise that, overall, any advantages of studded tires on ice could be offset by their disadvantages on bare pavements.

Aside from possible diminished stopping ability on bare pavements, there are other detrimental effects produced by studded tires that have year-round adverse influence on traffic safety. These effects are the direct consequences of the physical wear caused by the studs on the pavement surfaces. Most of these effects have not been evaluated quantitatively by research data but are based on observations and driving experience. Included among such adverse effects are the following:

1. Formation of shallow ruts or troughs in the pavement wheelpaths that interrupt normal transverse runoff of water, cause more splash and spray onto adjacent vehicles, and reduce driver visibility (water accumulation may also contribute to occurrence of hydroplaning);
2. Destruction of longitudinal pavement grooving provided as a safety measure, particularly on curves where skidding is a problem;
3. More rapid loss of paint stripes used to delineate pavement lanes;
4. Extremely rough wheel-rut surfaces that cause vibration of vehicles accompanied by pronounced noise increase both inside and outside the vehicle;
5. Adverse effects on vehicle handling, especially during lane-changing and passing maneuvers; and
6. Lateral displacement of vehicles that tend to shift from the normal center-of-the-lane courses and to crowd toward vehicles in an adjacent lane in the effort to avoid the rough-textured wheelpath.

ACCIDENT STUDY

The Minnesota Highway Department initiated the study by Cornell Aeronautical Laboratory to ascertain whether studded tires do, in fact, provide any greater safety in real-world mixed traffic on the highways and streets under all conditions.

The general approach of the study was to compare the performance of automobiles with studded tires to automobiles with other tire types in terms of 3 potential effects of studded tires: (a) reduced likelihood of being involved in an accident due to sliding, (b) improved pre-impact control, and (c) reduced accident severity. Data for the study were collected through questionnaires sent to Minnesota-registered automobile owners and through accident reports submitted by highway patrol officers and the police of 11 municipalities.

Collection of data for the study was carried out between February and May 1, 1970, and from October 15, 1970, to January 4, 1971, the termination date for the study.

This provided a total observation period of $5\frac{1}{2}$ months. All questionnaires and accident reports were gathered by the highway department and forwarded to CAL for coding, processing, analysis, and report preparation. A large volume of data was gathered, and numerous analyses were made in a search for significant relations.

About 84,000 questionnaires were mailed; the return was 47 percent. Of these, the sample coded and used in the study consisted of 17,040 returns. The main functions of the questionnaire were to determine the proportion of vehicles equipped with each type of tire and to measure the amount of their exposure to various road-cover conditions. Responses from the questionnaires as reported by CAL revealed the following for the total study period:

1. Thirty-six percent of the automobiles were equipped with studded tires, but only about 1 percent had them on all 4 wheels.
2. During the study period, 38 percent of the driving was with studded tires, 23 percent was with snow tires, and about 39 percent was with regular tires.
3. During the $6\frac{1}{2}$-month studded tire period, 6 percent of all driving in Minnesota was on roads reported as being completely covered with ice, snow, slush, or frost, another 6 percent was on roads mostly covered, and 18 percent was on roads with scattered cover. The remaining 70 percent was on roads essentially bare. This last figure corresponds reasonably well with the 75 percent estimated independently by the highway department.
4. Only about one-third of 1 percent of the respondents refrained from driving because of icy or snowy road conditions.
5. The type of tire used during the winter can be correlated, to a degree, with vehicle characteristics, such as size, body style, and model year, and with age and sex of owner and annual mileage driven.
6. Regarding nonaccident performance, respondents indicated that studded tires had a slight advantage over snow tires in terms of susceptibility to sliding.

Accident reports collected during the $5\frac{1}{2}$-month study period totaled about 4,500. This contrasts with the nearly 60,000 accidents that occurred in Minnesota during the periods in 1970 when studded tires were legal. The accident reports were provided principally by the Minnesota Highway Patrol and also by the police departments of the metropolitan cities of Minneapolis and St. Paul and 9 other municipalities. Some of the findings and conclusions from the accident study as reported by CAL included the following:

1. During the study period, 21 percent of all accidents and 30 percent of single-vehicle accidents were precipitated by sliding. Of all automobiles in accidents, 14 percent were said to have been involved because of slippery road surfaces.
2. Accidents caused by sliding on slippery road surfaces were, on the average, less severe than others, as measured by the degree of injury and by depth of penetration of the vehicle on impact.
3. The probability of precipitating an accident due to sliding on snowy or icy roads was least for studded-tired vehicles, followed by snow-tired vehicles, then regular-tired vehicles.
4. Accident rates that showed advantages for studded tires even on roads that were primarily bare suggest that there are extraneous effects that influence the results. After adjustments were made to attempt to correct for these extraneous effects, the adjusted sliding accident rates showed a slight advantage for studded tires over snow tires, with both studded and snow tires outperforming regular tires.
5. In accidents attributed to sliding, the most frequent pre-impact behavior was loss of directional control. Of all trigger vehicles (those causing accidents) that were involved because of sliding, 69 percent were considered to be associated with loss of directional control. Twenty-eight percent were associated with prolonged stopping distance, and only 3 percent with reduced acceleration. Therefore, stopping distance is seen to be of less significance than generally supposed.
6. On dry roads, regular tires performed best with regard to pre-impact rotation, and studded tires were poorer than both regular and snow tires. On wet surfaces,

there was little difference in pre-impact rotation among the 3 tire types. On snow-covered roads, both snow tires and studded tires were better than regular tires, and only on ice-covered roads were studded tires superior with respect to pre-impact rotation.

7. For vehicles that precipitated accidents because of sliding, studded-tired vehicles usually performed better than those with snow tires, and those with snow tires were usually better than those with regular tires in terms of reduced impact speed and pre-impact rotation. For driver injury, studded tires had an apparent advantage; there was little difference between snow tires and regular tires. These tire effects were most evident in single-vehicle accidents.

In summary, the research conducted by Cornell Aeronautical Laboratory attempted to determine whether studded tires were of sufficient value to provide real-world benefits in normal usage. The factors causing accidents and affecting their severity are so numerous and complex that it is extremely difficult to isolate and quantify the effect of any single factor such as tire type. It was determined that a major obstacle to drawing inferences about tire effects was the apparent presence of driver effects, which correlated with tire type and thus influenced the results that might otherwise have been ascribed to tires. No way was found to completely eliminate the influence of variables that were extraneous to tire type.

The data from the CAL study indicate that on icy or snowy roads the use of studded tires provides some observable, though slight, advantages over other tires in terms of accident precipitation, vehicle behavior in emergencies, and driver injury. Results reflecting sliding accident rates, when corrected for extraneous effects, showed studded tires to have only "a mild advantage over snow tires on snowy or icy roads during the winter months" (December through March).

Because of the apparent extraneous effect of driver characteristics on accident precipitation, any increase in the number of traffic accidents on snowy and icy roads that might occur if studded tires were replaced with unstudded snow tires would be slight when compared to the total number of accidents normally occurring in Minnesota.

Accident severity and pre-impact behavior may be similarly affected by extraneous driver-associated influence, as in the case of accident precipitation, but the exact nature and the extent of such effects are not known. Because of these uncertainties and the limited data in many categories, the degree of increase in accident severity that might occur if studded tires were replaced by unstudded tires cannot be reliably estimated. In any event, the effect of tire type on accident severity and pre-impact behavior is probably limited by the already lower-than-average severity of winter accidents that has been induced, in part at least, by increased driver care.

In summary, the CAL report concludes that, as one result of conditions encountered in the study (i.e., accident complexity, uncontrolled sampling, and driver effects), the data developed were judged to be of such nature as would not permit "overall quantitative estimates of studded tire effects in terms of accidents prevented, lives saved, etc." Contributing to that conclusion is the fact that the data available for determining the accident rates and other performance ratings in the report are frequently so few in number that the reliability of the results and conclusions is uncertain.

The CAL study, by design, takes into account only the facts and relations disclosed for the limited study period, primarily the winter months. It does not give consideration to other conditions prevailing during the remainder of the year or to the effects on traffic that are induced by pavement wear caused by studs. When all these aspects are taken into account with respect to overall, year-round traffic safety, the relatively slight advantage that can be attributed to studded tires on the basis of the CAL study becomes even less compelling. In sum total, the benefits of studded tires are by no means predominant over the disadvantages.

Many motorists, viewing this issue from only the standpoint of personal winter driving experiences, regard the position of highway engineers and administrators in opposing the use of studded tires as an unreasonable unsympathetic attitude, merely equating dollars against human lives. Engineers, administrators, and legislators alike not only are vitally concerned about the public safety but also are responsible for preservation of the public property. Because funds for highway maintenance and construction are not without limit, the administrators of those funds are concerned that each expenditure will yield a maximum return in public safety and convenience. Funds that would ultimately have to be expended for repair or prevention of road damage caused by the continued use of studs and the year-round road hazards they create could be more productive of safety for all motorists if utilized for construction of new and safer roads or for safety improvements on existing roads.

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