STUDDED TIRE EFFECTS ON PAVEMENTS AND TRAFFIC SAFETY IN MINNESOTA

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•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 4½ 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.

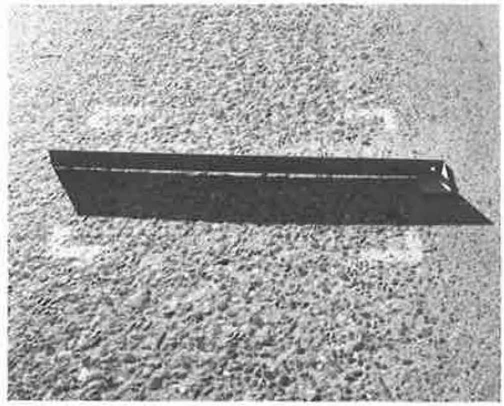


Figure 2. Depth of wheelpath wear on PCC pavement.

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

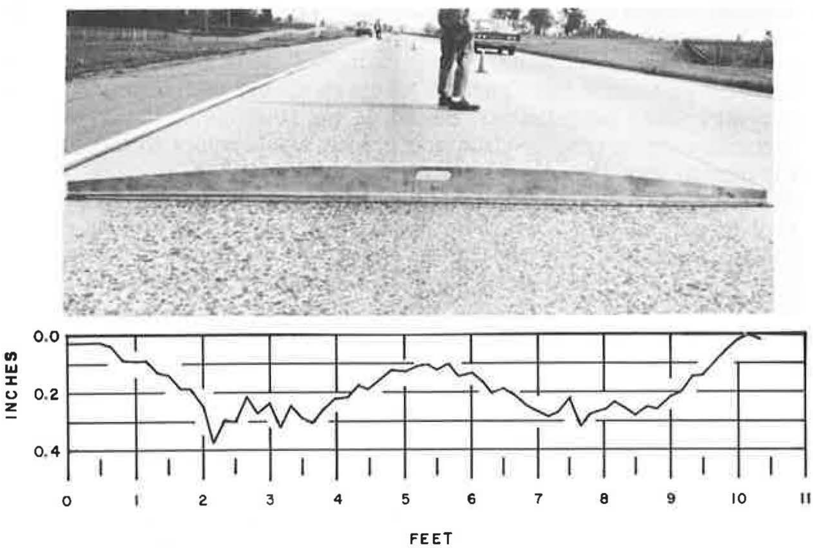
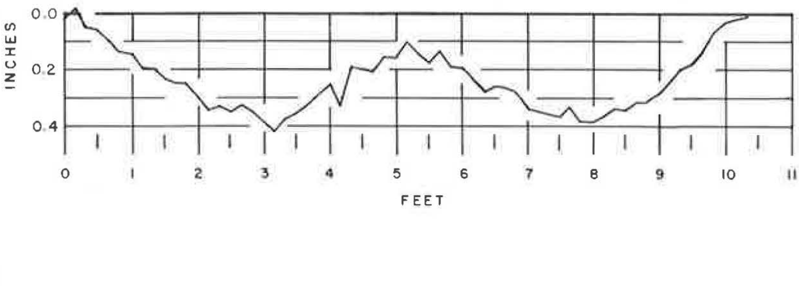


Figure 4. Transverse profile of wear on PCC pavement with limestone aggregate.



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.

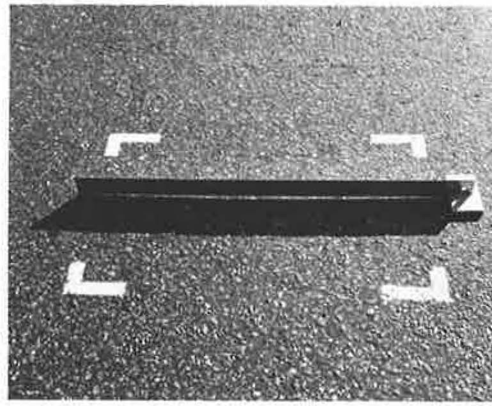


Figure 7. Average wear rate on different pavement types.

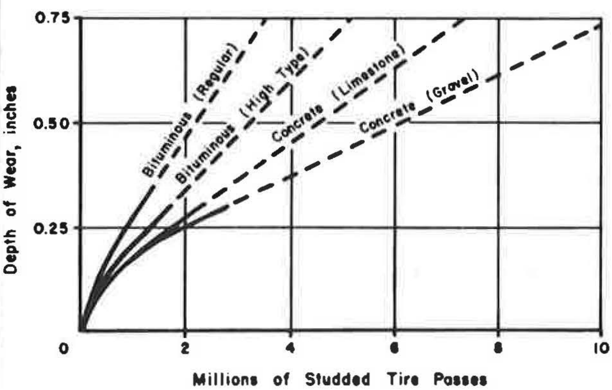
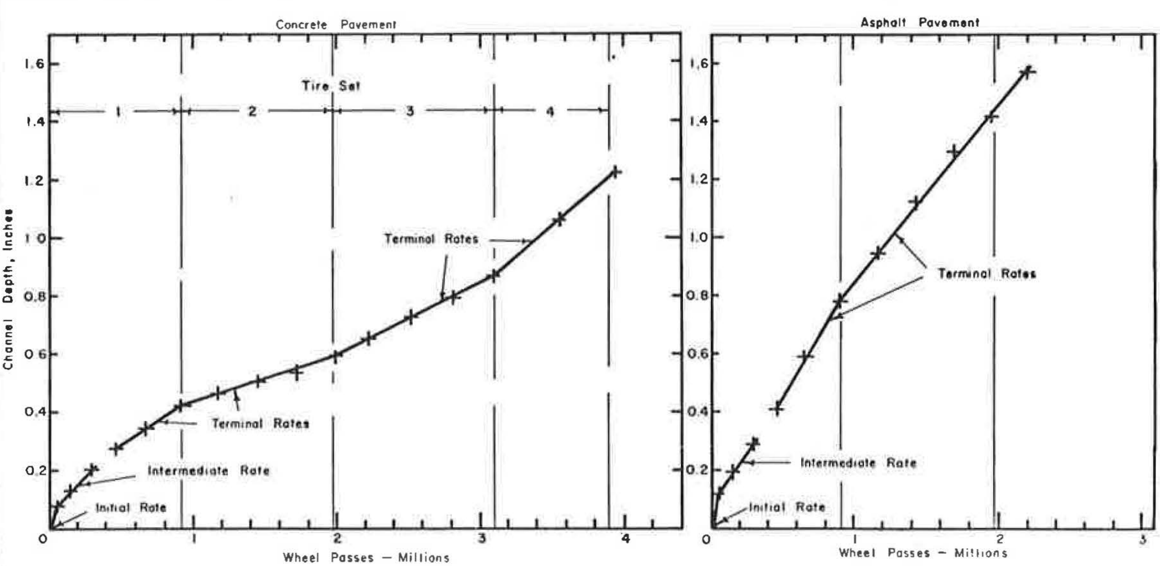


Figure 8. Individual laboratory wear rate curves.



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.

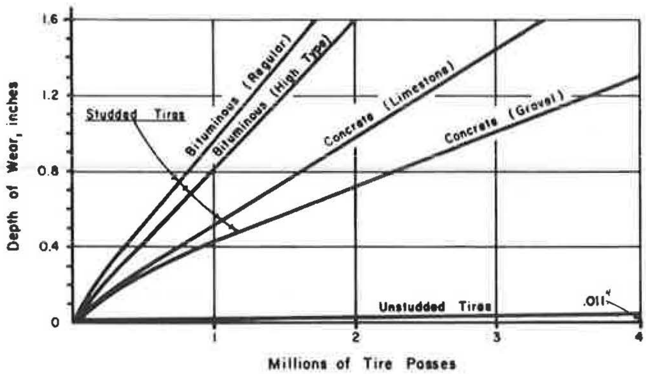


Figure 10. Pavement sections worn after laboratory test.

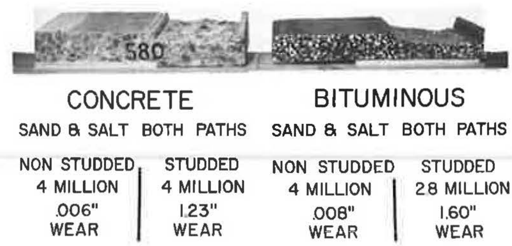


Figure 11. Wear by studded tires on roadway and on test track.

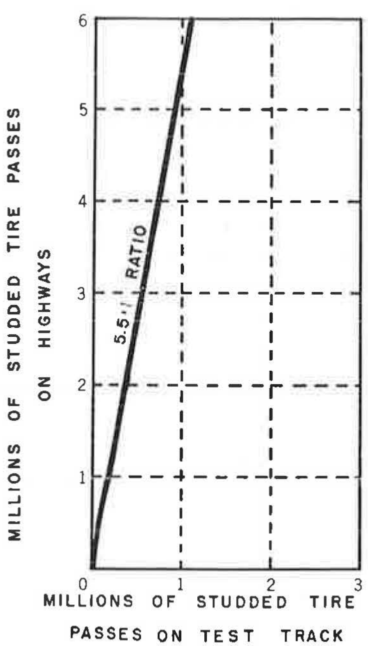
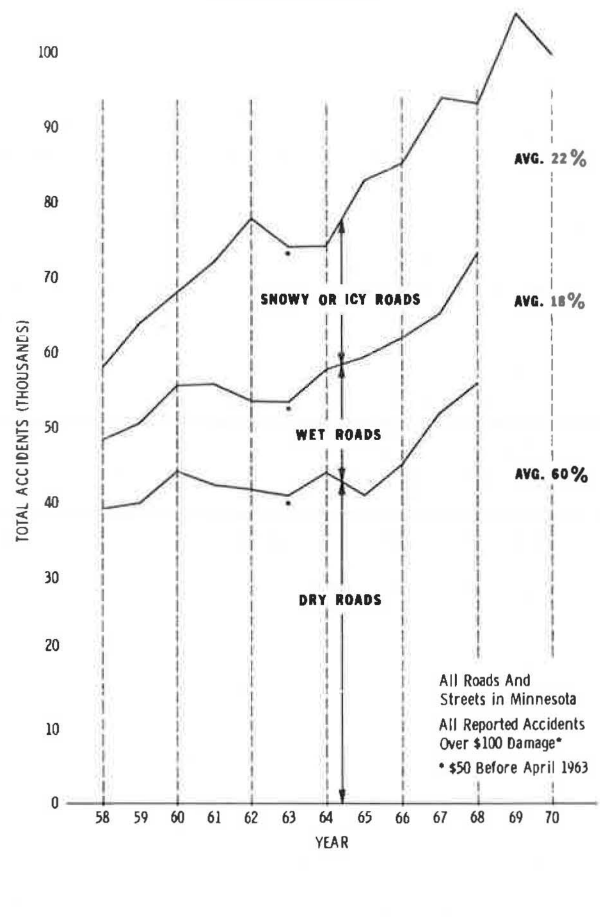


Figure 12. Minnesota traffic accidents.



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 $6\frac{1}{2}$-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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