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Research Project Agreement T9903, Task 92
Studded Tires

A SYNTHESIS ON STUDDED TIRES

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16. ABSTRACT

In the winter of 1998, the Washington State Department of Transportation (WSDOT) proposed legislation to amend the Revised Code of Washington with respect to studded tires. In April 1999, legislation was passed that changed Washington's laws regarding studded tire use. These legislative changes were intended to reduce pavement wear on Washington state's highway system caused by studded tires without losing any of the safety benefits that tire studs provide.

From the time that studded tires were first introduced, the advantages, disadvantages, and effects of studded tires on vehicles, drivers, and pavement systems have been the object of research and controversy. Some states have chosen to ban the use of studded tires altogether, while others, such as Oregon and now Washington, have passed legislation that is intended to reduce the road wear impacts of studs.

This report presents a brief history of the studded tire. The report also explores the relationship between pavement wear and developments in studded tires that have taken place over the past 40 years. This information should provide a background that helps to support and explain the amendments to the Revised Code of Washington regarding studded tires.

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STUDY APPROACH

These objectives were accomplished through an extensive review of world-wide literature covering research on studded tires—their evolution and their relationship to pavement wear—most of which was conducted from 1966 through 1975. The study also looked at new developments in studded tire features and their impacts on pavement wear. The primary source of information on these recent developments is research within Scandinavia.

This report deals in a limited manner with studded tire performance.

DEVELOPMENT OF TIRE STUDS

According to Cantz (1972), metallic cleats were used in pneumatic tires over 100 years ago (1890). These cleats were used to increase the wear resistance of tires against the difficult gravel road conditions that generally existed at that time.

Tire studs consist of two primary parts. The outside part of the stud is called a jacket or body, which is held in the tire tread rubber by a flange at the base. The core/insert or pin is the element that protrudes beyond the tire surface and contacts the pavement surface. The first true studs, which incorporated tungsten carbide cores (still used today) were used in Scandinavia in the late 1950s. The use of tungsten carbide enabled the wear of the stud to be similar to the wear of the tire tread.

The design of tire studs has evolved dramatically since they were first introduced in the early 1960s. In particular, two major elements that contribute to pavement wear, stud protrusion length and stud weight, have been significantly improved. These changes are described below.

EFFECTS OF STUDS ON PAVEMENT WEAR

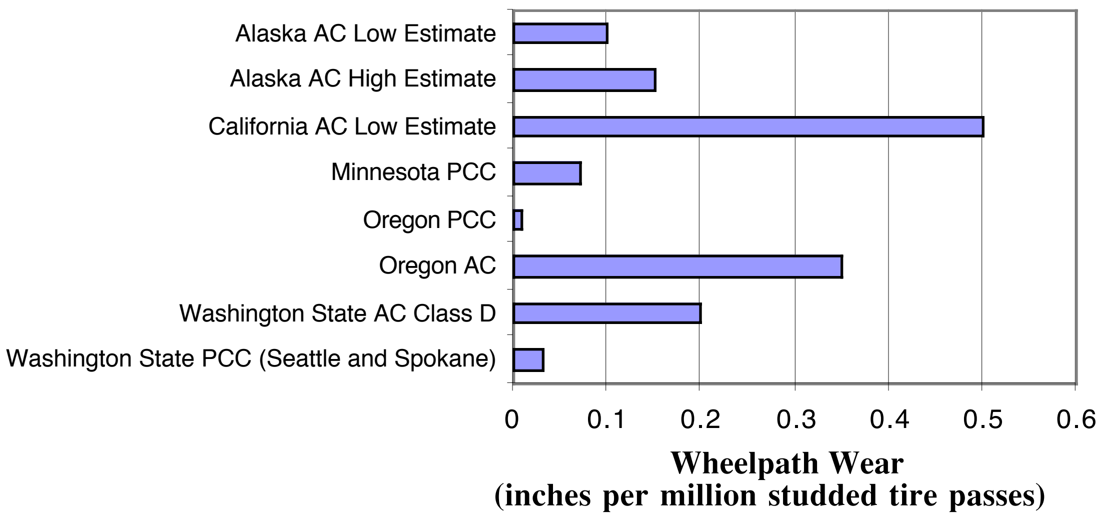
Data from Brunette (1995), the Washington State Pavement Management System (1996), and Malik (1994), show that the pavement wheelpath wear reported by different states varies widely (see below). In general, the wear per one million studded tire passes is significantly higher for asphalt concrete pavement surfaces in comparison to PCC surfaces when both values are reported for an individual state. The lowest wear rates are for Washington State and Alaska, which is not unexpected because of the higher quality aggregate generally available in these two states.

A number of stud-related factors have been found to affect pavement wear. Five of the most important are the following:

- stud protrusion
- stud weight

- driving speed
- number of studs per tire
- stopping effectiveness.

These are discussed below.



Stud Protrusion

Stud protrusion has been directly linked to pavement wear and, naturally, the more the protrusion the more the wear. Over the last 30 years or so, softer tungsten carbide has been adopted which has helped reduce tire-stud protrusion. Cantz (1972) noted that stud protrusion was generally 2.2 mm in 1966 and had decreased to 1.7 mm by 1971. Today, stud protrusion is closer to 1.2 to 1.5 mm. By 1971 stud wear had been reduced by about 25 percent over 1966 conditions, and today that reduction is almost 40 percent.

Stud Weight

Stud weight has been directly related to pavement wear in numerous studies conducted both in the United States and Europe. Work performed at The Technical Research Center of Finland (VTT) and recently summarized by Unhola (1997) shows how stud weight increases pavement wear. (The Finnish findings were later confirmed by research done in Sweden.) The Finnish results can be summarized in terms of cubic centimeters (cm^3) of pavement wear as a function of stud weight:

1.0 grams stud mass: 0.25 cm^3 wear.

1.5 grams stud mass: 0.35 cm^3 wear.

2.0 grams stud mass: 0.45 cm^3 wear.

2.5 grams stud mass: 0.60 cm^3 wear.

3.0 grams stud mass: 0.80 cm^3 wear.

Information provided by the tire industry indicates that currently, studs supplied for most passenger cars in Western Washington typically weigh about 1.7 to 1.9 grams. A reduction in stud weight to 1.5 grams would potentially reduce wear by about 12 to 13 percent. A reduction to 1.1 grams (the standard maximum stud weight used in most of Scandinavia for passenger car tires) could potentially reduce wear by about 30 percent.

Number of Studs

The number of studs per tire has been limited by most of Scandinavian countries (Unhola 1997) but not in the United States. The maximum number of studs is not likely a major issue here. For one reason, the more studs a dealer installs, the more expensive the tire.

Driving Speed

Driving speed can have a significant impact on pavement wear caused by studded tires. Unhola (1997) summarized work done at VTT that examined this issue. The results can also be characterized in terms of pavement wear (cm^3):

Speed = 50 km/h (30 mph): 0.20 cm^3 wear.

Speed = 70 km/h (43 mph): 0.27 cm^3 wear.

Speed = 90 km/h (55 mph): 0.42 cm^3 wear.

Speed = 110 km/h (67 mph): 0.78 cm^3 wear.

These results suggest that changing the Interstate rural speed limit from 55 mph (89 km/h) to 70 mph (113 km/h) has potentially doubled pavement wear caused by studded tires. In comparison with speed limits more appropriate for city streets (30 mph (50 km/h)), 70 mph Interstate speeds mean an increase in pavement wear by a factor of four.

Stopping Distances

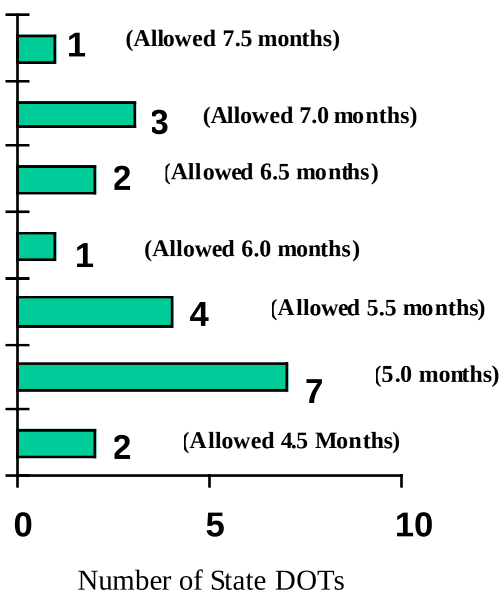
Stopping distance studies have been performed in the United States, Canada, and other countries to compare studded tire performance with various types of tires. One major study performed in Canada was reported by Smith and Clough (1972). This early 1970s test (winter of 1970-1971) was conducted to evaluate various tires under winter driving conditions. The results showed that all tire configurations performed about the same on both clear ice and sanded ice at 0°F. At 32°F, the differences between clear ice and sanded ice were significant, a reduction of 62 percent in stopping distance (or 411 ft. versus 157 ft.) on average for all tire configurations. As expected, sedans equipped with four studded tires performed better than studded tires on the rear wheels only, with stopping distance reductions of 28 and 10 percent, respectively, over standard highway tires. On sanded ice, the same configurations resulted in reductions of 17 and 34 percent, respectively. These comparisons showed that sand applied to ice offers a marginal benefit at very cold temperatures (i.e., 0°F), with all stopping distances ranging between 4.6 to 5.2 times greater than wet asphalt concrete. However, at 32°F, the sand application picture changes dramatically, with stopping distances being reduced to 1.8 to 3.0 times greater than wet asphalt concrete.

SURVEY OF NORTH AMERICAN STUDDED TIRE USAGE

A survey conducted by Brunette (1995) asked 25 state departments of transportation various questions related to studded tires. One question was, "Does your state permit studded tire use?" Of the 25 states that responded, all but three allow studded tires. The three states that do not are Illinois, Indiana, and Minnesota (Minnesota does allow the use of studs for rural mail carriers). All of the four Canadian provinces that responded to the question currently allow the use of studded tires.

Brunette asked about the allowable time period during which studded tires can be used. As shown below, of the 20 states that responded to the question, over 50 percent allow studs for 5 to 5.5 months (typically starting on October 15 or November 1 and ending April 1 or April 15). Current Washington State law allows their use from November 1 to April 1.

A survey conducted by WSDOT during the winter of 1996-1997 revealed that, on average, 10 percent of passenger vehicles use studded tires in Western Washington and 32 percent in Eastern Washington (the percentages are based on two studded tires per vehicle). The surveys were taken in parking lots and garages at 14 locations. Of these locations, the lowest stud usage was observed in Puyallup (6 percent) and the highest in Spokane (56 percent).



- Montana
- Alaska (North of Lat 60), Maine, Nevada
- Alaska (South of Lat 60), New York
- Oregon
- Connecticut, Minnesota, New Jersey, Utah
- California, Iowa, Kansas, Maryland, Nebraska, North Dakota, Washington
- Michigan, Rhode Island

Allowable Studded Tire Use Durations for State DOTs (after Brunette (1995))

STUDDED TIRE IMPACTS ON THE WSDOT ROUTE SYSTEM

Studded tires cause accelerated pavement damage, with some pavement surfaces being more susceptible than others. The wear rates for WSDOT Class D open-graded wearing course has been judged unacceptable, and it is rarely used on high volume routes today. This paving material was used to reduce noise, as well as enhance pavement friction and reduce splash and spray during wet weather, but it is very prone to studded tire wear.

The wear rates for WSDOT PCC pavement on both Interstate 5 in Seattle and Interstate 90 in Spokane are about the same (0.03 inches per million studded tire passes). In Spokane, a portion of PCC on Interstate 90 was ground in 1995 to eliminate wear of about 1.25 inches in the wheelpaths. These wear depths are more extreme in Spokane than Seattle because of the substantially higher studded tire usage rates in Eastern Washington.

Wear rate measurements were taken on SR 395 (south of Ritzville, Wash.) during August 1998. The measurements were intended to evaluate the surface wear in the wheelpaths, and specifically the tining grooves, attributable to studded tires. Because of experimental features built into these sections, different levels of PCC strength were incorporated into the original construction. For these three-year-old sections, the calculated wear rates ranged from a low of 0.02 in. per million passes to a high of 0.10 in. per million. However, these wear rates are likely high because tine grooves are more readily worn than the "flat" PCC surface.

How bad is the pavement wear problem? WSDOT uses the guideline that any pavement with rutting greater than 1/3 in. (9 mm) requires rehabilitation. The primary reason for this criterion is to reduce the potential for hydroplaning accidents. On the basis of measurements taken in 1998, about 8.0 percent of the WSDOT route system had ruts and wear depths of greater than 1/3 in. This amounts to about 1,400 lane-miles out of a total of 18,000 lane-miles. WSDOT knows that a major portion of this rutting and wear is due to studded tires because the width of the wheel track matches automobile tires. Rutting caused by structural deformation related to truck and bus traffic has a wider wheel track.

OREGON LEGISLATION

As discussed earlier, the weight of the stud, along with other factors, has an effect on pavement wear. This was recently recognized in Oregon and has resulted in legislation that went into effect for the winter 1998 season. A brief review of what led to the Oregon legislation is important. A review of other current western state laws pertaining to studded tires (specifically, in Idaho, California, Utah, and Montana) did not reveal any attempt by these states to define and mandate the use of lighter weight studs.

In 1995, Oregon passed legislation that limited the stud weight to 1.5 grams. This was accomplished in Oregon Revised Statutes, Chapter 815, "Vehicle Equipment Generally," Paragraph 815.167. The revised paragraph read as follows:

"815.167 Prohibition on selling studs other than lightweight studs.

- A tire dealer may not sell a tire equipped with studs that are not lightweight studs.
- A tire dealer may not sell a stud other than a lightweight stud for installation in a tire.

As used in this section:

- 'Lightweight stud' means a stud that weighs no more than 1.5 grams and that is intended for installation and use in a vehicle tire; and
- 'Tire dealer' means a person engaged in a business, trade, occupation, activity or enterprise that sells, transfers, exchanges or barters tires or tire related products for consideration."

This law took effect on November 1, 1996, thus requiring these lighter studs for the winter of 1996-1997.

Two problems arose with the new stud definition. First, it did not recognize that different stud weights are required for different tire sizes. Second, the studded tires that were used in Oregon in winter 1996-1997 that met this definition of "lightweight stud" did not perform well. Why this occurred is unclear.

In response to the studded tire performance problems, the Oregon legislature enacted a revised law that was signed by the governor in August 1997. The new law contains two revisions that merit review. First, Paragraph 815.165 amends the allowable usage dates for studded tires. The revised law reduces the allowable usage period by one month (the former period, November 1 to April 30, was changed to November 1 to April 1). Second, Paragraph 815.167 Subparagraph 3(a) was amended to read as follows:

"(3) As used in this section:

'Lightweight stud' means a stud that is recommended by the manufacturer of the tire for the type and size of the tire and that:

- Weighs no more than 1.5 grams if the stud is size 14 or less;
- Weighs no more than 2.3 grams if the stud size is 15 or 16; or
- Weighs no more that 3.0 grams if the stud size is 17 or larger."

1999 WASHINGTON STATE LAW REVISION

In April 1999, a revision to the Revised Code of Washington was passed. The definition of "lightweight stud" was patterned after the Oregon 1997 definition. However, a modest clarification regarding stud size was added. The use of Tire Stud Manufacturing Institute (TSMI) designations clarifies for stud installers the allowable weight of a stud for a given size of stud. The size of the stud is essentially dictated by the tire manufacturers, since they create the holes in the tread rubber for installing the studs.

A new section was added to Title 46 RCW "Motor Vehicles," Chapter 46.04, "Definitions," to read as follows:

"(1) 'Lightweight stud' means a stud intended for installation and use in a vehicle tire. As used in this title, this means a stud that is recommended by the manufacturer of the tire for the type and size of the tire and that:

(1) Weighs no more than 1.5 grams if the stud conforms to Tire Stud Manufacturing Institute (TSMI) stud size 14 or less;

(2) Weighs no more than 2.3 grams if the stud conforms to TSMI stud size 15 or 16; or

(3) Weighs no more than 3.0 grams if the stud conforms to TSMI stud size 17 or larger.

A lightweight stud may contain any materials necessary to achieve the lighter weight."

In addition, two new sections were added to Title 46 RCW "Motor Vehicles," Chapter 46.37, "Vehicle lighting and other equipment":

"(2) Beginning January 1, 2000, a person offering to sell to a tire dealer conducting business in the state of Washington, a metal flange or cleat intended for installation as a stud in a vehicle tire shall certify that the studs are lightweight studs as defined in section 1 of this act. Certification must be accomplished by clearly marking the boxes or containers used to ship and store studs with the designation "lightweight." This section does not apply to tires or studs in a wholesaler's existing inventory as of January 1, 2000.

"(3) Beginning July 1, 2001, a person may not sell a studded tire or sell a stud for installation in a tire unless the stud qualifies as a lightweight stud under section 1 of this act."

CONCLUSIONS AND RECOMMENDATIONS

Given the results of this literature review and the revisions to Washington State's law regarding studded tires, the following conclusions and recommendations are made:

- Washington State has a reasonable studded tire use period and at five months is in line with other western states.
- Few states have fully banned studded tires (in fact, only two). It is reasonable for Washington State to continue to allow their use but to attempt to reduce the pavement wear associated with them; however, the impact of stud-worn pavements on traffic safety has not been assessed in this study.
- Studded tires currently used in Washington state are less damaging to pavement surfaces than those that were available during the 1960s and early 1970s. The evolution of the studded tire clearly reveals this. Nationally available statistics suggest that studded tire wear rates in the 1960s were as much as four to ten times higher than current wear rates for both AC and PCC surfaces, although pavement wear rate statistics tend to be

imprecise. However, with today's traffic volumes, studded tire pavement wear is still significant on WSDOT highways.

- The wear experienced by both asphalt concrete and portland cement concrete pavement surfaces in Washington State is generally lower than the rates reported by other states. However, this undoubtedly varies throughout our state because aggregate sources (and associated hardness) vary.
- The change from 55 mph to 70 mph on our rural Interstate highways has potentially increased pavement wear caused by studded tires by a factor of two. The influence that high speed has on studded wear likely explains, in part, the modest studded tire wear noted on slower city streets.
- A modest change in studded tire wear is significant for some pavement types. A 1- to 2-year increase in pavement life due to reduced studded tire wear will be enough to allow some pavements to achieve their intended structural life.
- Currently available winter tires enhance snow and ice traction (see Appendix B). It is not unreasonable to speculate that these tires will likely reduce studded tire usage.

Considerations for future work include the following:

- Monitor the performance of the newer studless winter tires. Such information could result in further legislative/code revisions.
- Monitor the performance of lighter weight studded tires (less than 1.1 grams) used elsewhere.
- Examine PCC and AC mixes that are more stud-wear resistant. WSDOT paved a stone mastic asphalt (SMA) mixture during the 1999 paving season. That type of mix will be more resistant to stud wear than WSDOT Class A mixes. Experience from Sweden suggests that the wear resistance of SMA mixes can be 40 percent more than conventional, dense graded asphalt concrete mixes (see Appendix A).

1. INTRODUCTION

In the winter of 1998, the Washington State Department of Transportation (WSDOT) proposed legislation to amend the Revised Code of Washington with respect to studded tires. In April 1999, legislation was passed that changed Washington's laws regarding studded tire use. These legislative changes were intended to reduce pavement wear on Washington state's highway system caused by studded tires without losing the safety benefits that tire studs offer.

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The primary source of information on these recent developments is research within Scandinavia.

This report does deals in a limited manner with studded tire performance.

REPORT ORGANIZATION

This report contains three primary chapters. Chapter 2 discusses tire studs, including their composition, the history of their development and acceptance, and historical and current laws and restrictions on their use. Chapter 3 covers pavement wear: primary mechanisms of stud-related pavement wear, an overview of pavement wear studies, and a comprehensive discussion of stud-related factors that affect pavement wear. Chapter 4 discusses the use of tire studs in Washington State specifically, including their impacts on the WSDOT route system, the Oregon legislation on which changes to Washington's laws were patterned, and the proposed and final changes to Washington State law.

2. THE STUDDED TIRE: PAST TO PRESENT

TIRE STUD CHARACTERISTICS

Development and Stud Types

The studded tire concept can be traced as far back as the 1890s, when "metallic cleats" were used in pneumatic tires. The purpose of these cleats was to increase the wear resistance of the tires and provide better protection against damage while on the rough gravel roads of that time. However, these cleats were not necessary for long because of improvements in both roads and tires (Cantz 1972).

Tire studs consist of two primary parts. The outside part of the stud is called a jacket or body, which is held in the tire tread rubber by a flange at the base. The core/insert or pin is the element that protrudes beyond the tire surface and contacts the pavement surface. Figure 1 is a diagram of a typical first generation tire stud that consisted of a 0.094-in. (2.4 mm) diameter tungsten carbide pin (i.e., the insert), which typically protruded 0.063 in. (1.6 mm) from its 0.188-in. (4.7 mm) diameter steel body (i.e., the jacket) (Burnett 1966). This single-flanged tire stud design was adopted as the basic design by most of the tire stud manufacturers.

The European and Scandinavian countries are credited with initially marketing the tire stud to the driving public in the late 1950s. The core of the first tire studs consisted of a small piece of tungsten carbide, which was about the thickness of a ten-penny nail (0.128 inches (3.2 mm)), was approximately 0.313 inches (7.8 mm) long, and was held in place with a "jacket." As a unit, it was referred to as a "winter tire stud" (Miller 1966). Figure 2 shows the basic design of these tire studs (Cantz 1972).

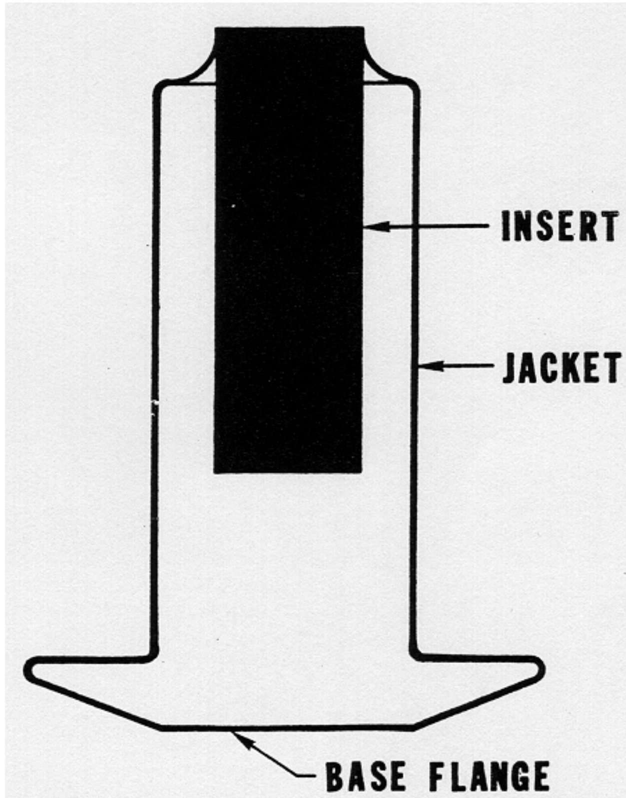

FIGURE 1. First generation single-flange tire stud (Miller 1967).

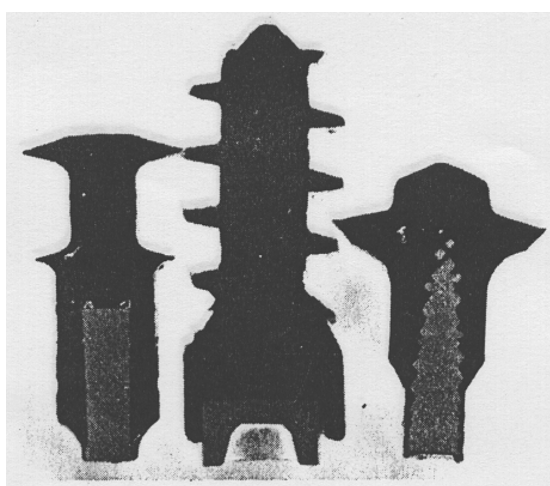

FIGURE 2. First tire studs with tungsten carbide cores (Cantz 1972).

Until the use of tungsten carbide as the core material, all previous attempts to develop anti-skid devices had been unsuccessful. The success of the tungsten carbide core was the result of its being one of the hardest man-made materials available at that time. When manufactured to the proper specifications, and under normal driving conditions, it closely matched the wear rate of the rubber tire tread (Miller 1966).

The jackets that hold the carbide core in place have been designed in various sizes and shapes and are manufactured from many different materials, such as low carbon steel, plastic, brass, aluminum, and porcelain. The original flanges on the jacket body numbered as many as four. A threaded shank similar to a screw was even used in place of the basic flange design (Miller 1966), as shown in Figure 2. Figure 3 shows the results of the initial research that led to a single-flange tire stud design, which was adopted by most of the world's tire-stud manufacturers by 1964 (Cantz 1972).

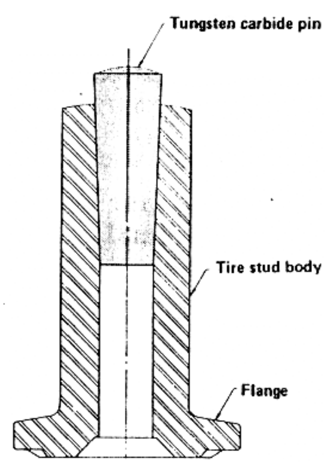

FIGURE 3. Cross-sectional view of single-flanged tire stud (Cantz 1972).

Although numerous types of tire studs have been tested throughout the years, as of 1972, only a few had been successfully marketed and used commercially. A list of the four basic types of tire studs available in 1972, along with a brief description of their characteristics, are shown in Table 1.

TABLE 1. Stud type and basic characteristics as of 1972 (Krukar 1972).

Stud Type	Basic Characteristics
Type I "Controlled Protrusion Stud"	• Carbide pin will move into stud body if protrusion is exceeded • 18 percent lighter in weight than conventional stud • 5 percent smaller flange than conventional stud
Type II "Perma-T-Gripper Stud"	• Pin found in other studs has been replaced with relatively small tungsten Carbide chips in a soft bonding matrix enclosed in a steel jacket • Designed to wear within 10 percent of tire wear, thus maintaining a protrusion of approximately 0.020 inches (0.5 mm) or less.
Type III "Conventional Steel Stud"	• Tungsten carbide pin • Stud protrusion will increase with tire wear
Type IV "Finnstop Stud"*	• Stud body made of lightweight metal or plastic with a tungsten carbide pin • Stud can be adjusted close to the tread rubber eliminating oscillation of the stud • Pin angle contact varies little with speed • Air cushion can be left under stud to reduce stiffness (floating stud) • Reduces heat build up between rubber and stud

*A plastic jacket stud.

Stud/Tire Interaction

During normal service, the stud is held in place within the tire by the rubber around the stud, which exerts compression on the jacket (Miller 1967). Once the stud has been inserted properly, the force required to pull the entire stud out of the tread is reported to be about 90 pounds (400 Newtons). According to the literature, the centrifugal force acting on the stud is less than 2 pounds (8.9 Newtons) when the tire is traveling at 50 mph (81 kph) (Miller 1966).

Evidently, a settling action takes place during the initial life of the tire stud. That is to say, the rubber begins to envelop the shape of the jacket. As shown by Figure 4, the rubber merely bridges the distance from the flange to the shank of the tire stud immediately after its insertion. The maximum ability to retain the stud in the tire is not developed until the rubber around the stud completely envelops the jacket (Miller 1967).

Manufacturers recommend that before drivers subject the studded tire to severe driving conditions, they drive 50 miles (81 kilometers) at speeds of less than 50 mph hour (81 km/h) to allow the stud to seat itself in the tire properly and to ensure maximum retention of the tire stud (Miller 1967).

Evolution: Change in Stud Length and Weight

Since tire studs were first introduced, the stud flange diameter and the hardness of the tungsten carbide pin have both decreased with time to be more comparable with tire tread wear performance (Brunette 1995). During the late 1960s and early 1970s softer carbides were chosen to better match the wear rate of the tire surface rubber, which also reduced the average tire stud protrusion length (Transportation Research Board 1995). These improvements to the tire stud were driven by pavement wear studies that revealed

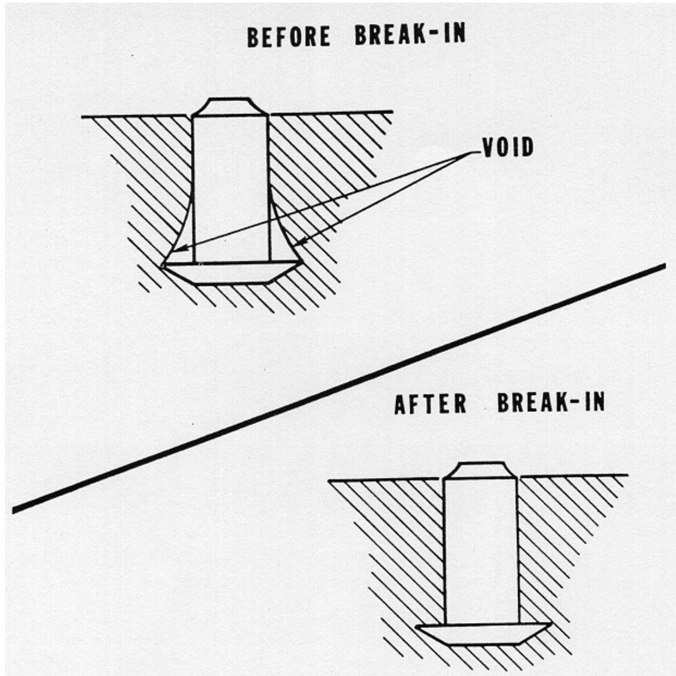

FIGURE 4. Tire stud before and after break-in-period (Miller 1967).

that stud protrusion length was a significant factor in pavement wear rates (Brunette 1995). Table 2 displays the changes in average tire stud protrusion from 1966 to 1972.

TABLE 2. Change of average tire stud pin protrusion by year (Cantz 1972).

Year	**Stud Protrusion** (inches (mm))
1966	0.087 (2.2)
1967	0.081 (2.0)
1968	0.076 (1.9)
1969	0.074 (1.9)
1970	0.068 (1.7)
1971	0.065 (1.6)
1972	0.045 (1.1)

Finnish, Swedish, and Norwegian stud technical data suggest that current stud pin protrusion is about 1.2 mm (Unhola 1997).

Research to develop a new stud design was intensified by the tire stud industry as the possibilities of a legal ban on the use of tire studs increased. A result was the development and marketing, in 1972, of "second generation studs," which were designed to control how much the pin protruded beyond the tire surface throughout the life of the tire (Transportation Research Board 1975). This stud became known as the "Controlled Protrusion" (CP) stud.

The CP stud was 18 percent lighter and the flange is 5 percent smaller than the conventional stud. It was designed with a tapered pin, which is allowed to move back into the stud jacket when the dynamic force reaches a critical level (Transportation Research Board 1975). The dynamic force is determined partially by the vehicle speed, but mostly by the tire stud protrusion length (Cantz 1972). This means that these studs maintained a certain protrusion level almost independent from the wear resistance of the carbide insert and the tire, as well as from driving conditions (Brunette 1995). The CP stud is graphically displayed in comparison with the first generation (conventional) stud in Figure 5.

The critical minimum force necessary to move the pin is determined by the dimensions of the tapered pin and the shape and dimensions of the hole in the stud body. The tire stud protrusion is determined by this pin movement (Cantz 1972). The average pin protrusion for these types of studs ranged between 0.040 to 0.050 in. (1.0 to 1.3 mm) in 1972 (Brunette 1995). At the time, this was approximately 30 percent less than the average tire stud protrusion associated with conventional studs. Tests in 1972 showed that the new CP studs reduced pavement wear by 40 to 50 percent.

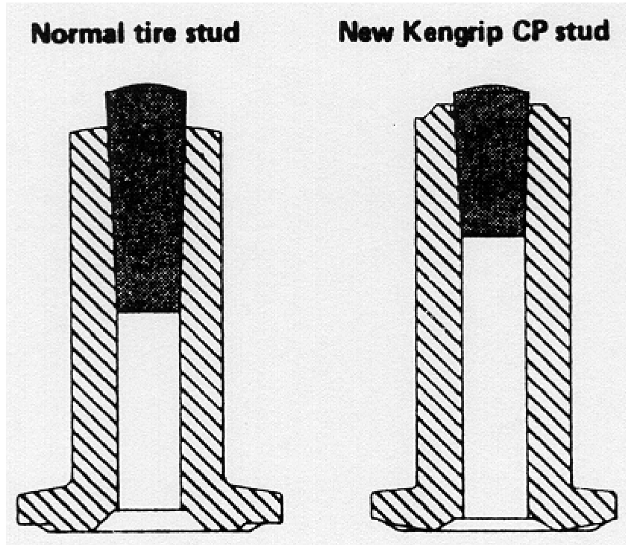

FIGURE 5. Comparison between the CP tire stud and the conventional stud (Cantz 1972).

Another advantage of the CP stud is a reduction in heat caused by the impact of the tire stud on the pavement (Cantz 1972). This means that the temperature between the stud and the tire tread is lower, which in turn eliminates the degradation of the of the rubber surrounding the stud (Brunette 1995). All of this provides better stud retention capabilities.

The manufacturing of the CP stud was further improved in 1983, which resulted in additional weight reduction and improved protrusion characteristics (Brunette 1995). The researchers also determined that radial tires with improved CP studs reduced pavement wear by as much as 75 percent of that previously recorded for bias tires with old conventional studs installed (Brunette 1995). The literature search revealed that in 1992, only the CP stud was being used in the United States and that the number of studs per tire generally ranged from 64 to 120 (Lundy 1992).

Research and development to improve tire studs by reducing stud weight, increasing stud durability, and decreasing pavement wear has continued in the Scandinavian countries. As an example, the Swedish National Road Administration performed research to investigate the pavement wearing characteristics of two new "lightweight" studs in 1992 (Brunette 1995). One of the lightweight studs tested consisted of a plastic jacket weighing 0.7 grams (0.02 oz.), while the other stud consisted of a lightweight metal jacket and weighed 0.95 grams (0.03 oz.). As a comparison, the older conventional studs weighed approximately 2.3 grams (0.08 oz.), and the controlled protrusion stud weighed 2.0 grams (0.07 oz.). The test results indicated that when lightweight studs were used, pavement wear was reduced by 50 percent in comparison to pavement wear caused by any of the early 2.3 gram (0.08 oz.) steel studs. The differences in pavement wear between the two lightweight studs was small; however, the lightweight metal studs produced less pavement wear than the plastic lightweight stud, despite its heavier weight. In addition to the pavement wear results, these lightweight studs also displayed durability and pin protrusion characteristics similar to those of the controlled protrusion studs.

Clearly, the tire studs of today have evolved dramatically since they were first introduced in the early 1960s. Specifically, two major elements that contribute to pavement wear have been significantly improved. The average stud protrusion length has decreased from 0.087 in. (2.2 mm) in 1966 to a range of 0.047 to 0.059 in. (1.2 to 1.5 mm) in today's tire studs. This is close to a 40 percent decrease in protrusion length. Another element that contributes to pavement wear is the average weight of the tire stud. This has also decreased substantially since the original studs of the early 1960s. The recent tire studs in Scandinavia (i.e., the lightweight studs) weigh about 1.1 grams (0.04 oz.) as opposed to the original conventional steel studs of the early 1960s, which weighed about 2.3 grams (0.08 oz.). This change has resulted in studs that are about 50 percent lighter today than what they were over three decades ago. However, the typical tire stud for passenger cars in the United States currently weighs about 1.7 to 1.9 grams (0.06 to 0.07 oz.) [54], which is only about 22 percent lighter than the older conventional tire studs.

In the United States, the size designation of the tire stud is based on a system derived by the Tire Stud Manufacturing Institute (TSMI). Although TSMI no longer exists, tire dealers in the United States still utilize its sizing scheme today. As an illustration, a TSMI No. 12 stud means that the stud hole in the tire tread, is 12/32s or 0.375 in. (9.5 mm) deep. In Europe, the stud manufacturers use a different designation system to describe a stud. As an example, a stud in Europe might have a designation of "9-11-1," which means that the stud head diameter is 9 mm (0.354 in.), the length of the stud is 11 mm (0.4330 in.), and the stud has one flange. This 9-11-1 stud is basically equivalent to the TSMI No. 12. Overall, approximately 85 to 90 percent of the tire studs currently sold within the United States are TSMI No. 11, 12, and 13, which are all used with standard size passenger car tires (Wessel 1997).

MARKETING THE STUDDED TIRE

The single-flanged tire stud was first accepted and extensively used on automobiles in the 1961-1962 winter season in Europe, primarily in the Scandinavian countries (Rosenthal et al 1969). This strong consumer acceptance during the studded tires' first season was encouraging to tire stud manufacturers. By 1962, studded tires composed up to 50 percent of the winter tire market in several Scandinavian countries (Miller 1966).

Given the favorable acceptance of the studded tire in the European countries, the North American market was a natural progression for various manufacturers.

The tire industry in Canada established a test market in the winter season of 1963-1964. An estimated 1.5 million tire studs were sold during that winter season. The following year, 6 million were sold, and by the end of the 1965-1966 winter season, Canadian sales of tire studs were estimated at over 25 million (Miller 1966).

A limited test market was established in the United States during the 1963-1964 winter season. One of the first tire studs to be marketed in the United States consisted of a tungsten carbide insert with a bell-shaped plastic casing, called the Keinas-Hokken. However, the method of inserting these studs into the tires was an issue (Miller 1966). The Keinas-Hokken was quickly replaced by an improved version made by the Scason Corporation, a European manufacturer. This new version allowed a more refined method of insertion.

As marketing plans for the improved stud were being prepared, marketers discovered that numerous states had laws on their books that read, "Any block, stud, flange, cleat or any other protuberance of any material other than rubber which projects beyond the tread will be illegal…" Because of those legal constraints, the initial 1963-1964 test market was confined to just two or three states, and little was learned about the market's potential.

During the 1964-1965 winter season 13 states were thought to allow the use of studded tires. These states were Connecticut, Kentucky, Maine, Maryland, Massachusetts, Missouri, Nevada, New Hampshire, New York, Ohio, Oklahoma, Tennessee, and Vermont (Miller 1966).

By the end of the 1965-1966 winter season, more than 30 states permitted the use of studded tires, while some 18 states considered their use illegal. This rapid increase in studded tire use in the first three seasons of their sale in the United States is summarized in Table 3 (Transportation Research Board 1975).

TABLE 3. Increase in use of studded tires during the initial U.S. marketing period (1963–1966) (Transportation Research Board 1975).

Winter Season	No. Legal States	No. of States Marketed	No. of Tire Studs Sold in USA (millions)	Approximate No. of Tires (100 studs/tire)
1963-1964	13	2 – 3	3 – 5	30,000
1964-1965	13	13	25 – 30	250,000
1965-1966	28	28	250 – 275+	2,500,000

Evidence that consumers were increasingly accepting of studded tires continued to grow, and marketers estimated that an excess of half-a-billion studs would be sold during the 1966-1967 winter season (Transportation Research Board 1975). Figure 6 shows the states, except for Alaska, in which studded tires were allowed by the end of the 1966-1967 winter season (Miller 1967).

During the period of 1965 to 1969, annual sales of studded tires increased threefold, with total sales estimated to be around $830 million in 1969 (Roberts 1973). These estimates implied wide-spread, popular acceptance of studded tires as a winter driving aid by a significant proportion of vehicle owners in the northern states of this country where their use was legal at that time. Sales of studded tires may have been as high as 25 to 50 percent of the total snow-tire shipments during the 1969–1970 winter season (Roberts 1973). This high level of use and acceptance by the general public had come about despite the numerous legitimate questions that had been raised regarding the performance of studded tires and their effect on pavement wear (Rosenthal et al 1969).

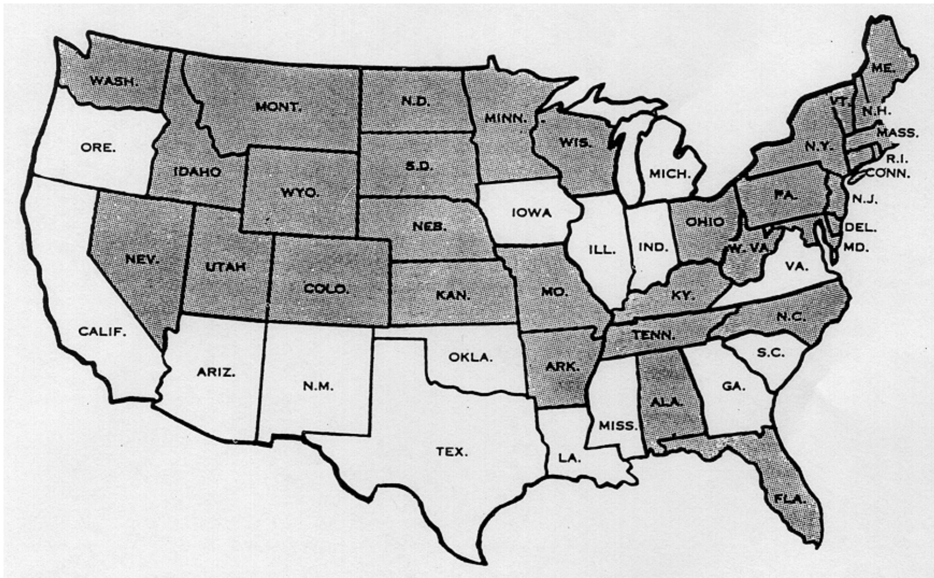

FIGURE 6. States (shaded), which allowed studded tires as of January 1, 1967 (Miller 1967).

STUDDED TIRE USAGE RATES

According to the literature review, the current actual usage rates of studded tires are generally unknown in the United States and Canada (Lundy 1992). The last time data were collected regarding the percentage of vehicles in North America with studded tires was in November 1972, when a questionnaire requesting use estimates was sent to the 45 states that allowed studded tires at that time, as well as to the Canadian provinces and Scandinavian countries. The five states that did not allow the use of studded tires in 1972 were Hawaii, Louisiana, Minnesota, Mississippi, and Utah. Although annual sales estimates demonstrated the studded tire's continuing popularity, highway engineers and administrators wanted to know the total number of vehicles in North America with studded tires (Roberts 1973).

Estimates of studded tire use were reported as a percentage of registered passenger cars by 37 states. Of these 37 states, seven reported studded tire use at not more than 5 percent, with the remaining 30 states estimating usage within the range of 6 to 61 percent. These data were presumed to indicate the status of studded tire use in the United States in 1972 north of the 37th parallel, excluding Minnesota and Utah (Roberts 1973). The collected data on the percentage of vehicles in the United States, Canada, and abroad with studded tires are shown in Table 4 (Transportation Research Board 1975).

In general, the data showed that Sweden and Finland had higher rates of studded tire use than most North American states and provinces in 1972. Evidently, Finland was the only country that compared truck and car use at the time the data were collected (Lundy 1992). The data also showed that the use of tire studs ranged from 0 to approximately 75 percent of all vehicles, with areas of harsh winters experiencing ranges from about 20 to 75 percent.

LAWS AND RESTRICTIONS FOR STUDDED TIRE USE

Since studded tires were introduced in the early 1960s, the decision to allow their use in the United States has continuously evolved. In 1963 only 13 states permitted the use of tire studs. An estimated 28 states had legalized their use by 1965, and by the end of the 1966–1967 winter season, 34 states had legalized the use of tire studs.

A great deal of research was performed from 1965 to 1967 on the effects of studded tires on highway pavements. As a result, the trend to legalize the use of studded

TABLE 4. Historical data on estimated percentage of studded tire use in 1972 (Transportation Research Board 1975).

Country	Agency	% of Vehicles with Studs	Agency	% of Vehicles with Studs
United States	Alabama	1	Montana	60
	Alaska	61	Nebraska	38
	Arizona	1	Nevada	6
	Arkansas	1	New Hampshire	30
	California	NA	New Jersey	20
	Colorado	30	New Mexico	NA
	Connecticut	25	New York	30
	Delaware	18	North Carolina	2
	Florida	NA	North Dakota	32
	Georgia	NA	Ohio	20
	Hawaii	NL	Oklahoma	1
	Idaho	27	Oregon	10
	Illinois	12	Pennsylvania	28
	Indiana	10	Rhode Island	NA
	Iowa	25	South Carolina	3
	Kansas	7	South Dakota	40
	Kentucky	12	Tennessee	NA
	Louisiana	NL	Texas	0
	Maine	NA	Utah	NL
	Maryland	NA	Vermont	60
	Massachusetts	32	Virginia	10
	Michigan	12	Washington	35
	Minnesota	NL	West Virginia	10
	Mississippi	NL	Wisconsin	20
	Missouri	14	Wyoming	35
Canada	Ontario			32
	Manitoba			20 – 25
	Quebec			50
	Maritime Provinces			50+
	Ottawa			48
Finland	Cars			90 – 95
	Trucks			40
Sweden				60

NA = estimate not available

NL = not legal

tires reversed by 1974, with tire studs being legal (without restrictions) in only 16 states, and permitted in 29 states (with restrictions) as well as the District of Columbia. Only five states actually prohibited the use of studded tires (Transportation Research Board 1975). Figure 7 shows the results of a 1975 survey by the Transportation Research Board that indicated the months during which studded tire use was restricted in the United States and Canada.

a) No restrictions:

Alabama	Missouri	North Carolina	Vermont
Colorado	Nevada	South Carolina	Wyoming
Georgia	New Hampshire	North Dakota	Alberta
Kentucky	New Mexico	Tennessee	Saskatchewan

b) Restricted to period Shown:

	Aug	September	October	November	Dec	Jan	Feb	March	April	May	June
		15 Sep					**Alaska** (except specified cities)				
			1 Oct				**Idaho, Nebraska**				
			1 Oct				**British Columbia, Manitoba**				
			1 Oct				**Arizona, Indiana, Maine**				
			1 Oct				**Montana, Prince Edward Island**				
			15 Oct			**Utah**					
			15 Oct			**Del, D.C., MD, ND, VA, N. Scotia, Quebec**					
			15 Oct				**Connecticut**				
			15 Oct				**New York**				
			16 Oct				**New Brunswick**				
				31 Oct		**Rhode Island**					
				1 Nov		**Iowa, OK, WA, W. Va.**					
				1 Nov			**Kansas, Ohio**				
				1 Nov		**Oregon, Pennsylvania, Newfoundland**					
				2 Nov			**Massachusetts**				
					15 Nov	**Arkansas**					
					15 Nov	**Mich., New Jersey**					

c) Prohibited:

California	Louisiana	Texas
Florida	Minnesota **	Wisconsin **
Hawaii	Mississippi	Ontario
Illinois		

** Limited use by out-of-state motorists permitted

FIGURE 7. Legal restrictions on use of studded tires in 1975 (Transportation Research Board 1975).

The 1975 survey remained one of the only complete listings of restrictions on studded tire use in the United States and Canadian provinces until 1990, when the Alaskan Department of Transportation and Public Facilities conducted a similar survey (Lundy 1992). The survey was sent to 30 highway agencies in the United States and 11 Canadian provinces and territories, as well as Finland, Norway, Sweden, and the former West Germany. The results of this survey are shown in Table 5.

TABLE 5. 1990 Restrictions on use of studded tires (Lundy 1992).

United States/Canada			
a) No restrictions	Colorado Vermont Saskatchewan	Note: Several other states outside the snow zone were not surveyed. These states may or may not restrict the use of studs.	
b) Restricted to time period shown	Alaska	(September 15 – April 30 (north of latitude 60° N) (October 1 – April 14 (south of latitude 60° N)	
	Connecticut	(November 15 – April 30)	
	Iowa	(November 1 – April 1)	
	Kansas	(November 1 – April 5)	
	Maine	(October 1 – May 1)	
	Nevada	(October 1 – April 30)	
	New Jersey	(November 1 – April 1)	
	New York	(October 15 – May 1)	
	Rhode Island	(November 15 – April 1)	
	Utah	(October 15 – March 15)	
c) Restricted (period unreported)	California Delaware Idaho Indiana Montana Nebraska	North Dakota Oregon Pennsylvania South Dakota Washington Wyoming	New Brunswick Nova Scotia Quebec
d) Prohibited	Arizona Illinois Maryland	Michigan Minnesota	Alberta Northwest Territories Ontario
Northern Europe			
a) No restrictions			
b) Restricted	Norway	(Period unreported)	
	Sweden	(31 October to Easter)	
	Finland	(1 November to 31 March)	
c) Prohibited	Germany		

A comparison of the results of this 1990 survey with the 1975 data (Figure 7) reveals the changes that occurred within that 15-year period. In 1975 Arizona, Maryland, and Michigan permitted the use of studded tires during specific periods; however, the 1990 data show that the use of tire studs was later prohibited in these three states. One state, California, changed its laws from completely prohibiting studs to permitting them, although the months of use were unreported. The 1990 data show that minor changes were made in the usage periods of states that restricted the use of studs to specific dates. There was a tremendous change in the regions that originally had no restrictions. In 1975, 14 states and two provinces had no restrictions on the use of studded tires. However, by 1990 only three agencies (two states and one province) had no restrictions. This shift in restrictions is likely the result of extensive research that had been performed in the mid-1960s and 1970s on the negative effects of studded tires on highway pavements.

To determine whether any changes had occurred since the 1990 survey, another survey was conducted in 1995 for the Oregon Department of Transportation (Brunette 1995). The survey was sent to 29 Northern states and 10 Canadian provinces to determine whether policy or agency perceptions regarding studded tire use, and effects on pavement wear, had changed much since the 1990 survey.

The response rate for the northern states was over 86 percent (25 responses out of 29 surveyed), and of the Canadian provinces, four of ten responded (40 percent). The responses to questions regarding restrictions on the dates of studded tires use are shown in Table 6.

TABLE 6. 1995 Restrictions on use of studded tires (Brunette 1995).

Unites States		
a) No restrictions	Wyoming Hwy Dept.	
b) Restricted to time period shown	Alaska DOT	(September 30 – May 1 (North of latitude 60° N) (October 1 – April 15 (South of latitude 60° N)
	California DOT	(November 1 – April 1)
	Connecticut	(November 15 – April 30)
	Iowa DOT	(November 1 – April 1)
	Kansas DOT	(November – April)
	Maine DOT	(October 1 – May 1)
	Maryland DOT	(November 15 – April 15)
	Michigan DOT*	(November 15 – April 15)
	Minnesota DOT**	(November 15 – May 1)
	Montana DOT	(October 15 – May 1)
	Nebraska Dept. of Rds	(November 1 – April 1)
	Nevada DOT	(October 1 – April 30)
	New Jersey DOT	(November 1 – April 15)
	New York DOT	(October 16 – April 30)
	North Dakota DOT	(November 15 – April 15)
	Oregon DOT	(November 1 – April 30)
	Rhode Island DOT	(November 15 – April 1)
	Utah DOT	(October 15 – March 31)
	Washington DOT	(November 1 – March 31)
c) Restricted (period unreported)	Colorado DOT Delaware DOT Idaho Trans.	
d) Prohibited	Illinois DOT Indiana DOT	
Canadian Provinces		
a) No restrictions	Alberta	
b) Restricted	Manitoba	(October 1 – April 30)
	Nova Scotia	(Period Unreported)
	Quebec	(October 1 – April 15)
c) Prohibited		

* November 1 – May 1 in the Upper Peninsula and Northern Lower Peninsula.
** Studs were banned in 1972, but reinstated for rural mail carriers (only) in 1994.

As with the comparison between the 1975 and 1990 surveys, these results indicated that only minor changes had occurred in the usage dates of agencies that restricted the use of studs to a specific period. Minnesota, which until 1994 had banned the use of studded tires altogether, now permits their use, but only for rural mail carriers. Wyoming changed from restricted use to no restrictions at all, while Indiana changed from restricted use to prohibiting tire stud use completely. Two states—Maryland and Michigan—also changed from completely prohibiting the use of tire studs to allowing their use during a restricted time period. Out of the 20 states that responded to the survey, over 50 percent allow studs for 5.0 to 5.5 months per year. The allowable period typically starts on October 15 or November 1 and ends April 1 or April 15. The four Canadian provinces that responded (Alberta, Manitoba, Nova Scotia, and Quebec) currently allow the use of studded tires. One of these provinces, Alberta, changed from prohibiting their use in 1990 to permitting their use with no restrictions.

Responses to other questions in the 1995 survey indicated that most of the states and provinces surveyed perceive studded tire use to be lower than in the past. Additionally, the results showed that winter studded tire use has dropped to less than 10 percent of all autos. It is also interesting to note that mixed responses were received regarding agency perceptions of the effect of studded tires on pavement wear. Fifteen respondents identified a concern for studded tire pavement damage, while only ten respondents (seven states and three providences) reported that they were not concerned. The seven states were Colorado, Kansas, Maryland, Montana, New York, North Dakota, and Wyoming.

3. PAVEMENT WEAR

MECHANISMS OF PAVEMENT WEAR

The results of the literature review showed that basically the abrasive action of the stud against the road causes pavement wear. A report from Finland in 1978, summarized in Table 7 (Brunette 1995), identified four main mechanisms by which studded tires cause pavement wear. Given that no studies have been published that definitively establish which cause has the greatest impact, the debate continues over which mechanism is most important. The current belief in Alaska is that the primary stud-related mechanism of asphalt surfaced pavement wear is scraping of the asphalt mastic and subsequent abrasion of the aggregate (Brunette 1995, Lundy 1992).

TABLE 7. Mechanisms of pavement wear under studded tires (Lundy 1992).

Cause	Description
1	The scraping action of the stud produces marks of wear on the asphalt mastic formed by the binder and the fine-grained aggregate.
2	The aggregate works loose from the pavement surface as a result of scraping by studs.
3	Scraping of the stud produces marks of wear on stone. Only in very soft aggregate does a rock fragment wear away completely by this action.
4	A stone is smashed by the impact of a stud and the pieces are loosened by the scraping action of the stud.

PAVEMENT WEAR STUDIES

Early Indications

Most of what is known about studded tire use and its effects on pavements in North America was recorded during the late 1960s to the mid-1970s. This surge of research coincided with the use of conventional steel studs (i.e., the first generation stud).

Some states within the U.S. performed their own research independently, while other states co-authored studies with bordering states.

These studies were undertaken to determine the amount of damage that might be done to highway pavements by vehicles equipped with studded tires. Many of the early research studies were carried out in the field as well as in the laboratory. However, researchers later determined that the end result was often a lack of correlation between the two study approaches (Brunette 1995, Transportation Research Board 1975).

Early (1965) field studies showed significant pavement wear from studded tires. However, because time limitations required researchers to obtain general information as quickly as possible, no provisions were made to gather quantitative measurements of pavement wear damage (Jensen 1966). Therefore, the results were qualitative (Transportation Research Board 1975).

These initial studies also indicated that wear was less severe on portland cement concrete pavements than on the bituminous pavements, and that most of the damage could be expected in areas where vehicles braked or accelerated (e.g., intersections, curves, and tollgate lanes) (Jensen 1966). The limited preliminary testing did not show any visual evidence of damage from constant-speed traffic.

On the basis of these 1965 tests, policy makers decided that the evidence that serious widespread pavement damage could result from the use of studded tires was not enough to withhold from the traveling public the potential safety benefits tire studs would provide (Jensen 1966). They recognized, however, that additional data were needed.

Laboratory studies performed in 1975, along with field measurements of actual pavement wear, confirmed the earlier findings. Unlike the previous studies, researchers were able to give quantitative values to wear rates in terms of inches of wear per million studded tire passes (Transportation Research Board 1975). Many of the laboratory test programs used special traffic simulators with circular test tracks. They were constructed to test the wear of various types of pavements under different studded tire applications. Unfortunately, the diameters of these circular test tracks were typically not sufficient to prevent stud scrubbing action, which resulted in minimal direct correlation to actual traffic situations (Brunette 1995).

Overall, the number of pavement wear studies was limited. However, the literature review yielded some basic information regarding tests on pavement wear. Table 8 summarizes the results of tests performed in 1966 and 1967 on pavement surface wear compiled from six sources (Keyser 1970).

Minnesota Comparisons, 1972

One important study compared the effects of pavement wear after one year without studded tires against wear during the previous six-year period with studs. After six winters of legalized stud use in Minnesota (1965 to 1971), the 1971 legislature opted not to legalize studded tires for the 1971–1973 biennium (Preus 1972). Since 1965, when studs were legally introduced in Minnesota, the Minnesota Department of Highways (MDOH) had been making field observations and taking measurements on pavement surfaces to determine the degree of wear associated with the use of studs. It measured wear at 83 sites around the state to obtain a representative sample of various pavements, traffic volumes, and geographic locations (Preus 1972). The legislature's action provided a unique opportunity for the MDOH to record and compare data on pavement wear from this period with data from winters when studs would not be allowed.

TABLE 8. Summary of tests (1966 and 1967) on wear of pavement surface by studded tires [Keyser 1970].

Vehicle	Load (Kg (lb.))			Studs		Tire Pressure (kPa)	Temp. (°C)	Speed (Km/hr) (mph)	Geometry	Track Width (cm (in.))	Volume of Wheel Passes	Contact Mode	Pavement Type	Wear (mm (in.))
	Front Wheel	Rear Wheel	Total	Front Wheel	Rear Wheel									
White and Jenkins, *1966*														
Pickup	585 (1,300)	765 (1,700)	2,700 (6,000)	72	72	---	---	24 – 32 (15 – 20)	Straight	30.5 (12)	10,660	Normal	BC	6.3 (0.25)
								16 – 24 (10 – 15)	Curve, r =36 ft	46 - 61 (18 –24)	5,330	Acceleration Deceleration	BC BC	2.8 (0.11) 4.5 (0.18)
Burke and McKenzie, *1966*														
Auto	---	---	---	---	52	---	---	---	---	---	25	Rapid Start	PCC	1.0 (0.04)
Tessier and Normand, *1967* *														
Auto	---	---	---	90	120	---	-18 to 4.4	88 (55)	Straight	91 (36)	33,500	Normal	BC	1.7 (0.068)
Lee, Page, and DeCarra, *1966*														
Truck	1,575 (3,500)	1,800 (2) (4,000)(2)	10,350 (23,000)	110	110	---	-11 to 18	64 (40)	Straight & Curved	76 (30)	10,000	Normal	BC PCC	2.2 (0.086) 1.4 (0.054)
Auto	180 (400)	405 (900)	1,170 (2,600)	104	104	---	-8 to 19	64 (40)	Straight	76 (30)	10,000	Normal	BC PCC	1.7 (0.068) 0.45 (0.018)
Bellis and Dempster, *1966*														
Auto	315 (1,400)	315 (1,400)	1,260 (2,800)	50 – 32	50 – 32	207 (30 psi)	---	32 max (20 max)	Straight	---	4,990	Normal acceleration	BC PCC	0.65 (0.026) 0.80 (0.032)
												Abrupt stop	BC PCC	0.50 (0.02) 0.25 (0.01)
												Emergency stop	BC PCC	1.4 (0.056) 0.38 (0.015)

* Data are from Keyser (1970).
BC = Bituminous Concrete
PCC = Portland Cement Concrete

Pavement wear measurements were continued following the statewide ban on studded tire use. In addition, MDOH established new test points on several new pavement sections that had never been exposed to studded tire traffic. This allowed pavement wear data to be collected during the winter of 1971–1972 from sites where wear was induced by normal traffic with sand and salt applications but with virtually no studded tires. A summary of the results from a number of typical measurement points is shown in Table 9.

These data show clearly that after the 1971–1972 winter season, and with the ban on tire studs in effect, pavement wear was reduced to virtually zero. Similarly, the report indicated that the results were the same on other test points throughout the state. These results confirmed the conclusions of previous MDOH studies that pavement wear in Minnesota was unquestionably related to studded tire use (Preus 1972).

TABLE 9. Depth of pavement surface wear in Minnesota at typical test points (in. (mm)) (Preus 1972).

Winter Season	**TP 6***		**TP 33****		**TP 32*****		**TP 83******	
	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative	Yearly	Cumulative
1966-67	0.04 (1.0)	0.04 (1.0)						
1967-68	0.07 (1.8)	0.11 (2.8)						
1968-69	0.07 (1.8)	0.18 (4.6)	0.09 (2.3)	0.09 (2.3)	0.10 (2.5)	0.10 (2.5)		
1969-70	0.05 (1.3)	0.23 (5.9)	0.07 (1.8)	0.16 (4.1)	0.03 (0.75)	0.13 (3.3)	0.08 (2.0)	0.08 (2.0)
1970-71	0.05 (1.3)	0.28 (7.2)	0.06 (1.5)	0.22 (5.6)	0.07 (1.8)	0.20 (5.1)	0.07 (1.8)	0.15 (3.8)
1971-72	0.00 (0.0)	0.28 (7.2)	0.00 (0.0)	0.22 (5.6)	0.00 (0.0)	0.20 (5.1)	0.01 (0.25)	0.16 (4.1)

*Test Point 6, portland cement concrete, gravel aggregate.
**Test Point 33, portland cement concrete, limestone aggregate.
***Test Point 32, asphaltic concrete, high type.
****Test Point 83, bituminous, intermediate type.

Applicability and Comparability of Past Research

Table 10 summarizes some basic information on road wear studies. This information was originally presented in a 1990 publication by Hicks, et al., but was obtained for this literature review from Lundy, et al. (1992). The synthesis indicated several things. First, reported wear rates, and the units used, varied considerably between highway agencies. Differences in wear rates were probably due to differences in materials and in percentages of vehicles with studded tires.

The information available about pavement wear from studded tires is not always in the same format. Some researchers have described wear on the basis of average annual daily traffic (AADT) while others have chosen to report wear in terms of a fixed number of studded tire passes. Still other researchers have reported wear in terms of total number of passes. More recently in Sweden (Carlsson 1995), pavement wear has been assigned a weight in grams per vehicle per kilometer driven, and is called the SPS index for pavements. SPS is a Swedish abbreviation for specific wear, and it indicates the actual wear from a certain amount of traffic from studded tires during a particular measuring period, usually one winter season. Although SPS is considered to be reliable for forecasting total pavement wear in Sweden, it does not provide an exact picture of pavement wear (Carlsson 1995). Nonetheless, the SPS index appears to be the reporting method that most Scandinavian researchers now use when reporting information on studded tire pavement wear (Brunette 1995).

The synthesis found in Lundy (1992) also indicated the following:

- Pavement type has a great effect on pavement wear. Asphalt surfaces wear at a faster rate than portland cement concrete.

TABLE 10. Historical summary of road wear studies (Lundy 1992).

Reference		Rate of Wear (in./passes)	Average Rate in in. (mm)/ 100,000 passes
a) **Literature**			
Quebec		0.25/100,000	0.25 (6.3)
Quebec	Acceleration	0.36-0.44/100,000	0.40 (10.0)
	Deceleration	0.18-0.20/100,000	0.19 (4.8)
	Normal	0.11/100,000	0.11 (2.8)
Germany		0.11/120,000	0.09 (2.3)
Finland		0.15-0.2/10,000 AADT	N/A
Sweden		0.5/40,000 AADT	N/A
Maryland		0.28-1.07/100,000	0.70 (17.5)
Minnesota		1.5/4,000,000	0.04 (1.0)
Oregon	Concrete	0.026/100,000	0.03 (0.8)
	Asphalt	0.066/100,000	0.07 (1.8)
b) **1990 Survey**			
California		0.0005-0.0018/1000	0.12 (3.0)
Connecticut		0.08/1,000,000	0.01 (0.3)
Maryland		0.028-0.107/10,000	0.68 (17.3)
New Jersey		0.05 per year for 5400 AADT per lane	N/A
New York		0.009-0.016/year PCC pavements 0.022-0.025/year ACC pavements	N/A N/A
Oregon		0.032/100,000 PCC pavements 0.073/100,000 ACC pavements	0.03 (0.8) 0.07 (1.8)
Norway		SPS* AC = 25 Topeka** = 15 Mastic stone = 10 – 15 PCC = 10	N/A
Sweden		35 grams/vehicle (4 studded tires)/km driven	N/A

* SPS = g/cm (specific wear in grams worn out of the surfacing when a car with 4 studded wheels drives a 1 km distance).

** Topeka is a sand-rich hotmix.

- In areas of acceleration and deceleration, pavements wear increases substantially.

Given all of the recent improvements that have been implemented in tire stud and pavement mix designs, it should be noted that this information is not considered representative of current tire stud wear. However, the information contained in Table 10 can be used in a general manner and as a reference for further studies in this area (Brunette 1995). With the exception of Germany, where studded tires have been banned since the 1974–1975 winter season, the European information in Table 10 is fairly recent for those countries reported and reflects more up-to-date wear rates.

Brunette (1995) reported that studded tire wear rates from two different Oregon pavement studies were about the same: 0.34 in. per million passes for AC surfaces and 0.008 in. per million passes for PCC surfaces. Data from Minnesota (as summarized by Brunette) suggest PCC wear rates of 0.06 to 0.07 in. per million passes.

<u>Alaska Study, 1990</u>

In North America, no substantial information regarding studded tire pavement wear had been published since the introduction of the improved controlled protrusion stud (Brunette 1995). However, in 1990 the state of Alaska conducted research that resulted in published wear rates for asphalt concrete (Lundy 1992). The wear rates are given for three sites in Juneau, Alaska, and the results are summarized in Table 11. The wear rate was calculated by dividing the maximum rut depth by the estimated number of studded tire passes.

TABLE 11. Juneau pavement wear per million studded tire passes (Lundy 1992).

Location	Total Stud Passes by 4/91 (million)	Wear Rate per Million Passes (in. (mm))
Juneau – Douglas Bridge:		
On Bridge	5.37	0.148 (3.8)
Before Bridge	5.37	0.134 (3.4)
Douglas Road	3.87	0.122 (3.1)
Mendenhall Loop	5.84	0.102 (2.6)

The rates of wear from this Alaskan study appear to be very consistent between the three sites, and they are considerably smaller than those shown in Table 10. The data collected at Douglas Bridge (before and on the bridge) show a consistency in wear rate, which eliminates the possibility that subgrade deformation had contributed to the rutting (Lundy 1992). Not surprisingly, the study reported that pavement wear from studded tires is greater in the winter than in the summer. However, although studs are not permitted during the summer season, about 10 percent of total wheel track wear was estimated to be caused by studded tire use during the summer (Lundy 1992). Additional research showed that the primary cause of this wear was from small, lightweight vehicles equipped with studded tires (Brunette 1995). This was determined by measuring the center-to-center distance between the wheel track wear paths, which ranged from 1.4 to 1.5 meters (56 to 58 in.), and these measurements coincide with small, lightweight vehicles.

Continuing Research in Scandinavia

The Road Administration, Road Institute, and tire manufacturers of Norway, Sweden, and Finland have continued to perform extensive research on studded tires and their effects on pavement wear (Barter et al 1996). The Scandinavian countries approached studded tire wear in three related ways. First, the countries began to pass legislation that mandated the use of lightweight studs (studs that weigh less than 1.1 grams (0.04 oz)) (Barter et al 1996). The core of these studs is tungsten carbide steel, but the jacket is made of plastic or lightweight aluminum oxide. All of this reduces pavement wear rates by as much as 50 percent. Second, they began to use a Stone Mastic Asphalt (SMA) concrete mix for surface courses; this mix contains up to 70 percent coarse aggregate (Barter et al 1996). The use of SMA was found to reduce pavement wear rates from 25 to 50 percent. Third, they started using a more durable aggregate that resisted tire stud wear at a higher success rate than aggregates from the local material sources. These harder aggregates consist of fine grained metamorphic and volcanic rocks. The use of these more durable aggregates has reduced wear rates by a factor of three to five in comparison to the previous aggregate source. Some tests with SMA surfacing have also been conducted in Alaska as recently as 1996. The overall result has been a 45 percent improvement in the pavement wear rate over conventional asphalt concrete pavement mixes.

Aggregate quality is the critical parameter that is most important to the wear-resistance of asphalt pavements to studded tires (Jacobson 1997). Today in Sweden, the best pavements are about five times more wear-resistant than the pavements of the mid-1980s and possibly up to ten times better than those built at the end of the 1960s (Jacobson 1997).

Wear Trends

A review of previous data suggests that studded tire pavement wear rates are significantly lower today than during the 1960s. Data from Keyser (1970), Lundy (1992), and Brunette (1995) indicate that the wear rates for both AC and PCC pavement surfaces have decreased by a factor of ten. Keyser's data suggest wear rates of about 2.0 to 6.8 in. per million passes (after scaling up the application rates) for AC pavements. This is about ten times higher if the current Oregon value of 0.34 in. per million is used. A comparison of current Oregon PCC rates to those reported by Minnesota in 1971 also results in a factor of about ten.

FACTORS THAT AFFECT PAVEMENT WEAR

An excellent summary of the several factors that have been identified as affecting pavement wear rate was first prepared in 1970 by Keyser (1970). Keyser originally identified the characteristics for each factor (i.e., vehicle, tire, stud, pavement, environment, and traffic) that affect the rate of pavement wear. Keyser also identified the most important factors for bituminous pavement wear as wheel load, stud protrusion, temperature, and humidity. Table 12 represents a slightly modified version of Keyser's original summary. This modified table is the result of Brunette's newer work (1995), which based the modification on recent research from Finland. This recent research quantified the effects that each of the factors contributes to pavement wear and added to the original list of characteristics for each factor (Brunette 1995). The modifications included the effect that the type of tire (e.g., radial or bias ply), the stud flange diameter, vehicle speed, and the weight of the stud have on pavement wear.

Pavement wear factors include vehicle, tire, and stud systems.

TABLE 12. Factors affecting pavement wear (Brunette 1995).

Factor	Component	Characteristic
Vehicle, Tires, and Studs	Vehicle	▪ Type and weight ▪ Axial load ▪ Number of studded tires (front, rear) ▪ *Speed*
	Tire	▪ Type (snow or regular, *bias ply vs. radial*) ▪ Pneumatic Pressure ▪ Age ▪ Configuration of studs ▪ Number of studs
	Stud	▪ Type (material, shape) ▪ Protrusion length ▪ *Flange diameter* ▪ *Weight* ▪ Orientation of studs with respect to tire wear
	Stud wear vs. tire wear	
Pavement	Geometry	▪ Cornering (curves, sharp turns) ▪ Tangent Section ▪ Intersection ▪ Slope
	Surfacing material	▪ Type and characteristics (bituminous mixtures, surface treatment, precoated aggregate, chipping. Portland cement, hardness) ▪ Age
	Surface condition	▪ Surface texture and profile ▪ Icy ▪ Compacted snow (compactness) ▪ Sanded and salted icy surface ▪ Slush
Environment	Humidity, Temperature	▪ Wet, dry, humid
Traffic	Volume	▪ Number of passes and composition
	Speed	
	Wheel track	▪ Width; Distribution of wheel loads
	Contact mode	▪ Start (normal, abrupt) = spin ▪ Stop (normal, abrupt) = skid ▪ Acceleration (rate) = spin ▪ Deceleration (rate) = skid

Vehicle

The heavier the vehicle, the greater the pavement wear. Another important factor is vehicle speed. In 1992, a Swedish study examined the effects of vehicle speed on pavement wear and determined that increased speed caused an increase in stud dynamic force, which directly affects the pavement systems and hence increases wear (Brunette 1995). These findings were confirmed by a 1992 study performed in Finland (Unhola 1997). The results of this study are presented in Table 13 with vehicle speed in kilometers per hour (km/h) and pavement wear in cubic centimeters (cm^3). These results show that the recent increase of Interstate rural speed limits in the United States from 90 km/h (55 mph) to 113 km/h (70 mph) has increased the potential for studded tire pavement wear by nearly a factor of two. That is to say, pavement wear could potentially increase from 0.41 cm^3 to 0.80 cm3 (0.025 to 0.049 in^3) as a result of this higher speed.

TABLE 13. Pavement wear due to vehicle speed (Unhola 1997).

Vehicle Speed (km/h (mph))	**Pavement Wear** (cm^3 (in^3))
50 (30)	0.20 (0.012)
60 (37)	0.23 (0.014)
70 (43)	0.27 (0.016)
80 (50)	0.32 (0.020)
90 (55)	0.42 (0.026)
100 (62)	0.56 (0.034)
110 (67)	0.78 (0.048)
120 (74)	1.19 (0.073)

In 1972, a study of pavement wear on a low speed (15 mph (24 km/h)) simulator determined that no difference in pavement wear could be found in similar studs of different weight. However, the researchers realized that the reason for this was the low speed of the simulator. At a speed of 15 mph (24 km/h), the variation in the dynamic force of studs with different weight against the pavement was negligible (Cantz 1972).

Tires

The performance characteristics of steel belted radials have proven to be superior to those of bias ply tires, thus inducing less pavement wear when used with studs.

Studs

Several factors related to the studs themselves affect pavement wear.

Stud Flange Diameter

Stud flange diameter influences the rate of pavement wear because the force exerted by the stud on the road surface is directly related to the diameter of the stud flange. Studs with a small flange offer less resistance and are pushed back into the tire during their contact with the road (Cantz 1972).

Number of Studs

The number of studs per tire has also been shown to be a significant factor in wheel path rutting. The number of tire studs used per tire has ranged over the years from 50 to 500 or more (Miller 1966). The latter, of course, represents an extreme situation, such as tires used in ice-racing. The number of studs per tire and road wear increase at a linear rate (Cantz 1972).

Unlike in the United States, the number of studs per tire has been limited by most of the countries throughout Scandinavia. The allowable number of studs by tire size as determined by the Scandinavian Tire and Rim Organization (STRO) in 1997 is shown in Table 14. In the United States, the number of studs used on modern studded tires ranges from 64 to 120, dependent on the size of tire, with a typical average of approximately 100 studs (Brunette 1995).

TABLE 14. Allowable number of studs by tire size (Unhola 1997).

Tire Size (in. (cm))	Allowable Number of Studs		
	Finland	Norway	Sweden
13 (33)	90	90	90
14 – 15 (35.6–38.1)	110	110	110
> 15 (> 38.1)	130/PC* 150/CV**	150	130/PC 150/CV

*Passenger Cars
**Commercial Vehicles

Stud Protrusion

The impact that stud protrusion length has on pavement wear has been recognized as an important studded tire performance variable because of an almost linear relationship between tire stud protrusion and dynamic force (Transportation Research Board 1975). The protrusion length affects the energy absorbed by the pavement (Rosenthal et al 1969). Thus, as stud protrusion increases so does the increase in road wear (Cantz 1972).

In 1966, tire stud protrusion was generally 0.087 in. (2.2 mm). This decreased to 0.065 in. (1.7 mm) by 1971 (Cantz 1972), a reduction of 25 percent. The development of the controlled protrusion stud in 1972 resulted in the possibility of average stud protrusion lengths ranging from 0.045 to 0.050 in. (1.1 to 1.3 mm) (Brunette 1995). Today, the typical stud protrusion length is more in the range of 0.047 to 0.059 in. (1.2 to 1.5 mm) (Brunette 1995), a reduction of almost 40 percent since the 1960s.

Stud Weight

According to reports from Finland, over the last 35 years the pavement wear rate has decreased by a factor of four because of a reduction in the size and weight of the studs. It is important to reduce the weight because of the kinetic energy that is transferred at impact between the stud and the pavement (Barter 1996).

The Technical Research Center of Finland (VTT) has performed extensive work in this area, which was recently summarized in a 1997 report (Unhola 1997). The results of this report, which show how stud weight increases pavement wear, are presented in Table 15 with stud weight in grams and pavement wear in cubic centimeters (cm^3). A comparison of lightweight studs, weighing approximately 1.0 grams (0.035 oz), to steel studs weighing approximately 2.0 grams (0.07 oz) revealed that a reduction in stud weight resulted in about one-half the wear.

Currently, the typical tire stud for approximately 85 to 90 percent of passenger cars in the United States (e.g., TSMI No. 11, 12, and 13 studs) weighs about 1.7 to 1.9 grams (0.06 to 0.07 oz) (Wessel 1997). This means that the potential to reduce pavement wear by adopting a 1.5-gram (0.05 oz) stud is about 12 to 13 percent. If some states decided to adopt the 1.1-gram (0.04 oz) stud for passenger cars—the stud of choice in Scandinavian countries—the potential to reduce pavement wear would be about 36 percent.

TABLE 15. Pavement wear due to stud weight (Unhola 1997).

Stud Weight (grams (oz))	**Pavement Wear** (cm^3 (in^3))
1.0 (0.035)	0.25 (0.015)
1.5 (0.053)	0.35 (0.021)
2.0 (0.070)	0.45 (0.027)
2.5 (0.088)	0.60 (0.037)
3.0 (0.105)	0.80 (0.049)

Pavement

As mentioned earlier, the pavement system itself also influences the rate at which studded tires cause pavement wear. The pavement community has known for some time that portland cement concrete pavements are much more resistant to tire studs than asphalt surfaced pavements. The geometry of the road also contributes to where pavement wear occurs. As an example, tire stud wear on tangent (straight) sections of highways is significantly less (Transportation Research Board 1975) than that observed on sharp curves, where the studs tend to scrape the pavement and thus increase wear (Brunette 1995). At areas where acceleration and deceleration occur, such as at intersections, tire stud wear appears to be extremely concentrated. One study determined that tire stud wear was 3.5 times greater at deceleration areas than at tangent sections (Keyser 1970).

Not surprisingly, tire stud wear of pavements is influenced by the condition of the pavement surface, that is whether it is wet or dry and whether ice or snow covers the surface. Studies have demonstrated, and it seems obvious, that on snow and ice covered pavements the use of tire studs will cause less pavement wear than on bare pavement surfaces. However, what may be surprising is that a wet asphalt pavement is worn down nearly twice as fast as a dry one (Brunette 1995). The effect of moisture and pavement surface temperature on the development of tire stud rutting is graphically depicted in Figure 8.

Temperature

Temperature can also influence the rate of studded tire pavement wear. Cook and Krukar (Krukar and Cook 1972; Sorenson et al 1973) determined that the lowest wear rate for asphalt pavements occurs at or near 0 º Celsius, with increases in pavement wear rates at temperatures below and above Celsius is 0 º Celsius. The increase in pavement wear with pavement temperatures below 0 º reportedly associated with an increase in tire hardness and pavement stiffness (Lundy 1992). As the temperature of the asphalt pavement decreases, pavement stiffness increases. With lower temperatures, the force required to push the stud into the stiffer tire also increases (Krukar and Cook 1972; Sorenson et al 1973) so that for given loading situation, more of the stud will protrude, which results in higher stud forces. The possibility of increased wear rates is the result of this combination of high stud forces and increased pavement brittleness (Krukar and Cook 1972; Sorenson et al 1973). Note that the effect of temperatures on concrete pavements is much different than that on asphalt pavements. The rate of wear from tire studs decreases on concrete pavements as the temperature increases (Brunette 1995).

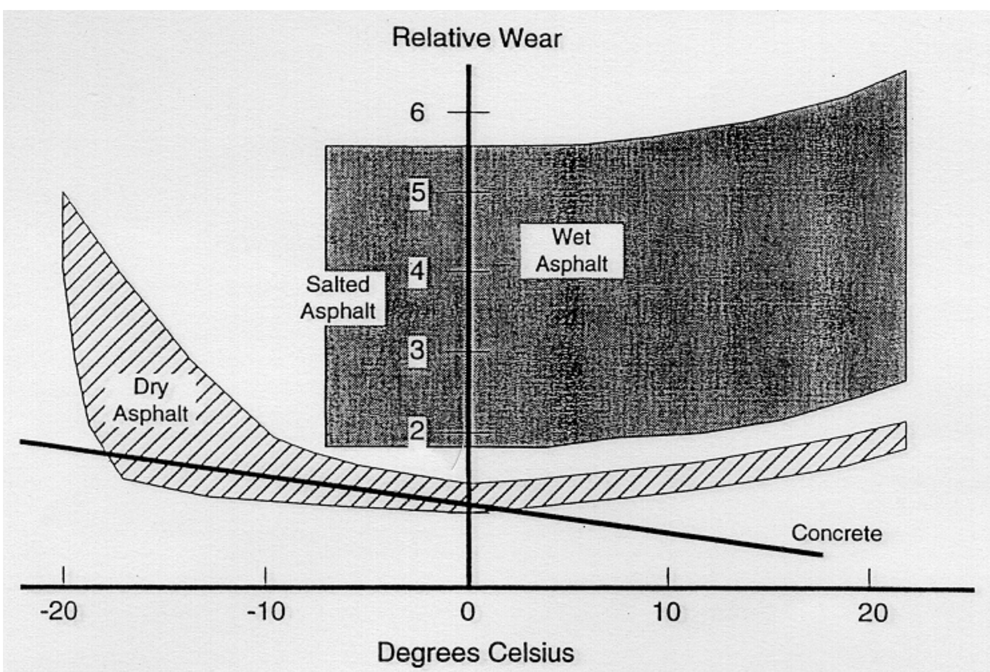

FIGURE 8. The effect of temperature and water on the wearing of pavements (Brunette 1995).

4. STUDDED TIRES IN WASHINGTON STATE

In the winter of 1998, the Washington State Department of Transportation (WSDOT) proposed legislation to amend the Revised Code of Washington with respect to studded tires. In April 1999, legislation was passed that changed Washington's laws regarding studded tire use. These legislative changes were intended to reduce pavement wear on Washington state's highway system caused by studded tires without losing any of the safety benefits that tire studs offer.

Below is an overview of the known impacts of studded tires on the WSDOT route system, recent Oregon and legislation on which WSDOT modeled its proposed changes, the suggested input for 1998 Washington State legislative action, and the outcome of the winter 1999 legislative session.

STUDDED TIRE IMPACTS ON THE WSDOT ROUTE SYSTEM

Studded tires cause accelerated pavement damage, with some pavement surfaces being more susceptible than others. For example, because of studded tires, the use of open graded asphalt concrete (WSDOT Class D) wearing courses on high volume routes in Washington has been virtually eliminated. This paving material was used to enhance pavement friction and reduce splash and spray during wet weather but it is estimated to wear at a rate of about 0.2 in. per million studded tire passes. This is based on wear and traffic experienced during the 1990s on SR 520 (Evergreen Point Floating Bridge).

The surface texture built into all new PCC pavements is quickly worn away after two to three winter seasons. This was particularly noticeable on the paving on SR 395 north of the tri-cities. Wear rate measurements on SR 395 south of Ritzville, Wash., in August 1998 revealed values ranging from 0.02 to 0.10 in. per million passes of studded tires. (The variation was largely due to different PCC strengths.) However, the noted wear was mostly associated with the tine grooves, which exhibited higher wear rates than the "flat" PCC surface. The surface texture (tine grooves) was generally worn away only three years after construction.

The wear rates for WSDOT PCC pavement on both Interstate 5 in Seattle and Interstate 90 in Spokane are about the same (0.03 inches per million studded tire passes). In Spokane, a portion of PCC on Interstate 90 was ground in 1995 to eliminate wear in the wheelpaths of about 1.25 in. These wear depths are more extreme in Spokane than Seattle because of the substantially higher studded tire usage rates in Eastern Washington.

How bad is the pavement wear problem? WSDOT uses the guideline that any pavement with rutting greater than 1/3 inch (9 mm) requires rehabilitation. The primary reason for this criterion is to reduce the potential for hydroplaning accidents. On the basis of measurements taken in 1998, about 8.0 percent of the WSDOT route system had ruts and wear of greater than 1/3 inch. This amounts to about 1,400 lane-miles out of a total of 18,000 lane-miles. WSDOT knows that a major portion of this rutting and wear is due to studded tires because the width of the wheel track matches automobiles tires. Rutting caused by structural deformation related to truck and bus traffic has a wider wheel track.

Stud usage is an important factor in any discussion of state pavement wear. A survey conducted by WSDOT during the winter of 1996-1997 revealed that, on average, 10 percent of passenger vehicles use studded tires in Western Washington and 32 percent in Eastern Washington (the percentages are based on two studded tires per vehicle). The surveys were taken in parking lots and garages at 14 locations. Of these locations, the lowest stud usage was observed in Puyallup (6 percent) and the highest in Spokane (56 percent).

OREGON LEGISLATION

As discussed earlier in this report, the weight of the stud, along with other factors, has an effect on pavement wear. This was recently recognized in Oregon and has resulted in new legislation that went into effect for the winter 1998 season. A brief review of what led to the Oregon legislation is important. A review of other current western state laws pertaining to studded tires (specifically, in Idaho, California, Utah, and Montana) did not reveal any attempt by these states to define and mandate the use of lighter weight studs.

In 1995, Oregon passed legislation that limited stud weight to no more than 1.5 g. This was accomplished in Oregon Revised Statutes, Chapter 815, "Vehicle Equipment Generally," Paragraph 815.167. The revised paragraph read as follows:

"815.167 Prohibition on selling studs other than lightweight studs.

- A tire dealer may not sell a tire equipped with studs that are not lightweight studs.
- A tire dealer may not sell a stud other than a lightweight stud for installation in a tire.

  As used in this section:

- 'Lightweight stud' means a stud that weighs no more than 1.5 grams and that is intended for installation and use in a vehicle tire; and
- 'Tire dealer' means a person engaged in a business, trade, occupation, activity or enterprise that sells, transfers, exchanges or barters tires or tire related products for consideration."

This law took effect on November 1, 1996, thus requiring these lighter studs for the winter of 1996-1997.

Two problems arose with the new stud definition. First, it did not recognize that different stud weights are required for different tire sizes. Second, the studs that were used in Oregon in winter 1996-1997 that met this definition of "lightweight" did not perform well. Why this occurred is unclear.

In response to the stud performance problems, the Oregon legislature enacted a revised law that was signed by the governor in August 1997. The new law contains two revisions that merit review. First, Paragraph 815.165 amends the allowable usage dates for studded tires. The revised law reduces the allowable usage period by one month (the former period, November 1 to April 30, was changed to November 1 to April 1). Second, Paragraph 815.167 Subparagraph 3(a) was amended to read as follows:

"(3) As used in this section:

‘Lightweight stud’ means a stud that is recommended by the manufacturer of the tire for the type and size of the tire and that:

- Weighs no more than 1.5 grams if the stud is size 14 or less;
- Weighs no more than 2.3 grams if the stud size is 15 or 16; or
- Weighs no more that 3.0 grams if the stud size is 17 or larger.”

PROPOSED WASHINGTON STATE LAW REVISION

The proposed WSDOT definition of “lightweight stud” is shown below and was patterned after the Oregon 1997 definition. However, a modest clarification regarding stud size was added.

In the United States, studs are sized according to the Tire Stud Manufacturing Institute (TSMI). Although this institute no longer exists, its sizing scheme is still used by tire dealers across the United States. To illustrate, a TSMI No. 12 stud means that the stud hole in the tire tread is 12/32’s of an inch deep (or 9.525 mm). Similarly, a TSMI No. 17 stud would fit into a stud hole 17/32’s of an inch deep.

WSDOT proposed that a new section added to Title 46 RCW “Motor Vehicles,” Chapter 46.04, “Definitions,” read as follows:

“’Lightweight stud’ means a stud intended for installation and use in a vehicle tire. As used in this Section, this means a stud that is recommended by the manufacturer of the tire for the type and size of the tire and that:

- Weighs no more than 1.5 grams if the stud conforms to (Tire Stud Manufacturing Institute) TSMI Stud Size 14 or less;
- Weighs no more than 2.3 grams if the stud conforms to TSMI Stud Size 15 or 16; or
- Weighs no more than 3.0 grams if the stud conforms to TSMI Stud Size 17 or larger.

A lightweight stud may contain any materials necessary to achieve the lighter weight.”

The use of TSMI designations clarifies for stud installers the allowable weight of a stud for a given size of stud. The size of the stud is essentially dictated by the tire manufacturers, since they create the holes in the tread rubber for installing the studs.

1999 WASHINGTON STATE LAW REVISION

The proposed revisions did not pass during the 1997-1998 legislative session. However, in April 1999, a revision to the Revised Code of Washington was passed.

A new section was added to Title 46 RCW "Motor Vehicles," Chapter 46.04, "Definitions," to read as follows:

"(1) 'Lightweight stud' means a stud intended for installation and use in a vehicle tire. As used in this title, this means a stud that is recommended by the manufacturer of the tire for the type and size of the tire and that:

(1) Weighs no more than 1.5 grams if the stud conforms to Tire Stud Manufacturing Institute (TSMI) stud size 14 or less;

(2) Weighs no more than 2.3 grams if the stud conforms to TSMI stud size 15 or 16; or

(3) Weighs no more than 3.0 grams if the stud conforms to TSMI stud size 17 or larger.

A lightweight stud may contain any materials necessary to achieve the lighter weight."

In addition, two new sections were added to Title 46 RCW "Motor Vehicles," Chapter 46.37, "Vehicle lighting and other equipment":

"(2) Beginning January 1, 2000, a person offering to sell to a tire dealer conducting business in the state of Washington, a metal flange or cleat intended for installation as a stud in a vehicle tire shall certify that the studs are lightweight studs as defined in section 1 of this act. Certification must be accomplished by clearly marking the boxes or containers used to ship and store studs with the designation "lightweight." This section does not apply to tires or studs in a wholesaler's existing inventory as of January 1, 2000.

"(3) Beginning July 1, 2001, a person may not sell a studded tire or sell a stud for installation in a tire unless the stud qualifies as a lightweight stud under section 1 of this act."

CONCLUSIONS AND RECOMMENDATIONS

Given the results of this literature review and the revisions to Washington State's law regarding studded tires, the following conclusions and recommendations are made:

- Washington State has a reasonable studded tire use period and at five months is in line with other western states.
- Few states have fully banned studded tires (in fact, only two). It is reasonable to attempt to reduce the pavement wear associated with them; however, the impact of stud-worn pavements on traffic safety has not been assessed in this study.
- Studded tires currently used in Washington state are less damaging to pavement surfaces than those that were available during the 1960s and early 1970s. The evolution of the studded tire clearly reveals this. Nationally available statistics suggest that studded tire wear rates in the 1960s were as much as four to ten times higher than current wear rates for both AC and PCC surfaces, although pavement wear rate statistics tend to be imprecise. However, with today's traffic volumes, studded tire pavement wear is still significant on WSDOT highways.
- The wear experienced by both asphalt concrete and portland cement concrete pavement surfaces in Washington State is generally lower than the rates reported by other states. However, this undoubtedly varies throughout our state because aggregate sources (and associated hardness) vary.
- The change from 55 mph to 70 mph on our rural Interstate highways has potentially increased pavement wear caused by studded tires by a factor of two. The influence that high speed has on studded wear likely explains, in part, the modest studded tire wear noted on slower city streets.

- A modest change in studded tire wear is significant for some pavement types. A 1- to 2-year increase in pavement life due to a reduction in studded tire wear will allow some pavements to achieve their intended structural life.
- Currently available winter tires enhance snow and ice traction (see Appendix B). It is not unreasonable to speculate that these tires will likely reduce studded tire usage.
- WSDOT Class D open graded asphalt mixes are highly susceptible to studded tire wear. These mixes reduce splash and spray caused by water and traffic and provide a high level of surface friction. However, currently WSDOT rarely uses these mixes because of studded tire wear effects.

Considerations for future work include the following:

- Monitor the performance of the newer studless winter tires. Such information could result in further legislative/code revisions.
- Monitor the performance of lighter weight studded tires (less than 1.1 grams) used elsewhere.
- Examine PCC and AC mixes that are more stud-wear resistant. WSDOT paved a stone mastic asphalt (SMA) mixture during the 1999 paving season. That type of mix will be more resistant to stud wear than WSDOT Class A mixes. Experience from Sweden suggests that the wear resistance of SMA mixes can be 40 percent more than conventional, dense graded asphalt concrete mixes (see Appendix A).

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APPENDICES

APPENDIX A
Notable Items from the Scandinavian Tire and Rim Organization 1997 Winter Traffic Conference, Ivalo, Finland

The proceedings for the Winter Traffic Conference (March 18-21, 1997) provide insights that merit notation. These include the following points made by various authors.

Anne Leppanen, "The Road Traffic in Winter Project"

- The grip quality of studded tires, even after 40,000 km of wear, was superior on ice in comparison to studless winter tires. (Note: the definition of a "winter tire" was unclear but probably included a broad range of winter tires than defined in Appendix B.)
- The durability of the best performing lightweight studs (1.1 g) was, in general, about the same as that of conventional weight studs (1.8 g). However, the various stud manufacturers reported significant variation in both stud durability and the ability of studs to remain in tires.
- In Finland 95 percent of all passenger cars were equipped with studded tires during the winter months.
- During the winter, frosty and icy road conditions were found 11 to 13 percent of the time in coastal and central Finland. For northern Finland, those conditions were found 20 percent of the time. Wet road conditions existed about 46 to 49 percent of the time.
- Hard packed snow was worn away twice as fast by studded tires as by conventional tires. For soft packed snow, the wear rates were about the same.
- Fuel consumption (as compared to dry, bare pavement)
  - increased 15 percent for slippery, snowy, and uneven pavements
  - increased 1.2 percent for studded tires in comparison to studless winter tires.

Finn Contact 3/95, Editor: Jarmo Ikonen

- Friction levels of 0.21 to 0.30 can be achieved on snow and ice by sanding. To achieve higher friction levels, salting had to be used. Very slippery road surface conditions were defined as having a friction value of below 0.20.
- A conclusion was drawn that the accident risk of drivers with unstudded winter tires was higher than those with studded tires over a wide range of road surface conditions (again, the precise definition of winter tires was unclear).

Anne Carlsson et al, "Studded Tyres"

- Lightweight studded tires produced, in general, 50 percent less pavement wear on both SMA and dense, graded asphalt concrete. SMA mixes exhibited about 40 percent less wear in comparison to traditional dense, graded asphalt concrete (as based on SPS Index values).
- Japanese studies were quoted that showed a relationship between studded tire pavement wear and particle content in the air and the lungs of humans and animals.
- Norwegian studies were quoted that have shown that inhalable particles can reach three times the recommended limit.

Antero Juopperi, "Prohibition of Studded Winter Tyres in Japan"

- In Hokkaido and northern Honshu, studded tire use was essentially 100 percent by the early 1970s.
- During the 1970s and 1980s, studded tire regulations attempted to reduce usage in order to decrease suspended particulate matter.
- Currently, studded tire use is close to zero. This was achieved by 1992-1993.
- The consequences of banning studded tires included the following:
  - Suspended particulate matter (mg/m^3) decreased as studded tire use decreased.
  - Pavement surface abrasion was reduced from 6 mm (0.24 in.) per year to 1 mm (0.04 in.) per year.

- Following the studded tire ban, winter accident rates increased significantly.
- The elimination of studded tires resulted in slippery snow surface conditions. Studded tires help to break up the crust of ice that forms on top of snow compacted by vehicles.

Halvard Nilsson, "Winter Tyres in Scandinavia"

- Bias belted tires of the 1960s contributed to excessive studded tire pavement wear.
- By 1989, the use of radial tires, reduced stud protrusion, the fewer number of studs on a tire, and improved pavement surfaces all led to a significant reduction in pavement wear.
- Finnish studies have shown that studded tires reduce fatal accidents by 48 percent on ice and snow and by 20 percent over the whole winter period.
- The optimum protrusion of a stud above the tire surface is about 1.0 to 1.5 mm. If it is less than 1.0 mm, the effect of the stud on the ice is too small; above 1.5 mm, the forces on the stud are too high, causing excessive pavement wear.
- "Although many new tyre types have been introduced, no tyre has been able to match the effect of studs on ice."
- "Many inventors have tried to find new ideas for studs, in particular studs with a low force against the road surface. These solutions usually incorporate moving parts, but experience has shown that these are expensive and durability is often insufficient."

APPENDIX B
New Technology Winter Tires

The M&S designation on many (if not most) passenger car tires implies that the tire has a tread design that is beneficial in mud and snow conditions. However, a new type of tire—termed a “winter tire”—has come on the scene. These winter tires have tread composed of special rubber compounds and tread designs that enhance their performance in snow and ice conditions. To recognize this new family of tires, the Rubber Manufacturers Association will be implementing a new tire designation for them (other than M&S).

Numerous winter tires are available from various tire manufacturers, such as Firestone, Michelin, Pirelli, and others. An example of these winter tires is the Bridgstone Blizzak (<http://www.bsfs_usa.com/tech/apps/blizzak.htm>). This tire was developed in Japan following the banning of studded tires there. It was first introduced into the U.S. market in 1993. The following describes how the tire works:

> The Blizzak ice and snow tire features a patented tread rubber compound which was developed to deliver ice and snow performance without the use of studs. The Blizzak was the first tire designed using a multicell tread compound with millions of microscopic pores that help stick to ice by removing the thin layer of surface water that can allow a car to slide. In winter, when a surface of ice or snow comes under pressure from a tire, a film of water is created. It is this film of water that causes icy roads to be slippery. As this water deepens, the tire's grip decreases making slippage more likely.
>
> The Multicell compound contains millions of microscopic pores. It is these pores which cut through and disperse water away from the tire and icy road surfaces. The result; the tread contact area is increased and greater grip is achieved. The microscopic pores on the tread surface not only help eliminate the film of water, but also create the "edge effect." The result: each edge of the pores bites the road surface creating greater driving and braking forces.
>
> Throughout the life of the Multicell compound, new microscopic pores are continuously exposed on the tread surface. This helps ensure water dispersion and greater grip on ice throughout the life of the Multicell compound.
>
> Exclusive Tracpoint sipes provide thousands of edges to help bite through snow, as well as help improve traction on icy roads. Lateral edges provide

excellent grip when accelerating and braking, while lengthwise edges help prevent sideways slippage.

Blizzaks on all wheels - Due to the revolutionary traction capabilities of the Blizzak, Bridgestone recommends using Blizzaks only in sets of four to provide the best handling characteristics and tire performance.

—(from <http://www.tirerack.com/tires/bridgestone/bs_blizz.htm>)

This new family of winter tires certainly has both advantages (good snow and ice performance, no studs) and disadvantages (cost, high tread wear rates, speed restrictions). It is not unreasonable to speculate that these studless winter tires will eventually reduce studded tire usage rages.