Studded Tire Wear on Portland Cement Concrete Pavement in the Washington State Department of Transportation Route Network

WA-RD 744.3

Alisa Cotter
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June 2010

Washington State
Department of Transportation
Office of Research & Library Services

WSDOT Research Report

Research Report
Agreement T2695, Task 88
PCCP Best Practices

Studded Tire Wear on Portland Cement Concrete Pavement in the Washington State Department of Transportation Route Network

by

Alisa Cotter	Stephen T. Muench
Graduate Assistant	Assistant Professor

Department of Civil and Environmental Engineering
University of Washington, Box 352700
Seattle, Washington 98195

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Prepared for
Washington State Department of Transportation
Paula J. Hammond, Secretary

and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

June 2010

1. REPORT NO. WA-RD 744.3	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE STUDDED TIRE WEAR ON PORTLAND CEMENT CONCRETE PAVEMENT IN THE WASHINGTON STATE DEPARTMENT OF TRANSPORTATION ROUTE NETWORK		5. REPORT DATE June 2010 6. PERFORMING ORGANIZATION CODE
7. AUTHORS Alisa Cotter and Stephen T. Muench		8. PERFORMING ORGANIZATION CODE
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center University of Washington, Box 354802 University District Building, 1107 NE 45th Street, Suite 535 Seattle, Washington 98105		10. WORK UNIT NO. 11. CONTRACT OR GRANT NUMBER T2695-88
12. SPONSORING AGENCY NAME AND ADDRESS Research Office Washington State Department of Transportation Transportation Building, MS 47372 Olympia, Washington 98504-7372 Project Manager: Kim Willoughby, 360-705-7978		13. TYPE OF REPORT AND PERIOD COVERED Research Report 14. SPONSORING AGENCY CODE
15. SUPPLIMENTARY NOTES		

16. ABSTRACT

Studded tires are legal in Washington State and are typically allowed to be used each winter between the months of November and April. They are known to cause accelerated wheelpath wear resulting in additional pavement preservation costs. While studded tire use rates are hard to quantify, the volume of studded tire equipped vehicles is rather consistent across Washington State. This report uses Washington State Pavement Management System (WSPMS) data to explore studded tire wear on Washington State Department of Transportation (WSDOT) roads. The average Portland Cement Concrete (PCC) pavement wears at about 0.01 inches per 1 million studded tire vehicle passes. The highest wear rates are near 0.5 mm/yr on I-90 in the Spokane area, while the lowest wear rates are in the range of 0.04-0.09 mm/yr in many locations. Stud wear rates are generally higher in the first 5 years of PCC pavement life and much less thereafter. While excessive stud wear problems are limited and not a widespread issue, specific locations with high stud wear rates are alarming. While several strategies have been attempted to limit stud wear, none outside of diamond grinding has proven effective. There are a few new materials (resin modified pavements, PCC surface texture techniques) that may yet prove effective. Tests to determine the susceptibility of aggregate sources to stud wear are generally not reliable, however the Micro-Deval seems to be the most favorably rated. The WSDOT current practice of designing in an extra inch of pavement to account for future thickness loss associated with diamond grinding is sound policy and should be continued. As more PCC pavement in Washington State is due for replacement, WSDOT should consider a hardness specification program like Alaska's in order to prevent the use of susceptible aggregate sources.

17. KEY WORDS Concrete, pavement, portland cement, studded tire, wear, rutting, surface characteristics			18. DISTRIBUTION STATEMENT
19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

1 INTRODUCTION

Studded tire use has been legal in Washington State since 1969 and has been limited to a 5-month winter period between 1 November and 31 March since 1972 (although specific weather conditions can be cause for extending this season). Generally, studded tires are thought to improve traction on compact snow and ice, while some research suggests they may be somewhat less safe on bare pavement due to a reduced coefficient of friction between tire and pavement. Studded tires have a marked effect on pavement condition: they tend to wear away the pavement surface in the wheelpath and create depressions that can be safety issues because of an increased potential for hydroplaning and unwanted/unanticipated steering feedback. Also, the worn wheelpath surfaces tend to increase tire-pavement noise. Oregon and Alaska have attempted to monetize the adverse impact of studded tire wear on pavements and have found costs in the \$8 to \$9 million range per year (Malik 2000; Zubeck et al. 2004).

Early investigation into design issues for the next generation of portland cement concrete (PCC) pavement in Washington State identified studded tire wear as an unresolved issue that could prevent desired pavement design lives of 50 years or more. While many other pavement design issues have been addressed, no solution to studded tire wear for PCC pavements has been developed.

This study examines the impact of studded tire use on Washington State Department of Transportation (WSDOT) PCC pavements on a meta-scale (across the entire pavement network) and assesses available techniques for (1) studded tire wear mitigation and (2) tests to indicate a pavement’s potential resistance to studded tire wear. First, a background literature review describes studded tire use, their effects on pavement and related financial implications. Next, studded tire wear is analyzed from Washington State Pavement Management System (WSPMS) data in order to determine typical values, trends and identify outliers. After this, a literature review discusses (1) means of mitigating studded tire wear and (2) testing methods to identify susceptible materials and pavements. Importantly, the WSPMS data reviewed may contain individual inaccuracies and errors, however it can still provide a broad view of the extent of studded tire damage to PCC pavements and perhaps identify any existing widespread trends.

2 BACKGROUND

Studded tires are tires that contain small, usually metal, protrusions that are used to provide better traction on glare ice and hard packed snow. Studs, which are now made from carbide steel, are comprised of a pin that protrudes from the tire to make contact with the pavement, and the outer jacket that surrounds the pin and holds it in the tire by a flange at the base (Angerinos 1999) (Figure 1). This section briefly reviews studded tire use including their effects on safety and pavement condition.

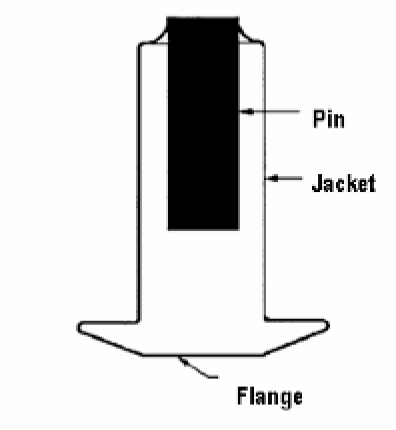


Figure 1: A typical stud.

2.1 Effects on Driving Safety

Studded tires are thought to improve driving safety by improving vehicle braking, traction and cornering performance on icy surfaces. While most departments of transportation across the country, including Washington State, agree that on untreated icy roads, at or near freezing, studs aid in stopping (WSDOT 2007); however these types of conditions occur less than 1% of the time in Washington State (WSDOT 2007).

Additionally, this improved handling can be offset by a slight increase in driving speed (Malik 2000), which may be likely, and in wet conditions studs can detract from stopping ability because the stud reduces contact between the rubber tire and the pavement (WSDOT 2007).

2.2 Effects on Pavement

The relationship between studded tires and pavement wear is well-established (Zubeck et al. 2004; Angerinos 1999; Malik 2000). Studded tires abrade all types of pavement leading to:

- **Wheelpath depressions**. These can lead to two safety issues:
    - *Potential for hydroplaning*. As wheelpath depressions deepen, they are apt to collect water. As the water depth in these depressions increases, the potential for a high-speed vehicle to hydroplane on this water and lose positive steering control increases.
    - *Unwanted/unanticipated steering feedback*. Wheelpath depressions tend to guide vehicle wheels in the direction of the depression causing unwanted or unanticipated steering feedback.
- **Increased tire-pavement noise**. Because of relatively hard local aggregates in Washington State, the mastic or paste between aggregate wears at a greater rate than the aggregate itself leaving a matrix of raised aggregate over which the tire travels. Especially on PCC pavements, the tire-pavement noise on this aggregate matrix is significantly louder than would otherwise occur on a PCC pavement surface.

Many factors of stud use affect this wear such as protrusion and weight of the stud, and volume and driving speed of the vehicle (Angerinos 1999). The resulting wheelpath depressions caused by studded tire wear are typically identified as “rutting” in pavement surveys. Because plastic flow rutting essentially does not occur in PCC pavements due to PCC’s high stiffness over a range of temperatures, these “rutting” observations for PCC pavements are generally attributed to stud wear (WSDOT 2003). Current estimates suggest that in Washington State 100% of damage classified as “rutting” on PCC pavements is due to studded tires and 60% of damage classified as “rutting” on HMA pavements is due to studded tires (WSDOT 2007). A common early indicator of stud wear on PCC is the disappearance of surface texture (usually constructed by tining or carpet drag) (Figure 2).

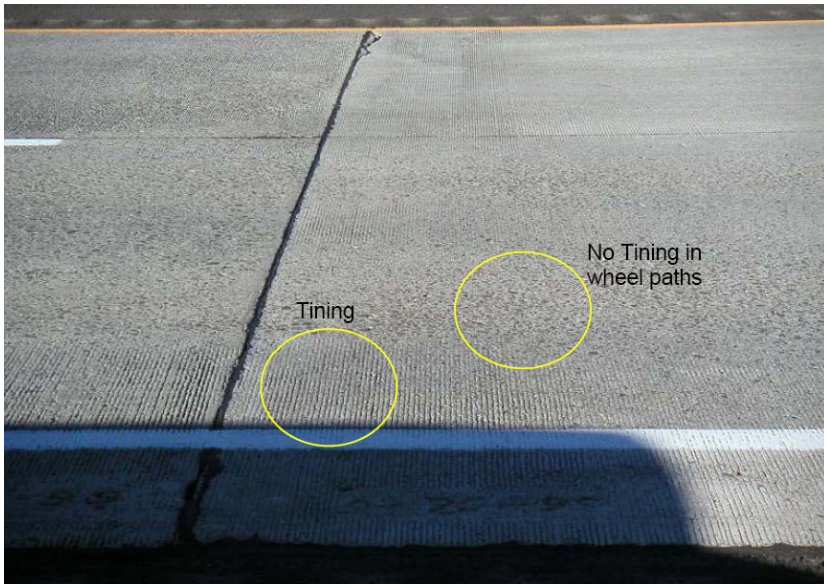


Figure 2: Early stud wear on 8 year old PCC pavement on SR 395 near Ritzville, WA (WSDOT 2006).

2.3 Financial Implications

Stud use has financial implications in both driving safety and pavement wear. As pointed out by Zubeck et al. (2004) some countries such as Finland and Japan have concluded that prohibiting studs produces a net increase in total costs due to increased accident costs. Other studies (Malik 2000; Zubeck et al. 2004) have concentrated on the pavement preservation costs of stud wear. These studies typically make estimations on stud usage rate, potential repair costs, repair strategies and vehicle operating costs and then calculate a cost based on these estimates. Malik's (2000) Oregon study concluded stud wear cost the Oregon Department of Transportation (ODOT) $103 million from 1995 to 2005 or about $9 million/year. Zubeck et al. (2004) found stud wear to cost the Alaska Department of Transportation (less overall traffic than Oregon but higher stud usage) $8.3 million/year, which equates to $2,671 per year per lane-mile.

2.4 Stud Use in the U.S.

Legalized stud usage varies throughout the U.S. and the world. Generally their use is justified on safety concerns and their prohibition is justified based on pavement preservation costs. Currently seven states allow stud use with no restrictions, eight states ban any usage, while the remaining 37 states allow restricted date usage and some also require lightweight studs (WSDOT 2006) (Figures 3 and 4). As defined by the Revised Code of Washington (RCW 46.04.272), a lightweight stud is:

> "…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:
>
> a) Weighs no more than 1.5 grams if the stud conforms to Tire Stud Manufacturing Institute (TSMI) stud size 14 or less;
>
> b) Weighs no more than 2.3 grams if the stud conforms to TSMI stud size 15 or 16; or

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

Interestingly, Minnesota, Michigan, Wisconsin and Illinois are all states that experience substantial winter weather yet they have all chosen to ban studded tire use.

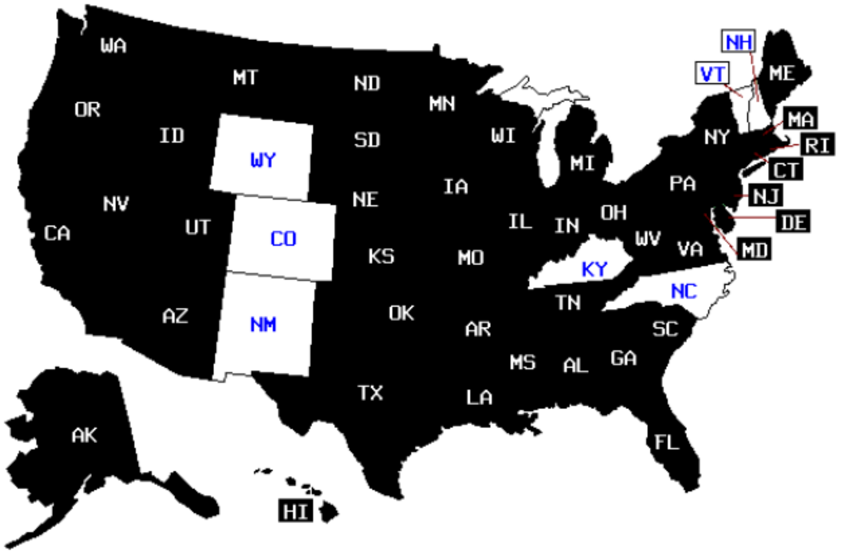


Figure 3: States with no stud restrictions (shown in white)

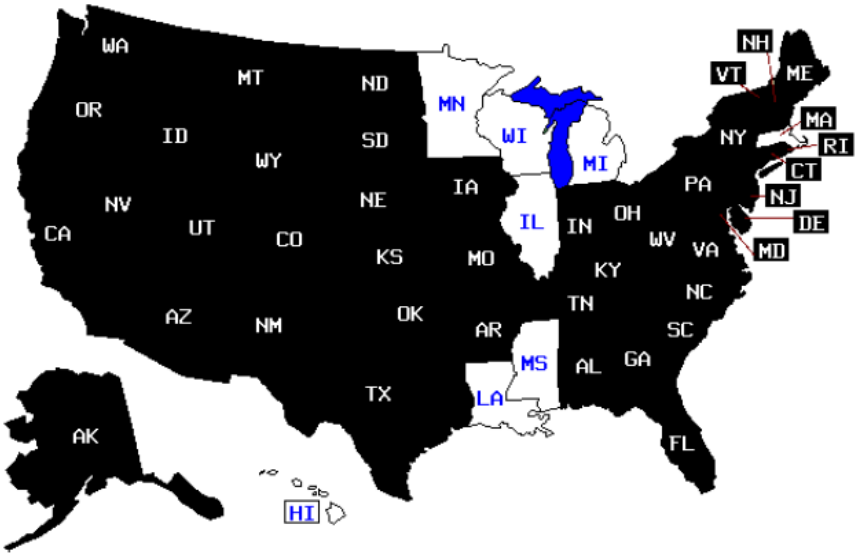


Figure 4: States that ban tire studs (shown in white)

2.5 Studded Tires in Washington

This section provides a brief summary of studded tire use in Washington State based on two WSDOT reports:

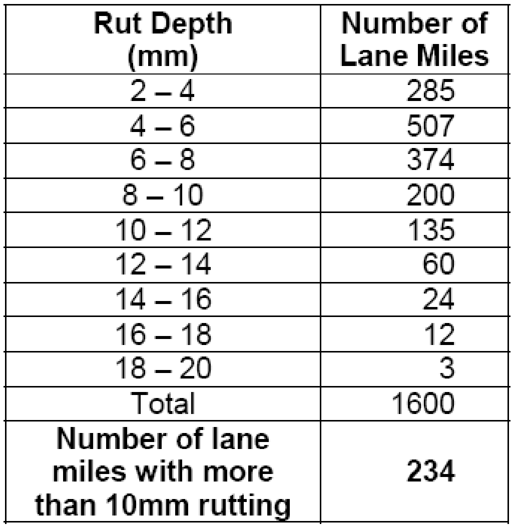
- WSDOT 2003. *Studded Tire Use in Washington State*. Washington State Department of Transportation.
- WSDOT 2006. *Pavements and Studded Tire Damage*. Washington State Department of Transportation.

Beginnings. Studded tires have been legal in Washington since 1969 and by 1972 sufficient research supported the notion of limiting the usage season to a five month period between November 1st and March 31st (WSDOT 2003).

Usage. Over time several usage rate estimates have been made. Most recently, a 1996-1997 WSDOT study estimated that the approximate studded tire usage rate in western Washington is 10% while in eastern Washington is around 32% (WSDOT 2003). A 1984 estimate showed usage was at 8% in the west and 25% in the east, which is quite similar based on the uncertainty involved in these estimates. It is also important to note that as of 2003, the number of studded tires sold was 50% lower than the number sold six years earlier in 1997, thus leading to the notion that new usage may continue to decline (WSDOT 2006). The usage rates from the 1996-1997 study are used in this report when making estimates of studded tire traffic since they are the most recent.

Impact on Pavement Condition. In 2003 WSDOT estimated that in general studded tires wear causes about a 4 year life reduction on PCC pavements with roughly a $10 million annual cost linked to this wear (WSDOT 2003). As of 2006 approximately 234 lane miles of PCC pavement were beyond the threshold for repair based on rut depth criteria (> 10 mm) with an estimated repair cost of over $18 million (WSDOT 2006). Table 1 summarizes this 2006 effort.

Table 1: Summary of Concrete Pavement Damage as of 2004 (WSDOT 2006)



Rut Depth (mm)	Number of Lane Miles
2 – 4	285
4 – 6	507
6 – 8	374
8 – 10	200
10 – 12	135
12 – 14	60
14 – 16	24
16 – 18	12
18 – 20	3
Total	1600
Number of lane miles with more than 10mm rutting	**234**

Experimental Projects. WSDOT has attempted a number of different design and construction techniques to reduce studded tire wear (Anderson et al. 2007) (Table 2). Results generally do not show any of the investigated options as being viable stud wear mitigation techniques.

Table 2: WSDOT Experimental Feature Projects (Anderson et al., 2007)

Experimental Feature	Location
Combined Aggregate Gradation for PCCP	I-90, Sprague Ave I/C Phase III, Contract 5947
Ultra-Thin Whitetopping/Thin Whitetopping	I-90, Sullivan Road to Idaho State Line, Contract 6582
PCCP Features (Carpet Drag, Flexural Strength, and Surface Smoothness) Use of Hard-Cem in Concrete Pavements	I-90, Argonne Road to Sullivan Road, Contract 6620

PCCP Features (Carpet Drag and Noise Mitigation)	I-5, Federal Way to S. 317th Street HOV Direct Access, Contract 6757
Use of Higher Slag and Cement Content in Concrete Pavements	SR 543, I-5 to International Boundary Widening
PCCP Features (Longitudinal Tining, Carpet Drag and Noise Mitigation)	I-5, Pierce Co. Line to Tukwila I/C - Stage 4, Contract 6883

3 WASHINGTON PCC PAVEMENT DATA ANALYSIS

This section examines the current status of Washington State PCC pavements using Washington State Pavement Management System (WSPMS) data from 2004. The purpose of this analysis is to identify stud wear trends and identify good/poor performing PCC pavements for further investigation.

3.1 Purpose

The general purpose of this data analysis is to describe the impact of studded tire use in Washington State on PCC pavements in terms of wear depth and wear rate. Specific investigative goals are to:

1. Determine any broad geographic trends.
2. Characterize the typical progression of studded tire wear over time.
3. Develop rules-of-thumb for typical studded tire wear rates.
4. Examine extreme cases (both good and bad) of studded tire wear in an attempt to characterize their possible causes.

3.2 Method

2004 WSPMS data was used to correlate PCC pavement wear depth with a number of factors including age, studded tire traffic and location. Specific methods used for obtaining the data used in this section follow.

3.2.1 Pavement Wear Depth

This comes directly from the recorded Pavement Rutting Condition (PRC) number recorded in WSPMS. PRC is based on the depth of maximum depression in the wheelpath. The range of values is from 100 (a flat surface) to 0 (representing 18 mm of rutting). The WSPMS trigger value for rehabilitation is a PRC of 50 corresponding to a rut depth of 10 mm (0.4 inches). A PRC value of 80 (3.5 mm) is used in this study to indicate a pavement that has significant studded tire wear.

3.2.2 Pavement Wear Rate

The pavement wear rate was calculated by taking the 2004 WSPMS recorded pavement rut depth (calculated from PRC) and dividing by the pavement surface age. Importantly, this gives an overall wear rate but does not indicate how wear progresses over time. A value of 0.50 mm/year is taken to indicate excessive wear because such a rate would result in a PRC value of 50, the WSPMS trigger value for rehabilitation, in 20 years. Even without studded tire wear it would be common to schedule a diamond grind at the 20-year point to restore smoothness. Therefore, wear rates in excess of 0.5 mm/year are likely to result in early PCC surface treatment to correct for stud wear. A value of 0.1 mm/year is taken to indicate exceptionally low wear rates because such a rate would result in a PRC value of 50 in 100 years, which is twice as long as WSDOT's current 50-year design life policy for PCC pavements.

3.2.3 Studded Tire Traffic

Traffic values recorded in WSPMS are modified by a factor that accounts for studded tire use rates and the allowable studded tire use season (usually November 1st through April 1st; about 5 months). While measures of studded tire use vary, this study assumes a use rate of 10% for western Washington roadways and 32% for eastern Washington roadways as this is the most recent Washington State data available. Although stud use in particular areas of Washington likely varies, these percentages are considered constant throughout their respective areas for the purposes of this analysis. This results in the following equation for studded tire traffic:

$$\text{studded tire traffic} = \text{WSPMS AADT} \times (\text{usage percentage}) \times \frac{5\text{ months}}{12\text{ months}}$$

While this equation provides a studded tire ADT estimate, it does not measure the total number of passes by studded tire vehicles over the life of the pavement, a number that cannot be accurately determined with existing data. However, areas with historically higher overall traffic (and by this analysis' assumption, more stud traffic) are apt to have higher current ADTs. Therefore, current stud ADT combined with pavement age can be considered a reasonable proxy for overall lifetime stud traffic on a particular pavement.

Amount of pavement analyzed. Currently, WSDOT maintains over 2,000 lane-miles of PCC pavement. Only the following major highway routes were analyzed: I-5, I-82, I-90, I-182, I-205, I-405, SR 195, SR 395 and SR 41. This leaves 798 lane-miles for analysis (Figure 5).

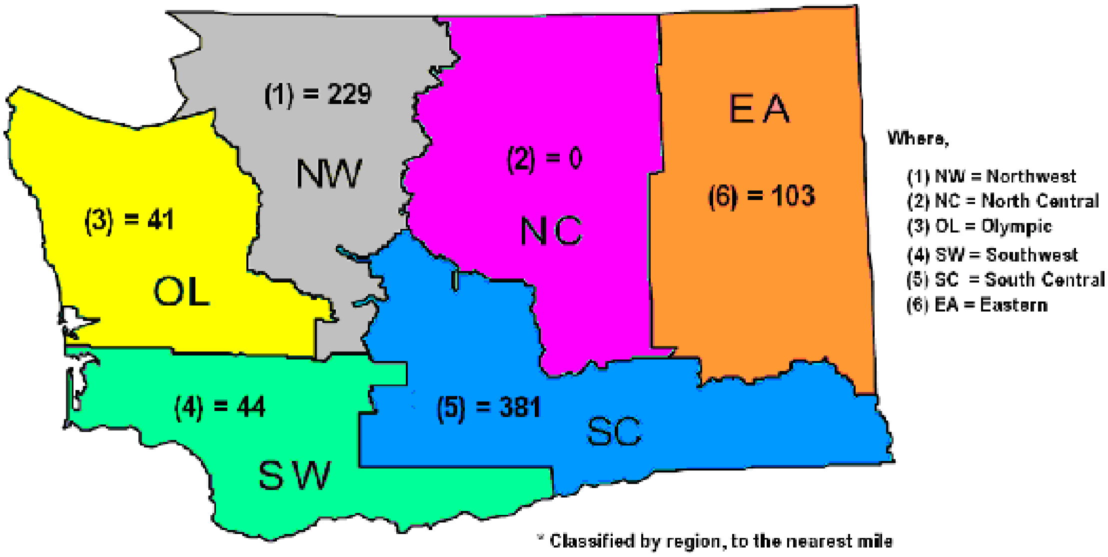


Figure 5: Analyzed lane miles of PCC.

3.2.4 Discrete Units of Pavement

The smallest discrete unit of pavement used is this analysis is the “analysis unit”, defined by WSPMS as the smallest units of pavement sharing similar properties such as width, pavement type, traffic, last construction date, region, etc. Analysis units vary in length from 0.1 mile to about 20 miles with a typical length being about 0.5-2 miles. Conversion of pavement quantities from analysis units to lane-miles is done by multiplying the analysis unit by the number of lanes it has and its length.

3.2.5 Cautions on Interpretation

Results of this analysis should be interpreted with caution based on the following significant limitations:

- **WSPMS typically measures pavement condition on only one lane of multi-lane highways**. This presents a problem because this lane is usually the predominant truck lane while the highest stud traffic is usually expected on other lanes based on their higher automobile usage. Exacerbating this, most PCC pavement resides in high-traffic multi-lane highways. Therefore, actual wear depths for the worst-condition lane are often not recorded in WSPMS since this worse-condition lane may not be the truck lane.

- **Traffic values are for the roadway as a whole and not per lane**. WSDOT traffic information is either for both directions (undivided highways) or for one direction (divided highways). In both cases traffic numbers are not broken down by lane. On multi-lane highways (where most PCC pavement resides) traffic counts on a per-lane basis are not reported and therefore not used in this analysis. This combined with the first caution on condition reporting results in the somewhat odd combination of measuring condition in only one lane but measuring traffic only for all lanes.
- **Long histories of wear depths on individual pavements are not available**. This happens for two reasons. First, WSDOT switched measurement instruments in 2004 although INO wear depths were not reported in WSPMS until 2009. Correlations of readings from the old 3-laser system to the current INO Laser Rut Measurement System (LRMS) have been attempted but are generally unreliable. Second, rut measurements are not readily available prior to the mid to late 1990s. For older PCC pavements, most studded tire wear would have already occurred by then.
- **WSPMS is not entirely accurate**. Best estimates (Kay et al. 1993) place WSPMS accuracy at about 90%. This is considered quite good by pavement management system standards. Also, wear depths as measured by WSPMS can be different that those measured manually in the field.

- **WSPMS does not track traffic over time**. This means that past studded tire wear rates can only be grossly estimated by knowing current traffic levels and pavement age. Test section evidence on SR 395 near Ritzville (Muench et al. 2006) suggests that stud wear may happen early on and then stabilize out at a much lower rate once the PCC paste is worn away and traffic mainly travels on the remaining PCC aggregate.
- **Studded tire usage is not accurately known**. Usage numbers only come from a few simple visual surveys and can be considered gross estimates at best. However, it is reassuring that different estimates in Washington State (1984, 1996-7) and Oregon (2000) have come up with similar numbers. This section assumes studded tire usage is 10% in western Washington (west of the Cascade Mountains) and 32% in eastern Washington (east of the Cascade Mountains).

3.3 Current Wear Conditions

Figure 6 shows the overall 2004 wear condition. From this graph it is clear that the Eastern (EA), Northwest (NW) and South Central (SC) regions have significant amounts of PCC with significant wear depth.

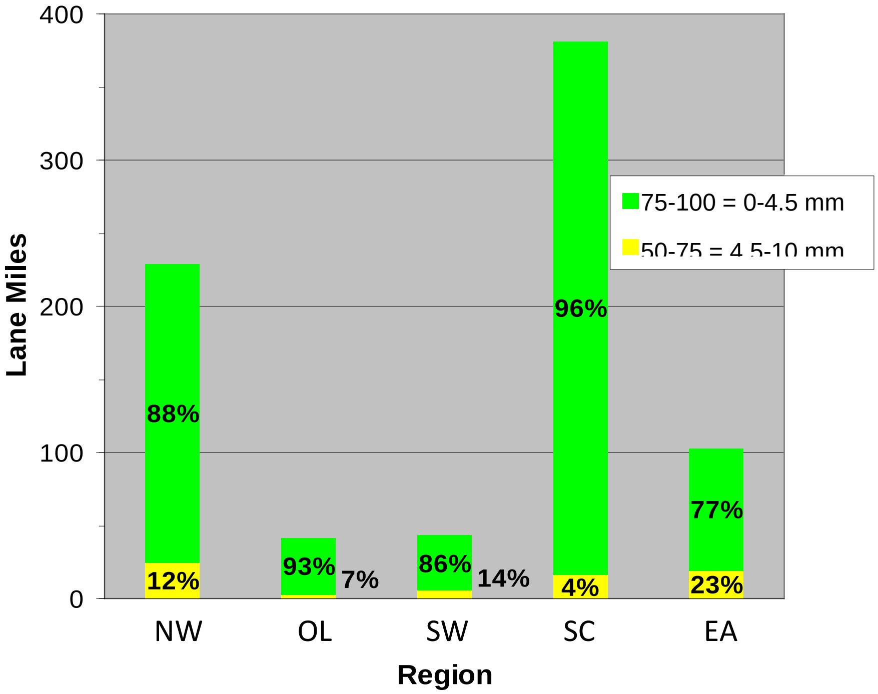


Figure 6: Current PRC by region.

3.3.1 Pavement Condition with Respect to Stud Volumes

Traffic volumes fluctuate significantly within each region, which impacts pavement condition. Figure 7 shows ADT per region (note that ADT implies this is an average over the whole region) with standard deviation of each shown also in parentheses. The ADT for each region was generated by taking the ADT per each analysis unit, and weighting it by the length of the unit. While it may appear surprising that the Northwest region (NW) does not have the highest ADT, it should be noted that the Olympic region (OL), has only 41 miles of PCC, much of which is on the highly trafficked I-5.

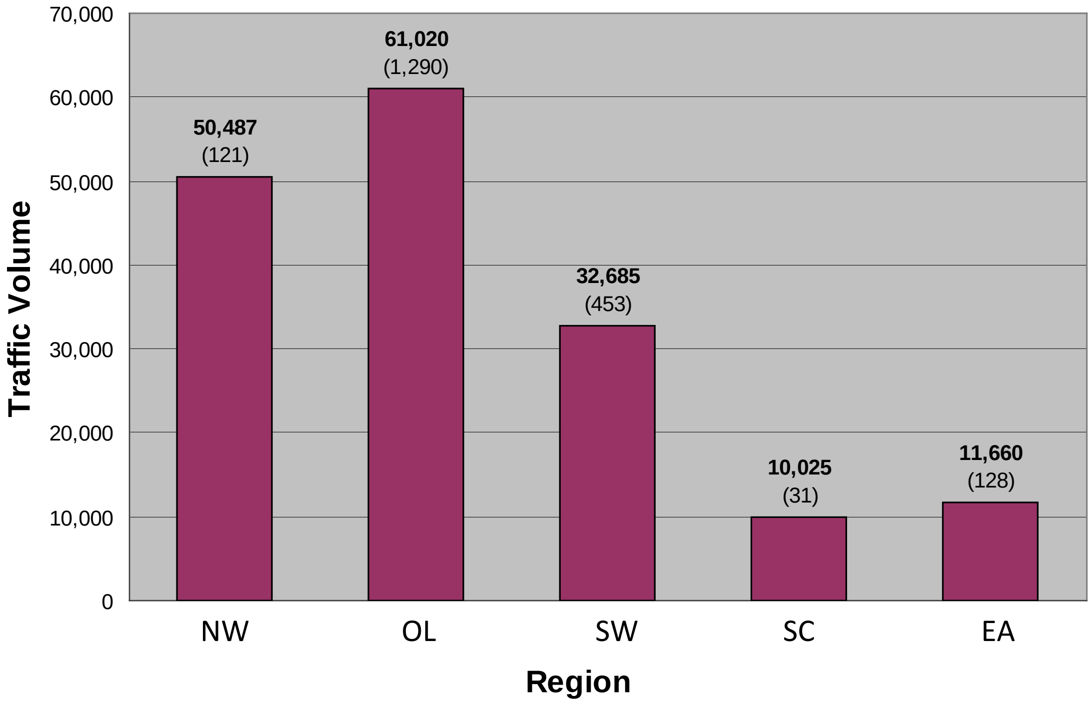


Figure 7: Average annual daily traffic (AADT) per region.

Figure 8 shows stud traffic in Washington State broken down into Eastern and Western areas (Western = Olympic, Northwest and Southwest regions, Eastern = Eastern and South Central). Overall, while stud use is much more common in eastern Washington the higher traffic volumes in the west side actually produce more studded vehicles per day. Given the gross estimates used to obtain these numbers, the stud ADT's for western and eastern Washington should be viewed as essentially equivalent. Also, while these numbers are yearly averages, it should be recognized that on any given day in the winter stud season these stud ADT's will be about double the values shown, and likewise in the summer months there should be no stud traffic.

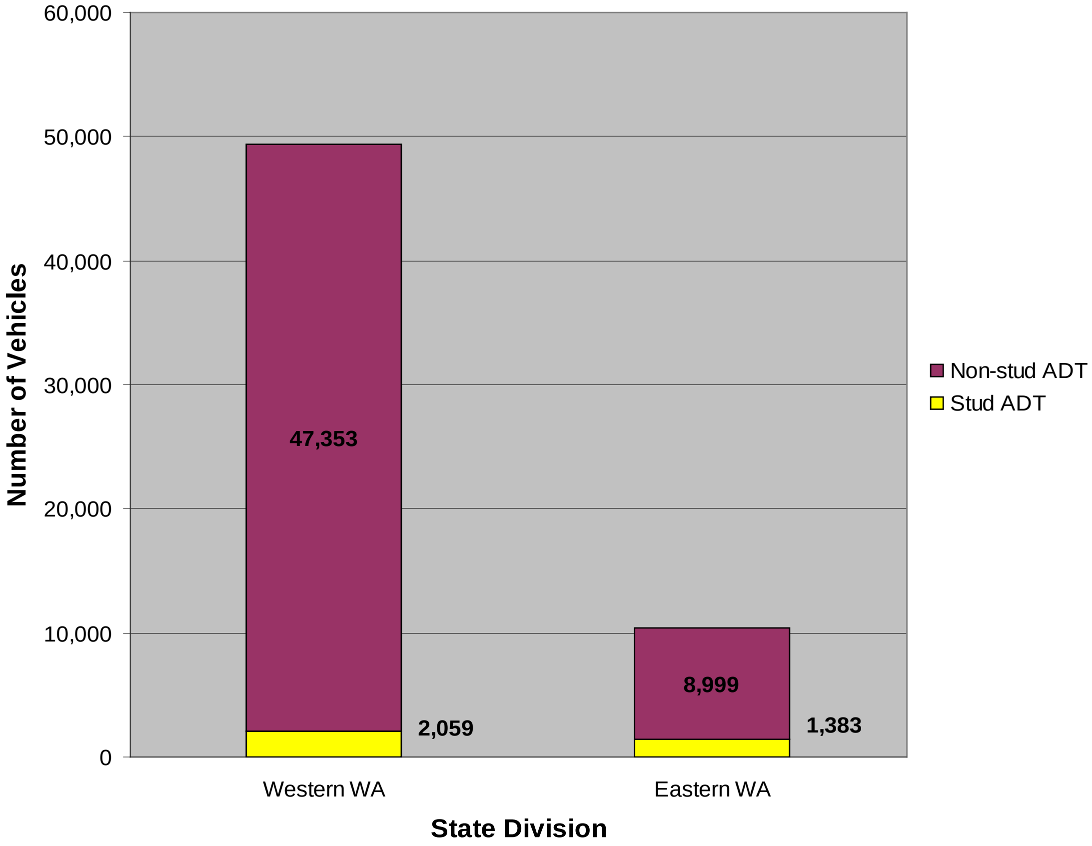


Figure 8: Average traffic levels in western Washington and eastern Washington showing non-stud ADT (top) and stud ADT (bottom).

Figure 9 shows stud ADT vs. PRC for each analysis unit. While Figure 9 shows the highest concentration of high-performance pavements are located where stud volumes are lower, there are many exceptions.

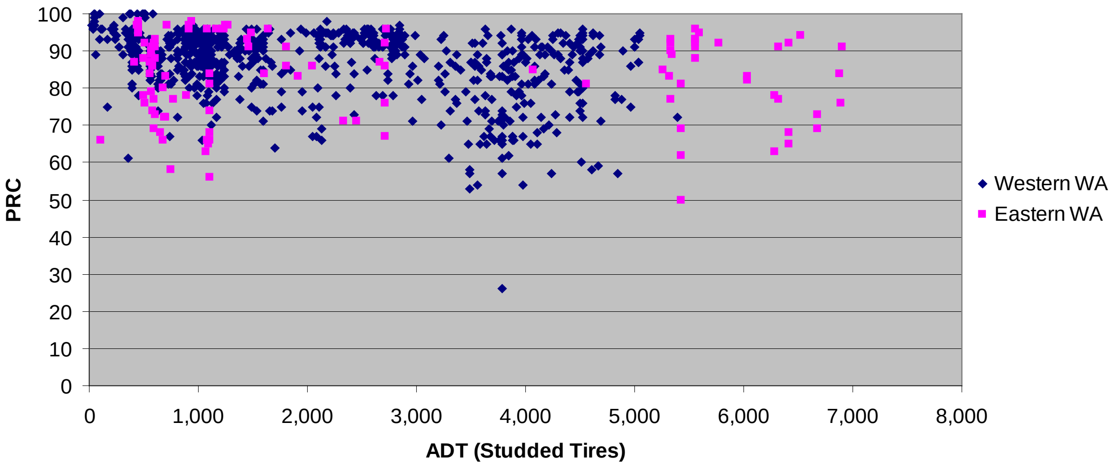


Figure 9: PRC vs. stud ADT.

3.4 Western Washington Studded Tire Wear

This section examines studded tire wear in Western Washington on major state routes. This grouping by major state route excludes small isolated sections of PCCP but is still representative of overall performance as a majority of WSDOT PCCP can be found on these major routes. All data examined are for pavements constructed after 1955 since there is an insignificant amount of data for pavements with construction completed prior to this time. PRC values are first explored with relation to stud traffic, age and wear rates. Sections with high and low PRC's and high and low wear rates are analyzed with respect to the construction and rehabilitation practices associated with these performances.

3.4.1 PRC in Relation to Stud Traffic

Figure 10 shows pavement performance for each state route with respect to stud volume. These data points are based roughly on project units.

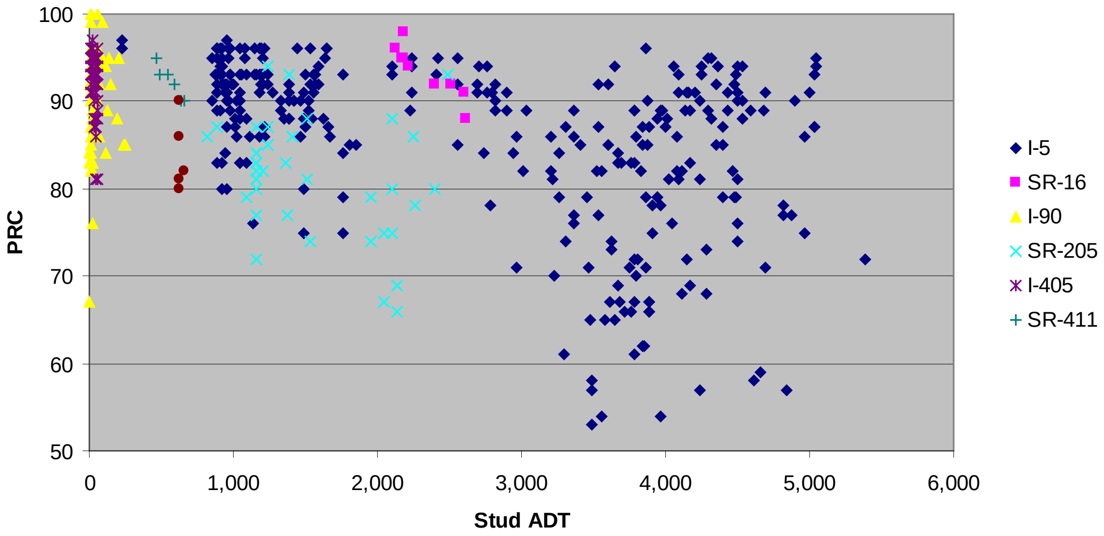


Figure 10: Distribution of PRC vs. stud ADT by western highway.

Figure 10 shows a concentration of sections with both lower stud ADT and high PRC scores. The majority of sections that fall below the PRC rating of 80 (the threshold in this study) have higher stud volumes. Some of the low scoring and high scoring sections are further analyzed in the following sections.

3.4.1.1 Analysis of Low Scoring PRC Sections Relative to Stud Traffic

Analysis units for each state route in Figure 10 were grouped into longer continuous sections of roadway with similar surface, traffic, and stud wear characteristics (similar to but not identical to project units). Table 3 shows all sections with low average PRCs. These sections also have higher than average stud traffic. I-5 sections are all original pavements 36-42 years old (at the time of 2004 measurement) that have not been rehabilitated. Given their age the actual rate of PRC loss averaged on a per year basis is rather small (less than one point per year). The SR-205 section was constructed in 1977 and was 27 years old at the time of measurement. This data suggests that the pavement surfaces with the most significant stud wear are generally old (> 27 years) and have high stud ADT.

Table 3: Western Sections with Poor PRC ratings (Average PRC < 80)

BARM	EARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Notes
I-5						
139.56	144.51	4.95	3,488	65	1970	New construction
146.24	147.7	1.46	3,745	75	1970	New construction
166.5	177.81	11.31	3,972	74	1965	New construction
SR-205						
0.51	4.43	3.92	2,069	76	1982	New construction

3.4.1.2 Analysis of High Scoring PRC Sections Relative to Stud Traffic

Using the same grouping of analysis units, Table 4 shows pavement sections with PRC scores above 90 and stud volumes above 1,000 ADT with stud wear rates of 0.2 mm or less per year (this wear rate criterion excludes pavements that may have high PRC scores just because they were recently rehabilitated).

Table 4: Western Sections with High PRC Ratings (Average PRC > 90)

BARM	EARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Notes
I-5						
43.88	51.01	7.13	2,107	93	1976	New construction
SR-16						
0.37	1.57	1.2	2,283	94	1973	New construction
I-405						
0.25[a]	4.47	4.22	2,572	94	1993	Reconstruction
10.25	11.73	1.48	2,897	92	1969	New construction
11.73[b]	14.67	2.94	4,122	91	1973	New construction

notes:

a. When this section was built the HOV lane was on the outside which would have reduced the stud ADT until the HOV lane was switched to the inside sometime in the mid to late 90’s.

b. These sections were widened and there may be new construction or lane shifts that affect the rut measurements. A detailed look at the as-built plans would be needed to verify.

This data suggest that those pavement surfaces with high stud ADT showing the least stud wear are generally old (> 28 years) but do not include any sections of I-5 through the heavily trafficked Seattle-Tacoma urban corridor. Specific mix design and construction information (if available) for these sections may be useful in identifying stud resistant materials. For example, the quarry source of aggregate used in these pavements may be highly wear resistant.

3.4.2 Pavement Wear Rates

Pavement wear rates can give another indication of performance. Figure 11 shows the most recent year of construction versus PRC score.

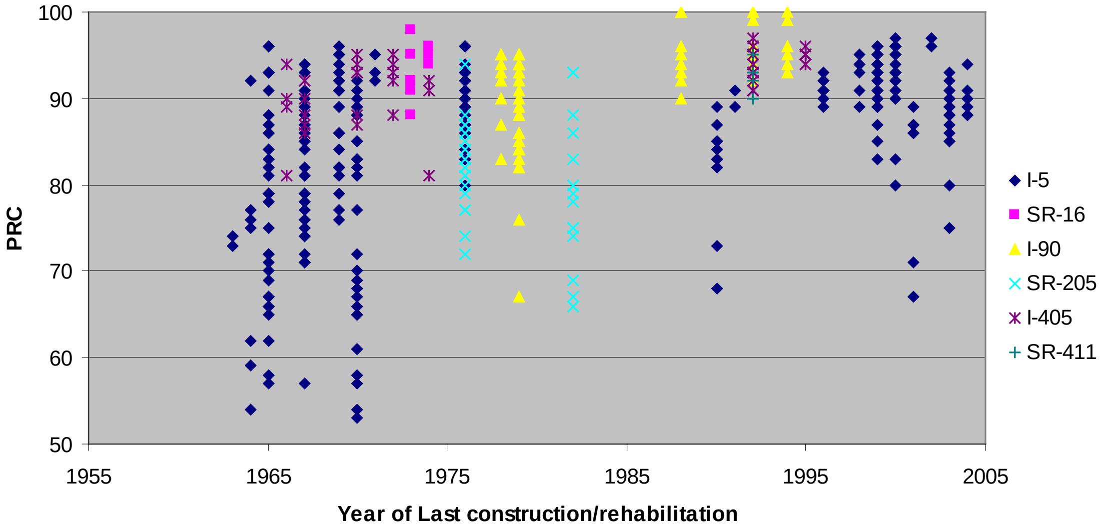


Figure 11: Distribution of PRC vs. age by western highway.

Projects and their construction times are clearly visible in Figure 11. For example the pink squares represent 1.2 lane miles of 9-inch PCCP at the beginning of SR-16 that was constructed during 1973 and 1974. The average PRC of 94 for this pavement means only 1.1mm of rutting exist after 21 years. It is interesting to note the wide range of rut condition for analysis units built in the same year; many of which likely used the same or similar materials. It is also interesting to note that some I-5 pavement surfaces that are over 40 years old show similar PRC numbers as those I-5 pavements that were constructed more recently.

Figure 12 is an alternate way to view wear rates as it plots wear rate against stud ADT. Note that in this figure there is just one section that stand out with an exceptionally high wear rate.

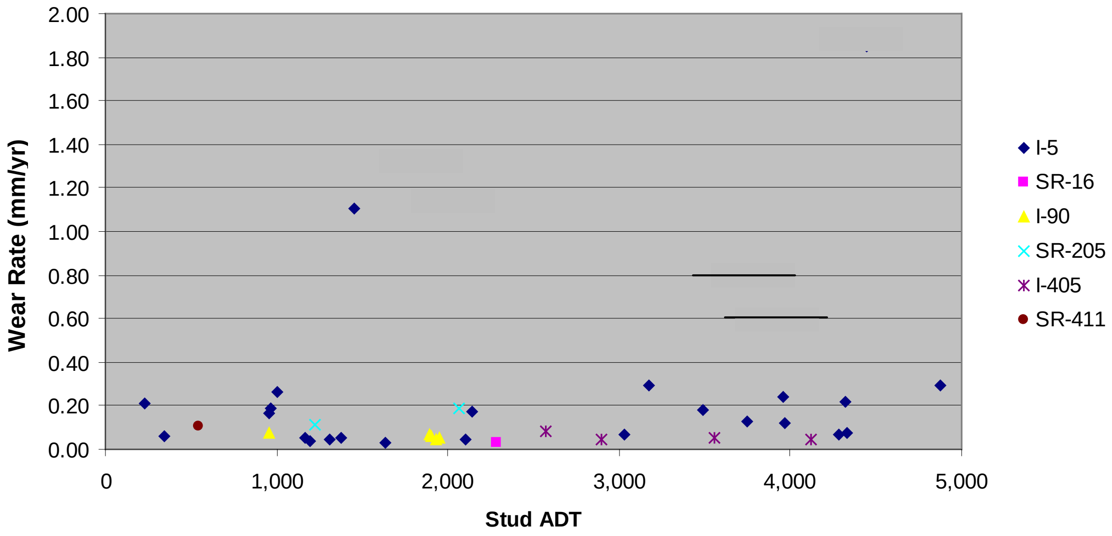


Figure 12: Western stud ADT vs. wear rate.

3.4.3 Analysis of Wear Rates

This section examines wear rate extremes in Western Washington.

3.4.3.1 Sections with High Wear Rates

Table 5 shows the poorly performing section in Western Washington based on wear rates (those 0.5 mm/year or higher). This section had some rehabilitation in 2003.

Table 5: Western sections with high wear rates (>0.5mm/yr)

BARM	EARM	Mileage	Stud ADT	Average PRC	Last Year of Work	Wear Rate (mm/yr)
I-5						
252.42[a]	255.42	3	1,456	88	2003	1.11

note:

a. The specification only required that 95% of the surface be ground on this project which resulted in low spots in the wheel path which also may have contributed to the high wear measurement in the first year after construction.

The I-5 ARM 252.42 to 255.42 section was constructed in 1961 and diamond ground in 2003. Thus, the 2004 results show the wear for just one year of service. Based on experience from SR 395 (Muench et al. 2006) it is likely that this high wear rate is attributable to the tined paste wearing away. As the aggregates become exposed and begin to dominate wear rate it is likely that this wear rate will decrease. Examination of another diamond ground section, I-5 from ARM 124.27 to 136.66, supports this as the wear rate for that section begun high and within 5 years stabilized at a much lower rate. Thus, there are no PCC pavements in Western Washington with high wear rates.

3.4.3.2 Sections with Very Low Wear Rates

Table 6 shows high performing sections in Western Washington based on wear rates (those less than 0.1 mm/year).

Table 6: Western sections with low wear rates (<0.1mm/yr)

BARM	EARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Wear Rate (mm/yr)
I-5						
0	3.06	3.06	1,168	87	1965	0.06
5.24	7.14	1.9	343	86	1965	0.06
7.98	14.59	6.61	1,635	93	1969	0.03
18.37	19.87	1.5	1,381	90	1970	0.05
43.88	51.01	7.13	2,107	93	1976	0.04
149.75	152.32	2.57	4,287	87	1970	0.07
158.24	166.42	8.18	4,332	84	1967	0.08
191.61	194.87	3.26	3,035	87	1969	0.07
209.15	218.86	9.71	1,312	93	1976	0.05
SR-16						
0.37	1.57	1.2	2,283	94	1973	0.03

I-90						
3.9	6.29	2.39	1,906	96	1992-1994	0.06
16.18	31.68	15.5	958	89	1979	0.07
I-405						
0.25	4.47	4.22	2,572	94	1993	0.09
10.25	11.73	1.48	2,897	92	1969	0.04
11.73	14.67	2.94	4,122	91	1973	0.05
14.72	16.45	1.73	3,552	89	1966	0.05

All high performing sections are original or new PCC reconstructions; even the sections of I-90 and SR-405 that show work done in the 1990's show low wear rates.

3.4.4 Summary: Western Washington Studded Tire Wear

PCC pavements in western Washington demonstrate low studded tire wear rates. It appears that a wear rate of about 0.25 mm per 1 million studded vehicles passes is typical for western Washington PCC pavements in the long term. In general, this wear is likely to progress at a much higher rate for the first few years after rehabilitation (e.g., diamond grinding) or new construction (as the cement paste wears away) and then decrease to a much lower stable long-term rate (as the harder aggregate becomes exposed and controls wear rate). Other specific observations are:

- All of the sections with low average PRC scores also have higher than average stud traffic. The vast majority of sections with high PRC scores also experience lower stud volumes.
- All of the pavements with the greatest wear depths (PRC <60) are original I-5 pavements constructed in the mid to late 1960s. Since they are all over 30 years old in 2004, they have low wear rates on a mm/year basis.
- There are no PCC pavements in western Washington that have high stud wear rates (>0.5 mm/yr).

- All of the sections with the lowest wear rates (<0.1mm/yr) are from original PCC constructions or reconstructions. Considering there has been significant traffic growth in the past few decades it is impressive for newer reconstructions (such as I-90 from ARM 3.9 to 6.29 in the early 1990's) to have the same low wear rate as an older original PCC pavement, although present day studs are somewhat less damaging.
- The mix designs and construction practices of the highest and lowest performing pavements discussed should be investigated for further insight.

3.5 Eastern Washington Studded Tire Wear

This section examines studded tire wear in eastern Washington on major state routes. This grouping by major state route excludes small isolated sections of PCCP but is still representative of overall performance as a majority of WSDOT PCCP can be found on these major routes. All data examined are for pavements constructed after 1955 as there is an insignificant amount of data for pavements with construction completed prior to this time. PRC values are first explored with relation to stud traffic, age and wear rates. Sections with high and low PRC's and high and low wear rates are analyzed with respect to the construction and rehabilitation practices associated with these performances.

3.5.1 PRC in Relation to Stud Traffic

Figure 13 shows pavement performance for each state route with respect to stud volume. These data points are based roughly on project units.

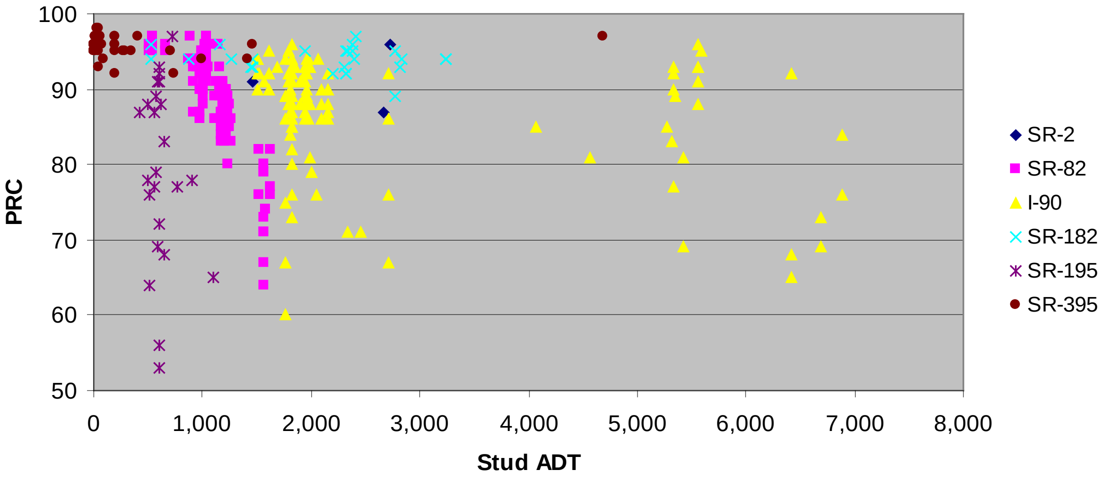


Figure 13: Distribution of PRC vs. stud ADT by eastern highway.

Figure 13 shows smaller stud volumes in comparison to western Washington except for portions of I-90 in the Spokane area that have the highest stud volumes in the state. PRC scores for the vast majority of analysis sections are above 80 (the threshold in this study), however it appears that SR-195, SR-82, and I-90 have some sections in poor condition. Some of the low scoring and high scoring sections are further analyzed in the following sections.

3.5.1.1 Analysis of Low Scoring PRC Sections Relative to Stud Traffic

Analysis units for each state route in Figure 13 were grouped into longer continuous sections of roadway with similar surface, traffic, and stud wear characteristics (similar to but not identical to project units). Table 7 shows all sections with low average PRCs. These sections are generally newer than those in western Washington that show low PRCs but, with the exception of I-90 ARM 280.2-282.18, they have lower stud ADTs.

Table 7: Eastern Sections with Poor PRC ratings (average PRC < 80)

BARM	EARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Notes
I-82						
38.83	54.14	15.31	1,493	78	1981	New construction
I-90						
71.49	75.97	4.48	1,767	74	1973	New construction
273.12	277.88	4.76	3,405	78	1995	Reconstruction
280.2	282.18	1.98	6,617	70	1995	Diamond grind

3.5.1.2 Analysis of High Scoring PRC Sections Relative to Stud Traffic

Using the same grouping of analysis units, Table 8 shows pavement sections with PRC scores above 90 and stud volumes above 1,000 ADT with stud wear rates of 0.2 mm or less per year (this wear rate criterion excludes pavements that may have high PRC scores just because they were recently rehabilitated).

Table 8: Eastern Sections with High PRC Ratings (Average PRC > 90)

BARM	EARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Notes
SR-82						
90.12	95.52	5.4	1,002	92	1988	Reconstruction
SR-90						
50.62	53.43	2.81	1,812	93	1990	New and Reconstruction
SR-182						
0	5.88	5.88	1,775	94	1987	Reconstruction
6.24	12.33	6.09	2,409	95	1985	Reconstruction

As seen in Table 8, all of the sections that boast high PRC ratings are original or fully reconstructed pavements. Specific mix design and construction information (if available) for these sections may be useful in identifying stud resistant materials. For example, the quarry source of aggregate used in these pavements may be highly wear resistant.

3.5.2 Pavement Wear Rates

Pavement wear rates can give another indication of performance. Figure 14 shows the most recent year of construction versus PRC score.

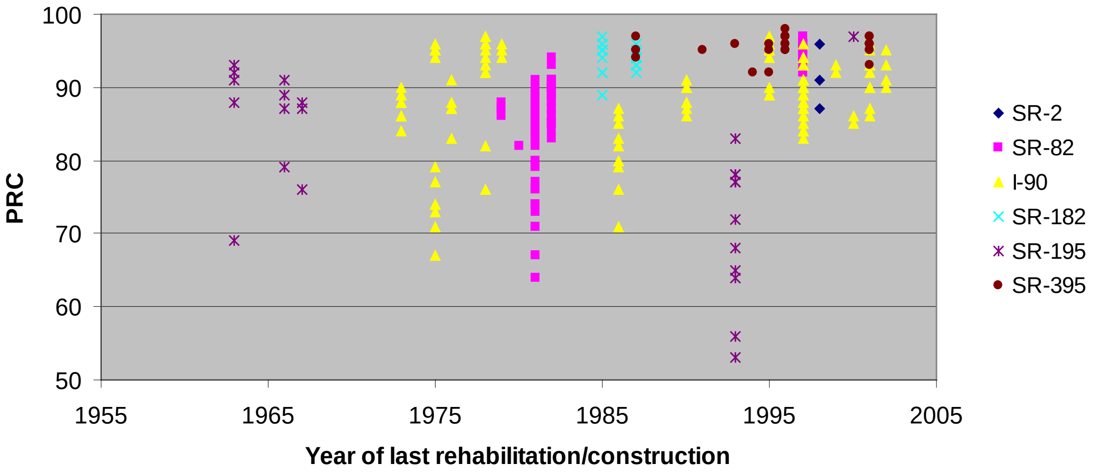


Figure 14: Distribution of PRC vs. age by eastern highway.

Projects and their construction times are clearly visible in Figure 14. For example sections of SR-90 have been reconstructed or rehabilitated various times over the past few decades, while other highways like SR-82 have not been worked on much since the early 80's. On the other hand it is interesting to see that the work done on SR-195 in the early 90's is performing poorly while the original sections from the 1960's are doing much better.

Figure 15 is an alternate way to view wear rates as it plots wear rate against stud ADT. Note that in this figure there are a few sections that stand out with exceptionally high wear rates. A trend of higher wear rates for increasing stud ADT is evident but it may be overemphasized because of the excessive wear rates of the three I-90 sections shown in Table 9.

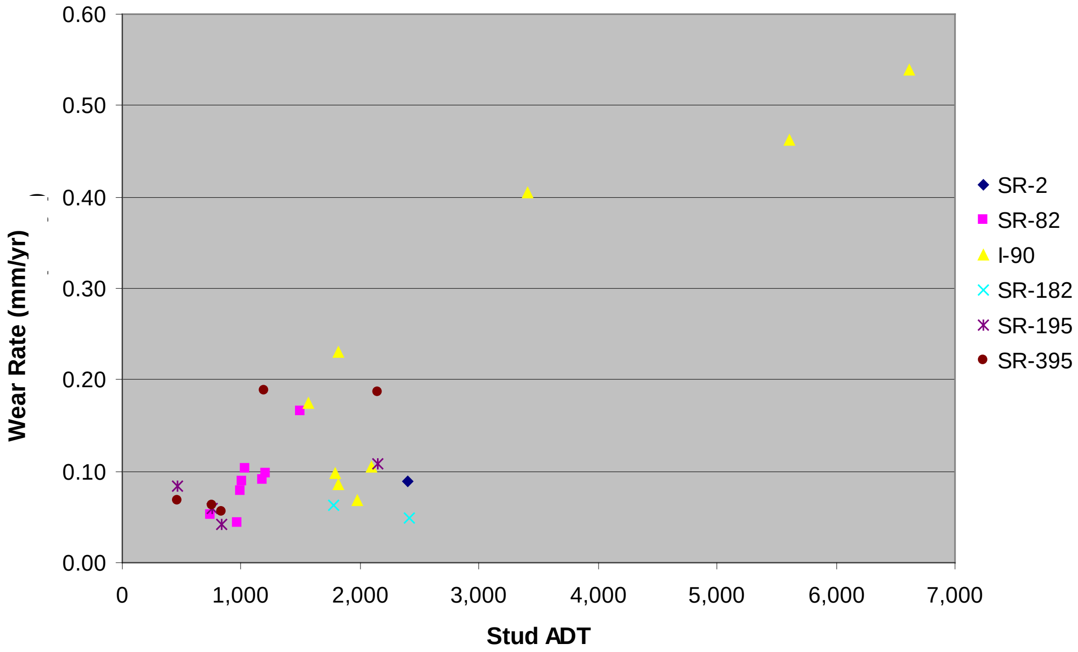


Figure 15: Eastern stud ADT vs. rut rate.

3.5.3 Analysis of Wear Rates

This section examines wear rate extremes in eastern Washington.

3.5.3.1 Sections with High Wear Rates

Table 9 shows poorly performing sections in eastern Washington based on wear rates (those 0.5 mm/year or higher). All sections with high wear rates have had some rehabilitation. For this reason it is beneficial to analyze some of these sections to see what rehabilitation was used and how exactly it is performing with respect to stud wear.

Table 9: Eastern sections with poor wear rates (>0.5mm/yr)

BARM	ARM	Mileage	Stud ADT	Avg. PRC	Last Year of Rehab	Wear Rate (mm/yr)
I-90						
273.12	277.88	4.76	3,405	78	1995	0.40
280.2	282.18	1.98	6,617	70	1995	0.54
282.18	285.71	3.59	5,602	90	2001	0.46
Note: Sections with wear rates of 0.40 and 0.46 are shown in this table because they are close to the limit of 0.54 mm/yr.						

3.5.3.2 Diamond Ground Section (I-90 ARM 280.2 to 282.18)

This section of I-90 has the highest wear rate and was also identified for having a low PRC. After 10 years in service the average wear is 5.4 mm, which is relatively high for a diamond grind. While this section has one of the heaviest stud traffic levels in the state, a wear rate this high will lead to a rut depth rehabilitation trigger in less than 20 years.

3.5.3.3 Full Reconstruction Sections

- I-90 from ARM 273.12 to 277.88. This section was previously mentioned for being a fully reconstructed PCCP that has rutted 4 mm in just 9 years.
- I-90 from ARM 282.18 to 285.71. While this section still has a PRC of 90 it is one the fastest wearing sections in eastern Washington. Reconstructed in 2001, just 3 years later this section is down to a PRC of 90. This section happens to be in one of the highest stud trafficked areas as well.

3.5.3.4 Sections with Low Wear Rates

There are many sections in eastern Washington that have low wear rates and Table 10 shows all sections that have wear rates less than 0.1 mm per year.

Table 10: Eastern Sections with Low Wear Rates (<0.1mm/yr)

BARM	ARM	Mileage	Stud ADT	Avg. PRC	Last Year of Work	Wear Rate (mm/yr)
SR-82						
54.14	57.82	3.68	1,184	87	1979	0.09
79.59	82.01	2.42	967	94	1979	0.04
90.12	95.52	5.4	1,002	92	1988	0.09
100.8	118.62	17.82	745	94	1986	0.05
118.62	132.01	13.39	993	90	1983	0.08
I-90[a]						
31.68	45.34	13.66	1,972	89	1976	0.07
50.62	53.43	2.81	1,812	93	1990	0.09
SR-182						
0	5.88	5.88	1,775	94	1987	0.06
6.24	12.33	6.09	2,409	95	1985	0.05
SR-195						
46.62	51.9	5.28	603	90	1963	0.04
53.28	60.08	6.8	566	87	1966	0.06
SR-395						
31.05	46.11	15.06	833	94	1987	0.06
46.11	53.53	7.42	754	96	1992	0.06
53.53	98.36	48.51	464	97	1996	0.06

note:

a. These sections are technically in western Washington even though they are in South Central Region. The stud ADT would be less if the western Washington stud use rate were used.

Just as in western Washington, all of the sections identified above for exemplary wear rates are either new constructions or reconstructions. Of note, while there are several PCC pavements experiencing high wear rates in eastern Washington, there are also some experiencing low wear rates (although their stud traffic volumes are all less than the high wear rate sections). One final note is that among some of the yearly wear rates that are similar in western and eastern Washington, the corresponding wear rate per studded tire pass is higher in eastern Washington. This might suggest that some western pavements are more durable if they are wearing at similar rates but under heavier stud volumes.

3.5.4 Summary: Eastern Washington Studded Tire Wear

PCC pavements in Eastern Washington demonstrate low studded tire wear rates with notable exceptions on I-90. In some cases lane specific wear rates as high as 45 mm in 15 years have been reported but not in all lanes of a multi-lane section. It appears that a wear rate of about 0.25 mm per 1 million studded vehicles passes is typical for eastern Washington PCC pavements in the long term (the same number as for western Washington PCC pavements). In general, this wear is likely to progress at a much higher rate for the first few years after rehabilitation (e.g., diamond grinding) or new construction (as the cement paste wears away) and then decrease to a much lower stable long-term rate (as the harder aggregate becomes exposed and controls the wear rate). Other specific observations are:

- There is less correlation between stud volumes and wear than in western Washington. This is likely due to the observed stud volumes being quite similar (and low) on most pavements with the exception of I-90.
- Like in western Washington, the sections that currently have the highest PRC scores (<90) are reconstructions.
- Two new construction sections and one diamond ground section have the highest wear rates. This is alarming because it indicates that perhaps something in construction practice or (more likely) materials selection has changed such that newer sections are at greater risk of excessive stud wear.
- The mix designs and construction practices of the highest and lowest performing pavements discussed should be investigated for further insight.

3.6 Summary: Washington PCCP Data Analysis

- Stud volumes are comparable between eastern and western Washington. In general, western Washington has higher AADTs and lower stud use, while eastern Washington has lower AADTs and higher stud use. Given the existing data, there does not seem to be much merit to the argument that stud traffic is significantly higher in eastern Washington with the possible exception of I-90 through Spokane.
- There is an expected correlation between higher stud volumes and lower PRC in Washington State although the correlation is not as strong in eastern Washington because most PCC pavements there have similar low stud traffic.
- The average PCC pavement wear rate across Washington State is about 0.25 mm per 1 million studded vehicle passes according to WSPMS data.
- The highest wear rates are near 0.50 mm/yr (I-90 in the Spokane area) according to WSPMS data.
- The lowest wear rates are in the range of 0.04 to 0.09 mm/yr (many locations) according to WSPMS data. It is likely that this wear rate over the life of a pavement is about as low as can be expected in Washington State.
- It is fairly clear that PCC pavement wears more quickly during the first 2-5 years of existence and then wears more slowly after that. The general assumption is that the initial high wear rate occurs as the paste on the pavement surface from finishing is worn off, and the lower ultimate wear rate occurs as the underlying

aggregate becomes the controlling factor. This same phenomena seems to occur after a diamond grind as the pavement paste wears away again.

- Issues with excessive PCC stud wear rates seem to occur on a limited basis as most pavement sections showed reasonably small wear rates. Therefore, it is likely a project-specific factor that contributed to the excessive wear rate. Given that aggregate exposure generally slows initially high wear rates, it is somewhat likely that these projects may have used a softer aggregate. Further, since all three sections showing excessive wear rates beyond their first year are near Spokane, aggregate sources there may be the culprit.

4 STUD WEAR MITIGATION

Because stud wear degrades pavement condition and results in safety issues, it is desirable to eliminate it or at least mitigate its effects. Approaches can involve any combination of the following:

- Legal efforts to ban or limit stud use.
- Alternatives to traditional studded tires.
- Preservation efforts to improve existing worn pavements.
- Materials used in overlays or surface treatments to prevent or lessen stud wear.
- Testing to identify wear resistant material for use in overlays or new construction.

4.1 Legal Measures

In general, studded tires could be (1) banned completely, (2) taxed or (3) allowed using a permit system.

4.1.1 Banning Studded Tires

There are currently 8 states that have banned stud usage and laws otherwise vary on stud weight, protrusion, sales, and duration of use. A common situation, such as Washington's, is for studs to be legal for a certain period of time in the winter, such as November to April. In 2004 WSDOT released an official position supporting the Transportation Commission's request to ban studded tires in Washington. The two main points from WSDOT relate to the severe road damage caused by studs, and the availability of alternatives. Although the issue is a political one, WSDOT continues to support a ban.

4.1.2 Taxes/Fees

Past legal measures, as previously mentioned, such as extra fees or taxes on studded tires, have been implemented in various states to reduce stud use, and financially aid the resulting damage. For example in Alaska there is an additional tax of $2.50 on the sale of all tires, and as of 2004 the law added an extra $5 tax on the sale of all studded tires (Zubeck et al. 2004). In Oregon a tax on the sale of studded tires was proposed as a means to cause a reduction in use and cover repair costs. The price that was calculated to meet damage costs was $30 per tire (Malik 2000).

Washington has attempted both studded tire fees and permit legislation, none of which has yet been passed. In 1994 Washington attempted a bill which would impose a fee of $8 per studded tire annually (WSDOT 2006). To regulate and monitor this law the Department of Licensing would issue windshield stickers for stud use. Although the Washington State Patrol testified in favor, the bill was not passed. In 2001 new proposals (which ultimately did not pass) suggested a $15 fee on each studded tire sold as well as reducing the duration of stud use in Western Washington to just December, January, and

February. The $15 fee was attempted one more time in 2003 and again was not passed (WSDOT 2006).

4.1.3 Studded Tire Permits

A step down from banning studded tires is the approach of establishing a permit program. This effectively allows continued use of studded tires but attempts to collect money from users to offset resulting pavement damage. This type of program would require users of studded tires to purchase an annual permit. These permits could apply to out of state users as a regular permit or on a single or multiple trip permit basis (Malik 2000). A proposal in 2002 suggested that such permits should vary by region based on the studded tire damage in each region. In this idea presented by the Road User Fee Task Force of Oregon, the permit fee would be very small, perhaps $1 in regions where studded tire use exists but is either small or does not significantly reduce pavement life. Further, a higher fee would be placed in areas where damage is significant, potentially reducing usage. The total target collection fee would be based on the state's annual damage caused by studded tires, estimated to be around $11 million for Oregon (Whittey et al. 2002). To cover the level of annual expenditures and the costs of administering the program in Oregon it was estimated that the annual studded tire permit fee would need to be at least about $7 to $8 per tire (Malik 2000). Enforcement and logistical details for this type of program need further exploration, however this idea has the potential to reduce stud use and generate funds to repair damages.

Table 11: Legal Measures to Reduce Stud Use

Legal Measure	Procedure	Cost	Potential to Reduce Stud Wear	Potential for Implementation
Ban	Legislation to prohibit studs	N/A	Would eliminate all studded tire wear	Not likely in the near future
Taxes/Fees	Sales tax	Administration fees	Likely to reduce usage	Potential
Use Permits	Permit with a fee that may be based on regional damage	Administration and law enforcement costs	Likely to reduce usage	Potential

4.2 Preservation Efforts

Preservation efforts are directed at removing or covering up stud wear in PCC pavements. Removal involves diamond grinding the existing surface, while covering efforts involve overlays of all types. Each method will be briefly described here with an emphasis on (1) the process, (2) results and limitations, (3) construction costs, (4) performance, and (5) examples.

4.2.1 Diamond Grinding

Process. Diamond grinding removes a top layer of pavement that contains irregularities and leaves behind a new, finished surface essentially free of defects. The grinding process uses diamond saw blades that are gang mounted on a cutting head. As the front wheels of the equipment pass over the pavement the highest surface is shaved off by the cutting head and the rear wheels follow in the smooth path. Standard cutting head widths are from 36 to 38 inches although newer machines can grind up to 48 inches wide in a single pass as was seen in summer 2009 on the I-5 Boeing Access Road to King/Snohomish County Line Pavement Repair job. According to the FHWA the desired corduroy texture is produced using a spacing of 164 to 194 diamond blades per meter (50 to 60 per foot) of shaft. The process necessarily reduces PCC slab thickness by at least 4 to 6 mm (FHWA 2006a) but can be done in multiple passes to reduce depth to the elevation of the lowest wheelpath depression. Currently, WSDOT designs PCC pavements with an extra inch of thickness in anticipation of a grinding operation at some point during the service life (WSDOT 2006).

Results and limitations. The resultant smoother surface increases safety (by reducing hydroplaning risk and unwanted/unexpected steering feedback) and reduces tire-pavement noise. Diamond grinding does not fix structural PCC pavement defects (e.g., slab cracking, corner breaks) and it only treats the symptoms of faulting rather than the root cause. Aggregate hardness in Western Washington generally leads to low production rates and high blade replacement rates. Observed rates on I-5 in the Seattle area in 2009 were about 3 ft/min.

Cost. The average 2006 cost for diamond grinding is approximately $90,000 per lane mile, including all construction costs, traffic control, mobilization, etc (WSDOT 2006).

Performance. Based on surveys from across the U.S. the American Concrete Pavement Association (ACPA) expects a typical diamond grind to extend pavement life (by reducing roughness) by at least 14 years (ACPA 2006). A California study (Stubstad et al. 2005) concluded that diamond grinding adds 16-17 years of service life to California

PCC pavements. For roads that experience significant stud traffic and use potentially soft aggregate a reasonable service life estimate might be closer to 10 years, like that mentioned in the Idaho Transportation Department's (ITD) Preventive Maintenance Manual (2001) where stud use is common.

4.2.2 Hot Mix Asphalt Overlays

Process: A layer of hot mix asphalt (HMA) is placed over existing PCC to create a new, smooth surface. WSDOT generally performs HMA overlays to provide increased structure rather than to mitigate studded tire wear. For the purpose of adding structure to the existing pavement, the HMA lift is usually anywhere from 2 to 4 inches or more, while thin surface overlays are generally between 0.5-1.5 inches.

Results and limitations. HMA overlays tend to restore a smooth surface to the pavement however HMA is also subject to studded tire wear (WSDOT 2006).

Cost. In Washington, the general current overlay procedure averages \$230,000 per lane mile for 1.8 inches of dense graded HMA. Other states experience similar costs as in North Dakota where a bituminous hot mix overlay costs anywhere between \$170,000 and \$330,000 per lane mile depending on the project scope and pavement thickness (NDDOT 2007). From a construction cost standpoint, then, a typical HMA overlay costs over twice as much as a diamond grind. This has led Caltrans (Stubstad et al. 2005) to conclude that under appropriate existing pavement conditions (e.g., no highly progressive structural cracking), diamond grinding is the more cost-effective rehabilitation technique.

Performance. HMA overlays are expected to perform as typical HMA surfaces. Typically, this means performance ranging from about 7 to 16 years in Washington State depending upon location (eastern Washington generally experiences shorter wearing course life in the neighborhood of 8-12 years while western Washington experiences wearing course lives of 12-18 years), studded tire use, mix design, construction and structural design.

4.2.3 PCC Overlays

Process. There are two main types of PCC overlays applied to existing PCC pavements: bonded and unbonded (FHWA 2007b). A bonded overlay is a thin (typically 4 inches or less) PCC overlay over an existing PCC pavement with a prepared surface. As with a typical HMA overlay, a bonded PCC overlay relies on creating a good bond between the existing pavement and the overlay such that the result behaves as one unified structure (rather than two independent ones). An unbonded overlay is a thicker PCC overlay (usually 6 inches or more) placed over an existing PCC pavement (Figure 16). The overlay is intended to act as a separate pavement and thus steps are taken to ensure bonding to the existing pavement does not occur (ACPA 1998).

Figure 16: Thin unbonded PCC overlay (Kuennen, 2006)

Results and limitations. The major drawbacks to PCC overlays include higher construction costs, the risk of bond failure (in bonded overlays), added height (for bridge clearance), and a general unfamiliarity with the procedure by many DOTs.

Cost. Costs for PCC overlays can vary significantly depending on the particulars of the site and other work being done in conjunction with the overlay. In 2004 Minnesota reviewed the bids of 16 unbonded concrete overlay projects completed between 1998 and 2002. The average cost for these projects ranged between $500,000 and $1 million per lane-mile (Concrete Paving Association of Minnesota 2002).

Performance: Estimates of performance vary greatly and are often based on structural considerations rather than studded tire wear. Measured wear rates in Eastern Washington, where there is a significant amount of stud traffic, show a time to surface rehabilitation of less than 6 years (Anderson et al., 2006) while information from Minnesota, where studded tires are banned, suggests the newest unbonded PCC overlays there should last up to 30 years (Concrete Conveyor, 2002).

4.2.4 Summary: Common Rehabilitation Measures

All rehabilitation measures are designed to restore surface smoothness, however none have been effective at actually preventing further studded tire wear. Despite experimenting with new techniques, familiarity with the practice seems to be a driving factor for the technique chosen. For Washington the most common successful practice to mitigate studded tire wear is diamond grinding. HMA overlays are also viable options. Table 12 summarizes the measures examined in this section.

Table 12: Summary of Common Rehabilitation Measures

Method	Procedure	Ability to Prevent Stud Wear	Cost/lane mile (2007 dollars)	Service Life
Diamond Grind	Grinds a top layer of the pavement surface	Restores new PCC surface	$90,000 (WA)	10 yrs (heavy stud traffic) 15-20 (otherwise)
HMA Overlay	Places a layer of HMA over existing PCC	Provides new surface but is typically more susceptible to stud wear than PCC	$230,000 for dense graded 1.8” HMA (WA)	5 yrs (heavy stud traffic) 8-16 yrs (otherwise)
PCC Overlay	Places a layer of PCC over existing PCC	Thin overlays do not appear to resist studs	Little data but typically in excess of a HMA overlay, some at $ 0.5-1 million (MN)	6 yrs (heavy stud traffic) 30 yrs (otherwise)

4.3 Other Paving Practices

This section looks at some less common paving practices that may show promise for stud wear mitigation. Most have not been adequately explored to produce strong recommendations.

4.3.1 Resin Modified Pavement (RMP)

For the past two decades resin has been used in conjunction with HMA to resist rutting and abrasive traffic primarily on military bases. In recent years test sections have been researched on highways as well. RMP is a surface overlay of an open graded HMA mixture where 25-35% of air voids are filled with a latex-rubber modified portland cement grout (Figure 17). In the overlay procedure the open-graded mixture and grout are produced and placed separately to result in a 1.8 to 2.5 inch thick composite material. The benefit to this option is that it provides many of the performance characteristics of PCC but can be constructed easier and less expensively. Also, the additive is believed to increases the flexural and compressive strength of the hardened material, thus increasing abrasion resistance, and potentially studded tire wear as well (Battey & Whittington 2007).

Figure 17: Latex additive going into the grout (Battey & Whittington, 2007)

For the most part RMP is used as a rehabilitation overlay, however it can also be used with new construction as well. Often it is placed over a pavement that has already been rehabilitated with HMA (AFCESA/CES 2001). The initial cost for a typical 2-inch RMP layer is $12.00 to $20.00 per square yard, which is generally 50-80% higher than a HMA pavement with the same thickness but 30-60% cheaper than a PCC pavement with the same thickness (FHWA 2006b). When RMP is placed over jointed PCC (JPCP), matching joints must be cut in RMP at an approximate additional cost of $5.00 per square yard. Overall, RMP maintenance costs are minimal if it is placed over a structurally sound HMA pavement or rubblized or cracked and seated PCC (AFCESA/CES 2001).

A Mississippi study placed RMP test sections on two HMA pavement intersections on US 72 with histories of traditional rutting (from pavement deformation) (FHWA 2006b). Ultimately, after 5 years of observation between 2001 and 2006, the Mississippi Department of Transportation (MDOT) published a final report in 2007 which featured both positive and negative reviews of their experience with RMP. From the construction end, the project was reported to be very challenging overall. Despite attention to detail, as shown in Figure 18 below, there was one area of failure where the removal of a 75-ft section of the pavement due was required due to a lack of grout penetration of the mat.

Figure 18: Excess grout worked into areas needing more (Battey and Whittington 2007).

Performance measurements also showed skid resistance below state standards. The major positive result of the project however was that after 5 years there was no rutting at all (Mississippi does not allow studded tires so this was a measure of plastic flow deformation rutting and not stud wear) reported on the RMP sections and overall pavement condition ratings were acceptable. The resulting pavement appears to be successful in its goal of withstanding abrasive traffic, heavy static loads, and channelized traffic, however the construction practices have not been perfected, and long term observation is needed (Battey & Whittington 2007).

4.3.2 Two-Lift PCC Paving

It is possible to construct a new PCC pavement in two separate lifts, which allows different materials to be used in each lift. This technique has been Germany, Austria and Belgium to place a high-quality, carefully engineered top lift over a more basic bottom lift. Often the top lift is constructed with an exposed aggregate finish to lessen tire-pavement noise (Figure 19).

Figure 19: An exposed aggregate surface (Silent Roads, 2003)

Noise reduction is attributed to the aggregate structural design in the top layer. For example the maximum aggregate size typically used in Europe is 0.8 inches and the top layer of concrete usually has a 0.3- to 0.4-inch maximum aggregate size. In the Netherlands, where more single-lift construction is done, 1.25 inches is the maximum aggregate size (FHWA 2007a). WSDOT maximum aggregate size on existing pavements ranges from about 0.75 inches to over 2 inches (on older pavements).

It could be possible to construct a two-lift pavement where the bottom (and thicker lift) is made from more readily available and less expensive local materials and the top lift is made from specialized wear-resistant materials. The economic viability and sustainability implications of this idea, which involves transporting low-value, heavy materials over potentially long distances by train, have not been evaluated.

4.3.3 Surface Textures

Surface texture is thought to have some correlation to studded tire wear. As the two primary textures used in Washington, the results of transverse tining and artificial turf carpet drag were explored in a WSDOT experiment on the performance of different surface textures (Figure 20). The amount of exposed aggregate relating to surface wear was also examined and it was recognized that pavements initially wore at a higher rate when first exposed to studded tires but then stabilized with time (Anderson et al. 2007). One idea suggested that the difference could be attributed to the paste on the surface of the new concrete. For example the paste wears quickly but then when the aggregate underneath is exposed the pavement wears at a much slower rate. One final conclusion noted was that all of the tined sections in this experiment had faster wear rates than other sections with equivalent mixes. Due to this it was suggested that tining may weaken the surface of the pavement by exposing more surface area to rapid drying, which is an idea that the Texas DOT has also proposed. The additional paste on the tined surface was also noted as a possible contributor (Anderson et al. 2007).

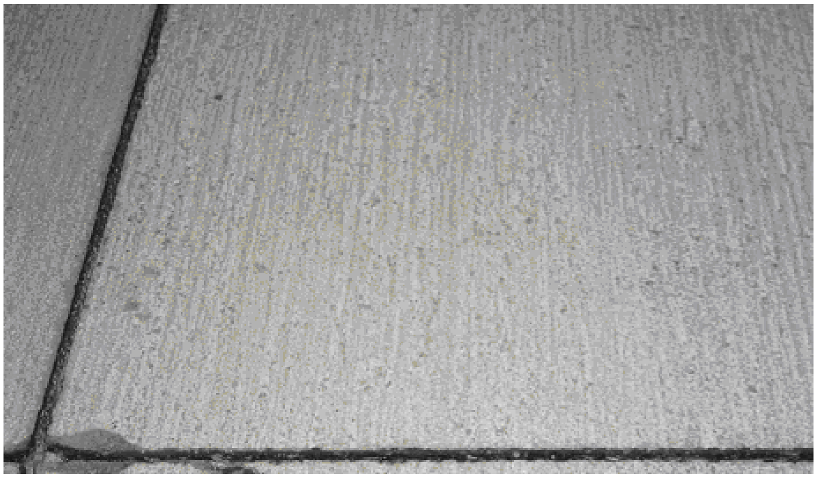


Figure 20: Surface texture from a carpet drag (Anderson et al. 2007).

4.3.4 Summary: Other Paving Practices

Resin modified pavements, specifically overlays, seem to have some potential for resisting abrasion, however the technique is relatively new and the construction practices have not been perfected. Two-lift techniques may have some potential if a wear-resistant top layer can be designed, while surface texturing may influence early wear rates but is not likely to much influence wear beyond the tine depth. Table 13 summarizes these practices.

Table 13: Summary of Other Paving Practices

Paving Practice	Procedure	Stud Wear	Initial Construction Cost	Potential with Further Research
Resin Modified Pavement	Surface overlay of an open graded asphalt mixture where 25-35% of air voids are filled with a latex-rubber modified Portland cement grout	May be more resistant, no definitive study	50-80% higher const than an asphalt pavement but 30-60% cheaper than a PCCP	Yes
2-Lift Paving	Pave new PCC using 2 lifts with wear resistant materials in the top lift and less resistant but cheaper materials in the bottom lift	As resistant as the top layer of materials	Unknown but likely more expensive than typical PCC due to potential materials transport costs	Maybe
Surface Textures	Creates friction mainly by transverse tinning or turf-drag	Tined sections had faster wear rates than turf-drag	Not significant with respect to paving practices	Maybe

4.4 Materials & Additives

This section will cover information regarding typical PCC mixes, aggregate properties, and some specific components and admixtures which either have been or could potentially be linked to either slowing or expediting studded tire wear.

4.4.1 Typical PCC Mix Considerations

4.4.2 Aggregate Selection

In general, harder aggregate seems to slow but not stop studded tire wear. Therefore, some agencies look to use the hardest aggregate available (as measured by durability and abrasion tests) for roadways with high wear potential based on traffic.

Alaska has done a fair amount of work to reserve the use of premium hard aggregate for roadways with volumes susceptible to stud wear (Kuennen 2004). Although much of this work is focused on HMA, the results are relevant to PCC stud wear prevention as well as they could be used in overlay materials or two-lift PCC paving. As shown in Figure 21 aggregate hardness varies not only in Alaska, but across the U.S. and from eastern to Western Washington as well. This has two implications: either transporting harder aggregate when necessary, and/or restricting the use of hard aggregate to areas that experience the greatest amount of stud wear.

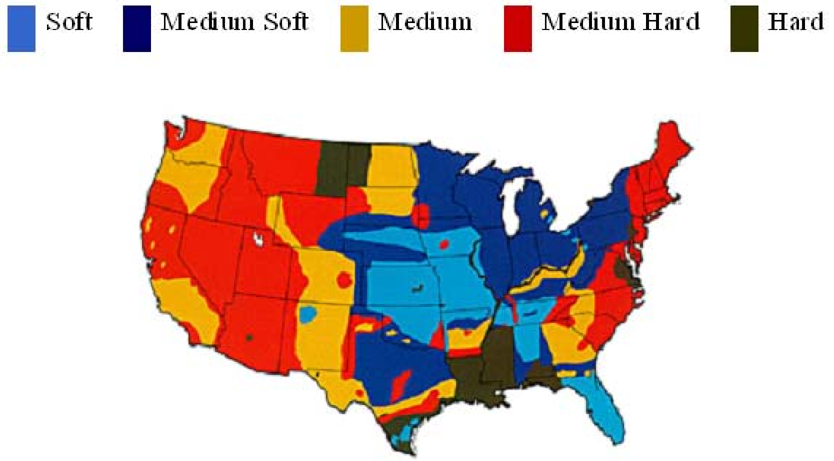


Figure 21: Aggregate classification map of the U.S. (Concut, no date given)

4.4.3 Fly Ash Content

Currently, fly ash is one ingredient that is routinely added to PCC mixes. Varying the content of fly ash may have an effect on stud wear. Typically Class F fly ash is used at the rate of 15% to 20% of total cementitious material, and Class C fly ash is normally used in the range of 15% to 35% (Ansari et al. 2000). The possibility exists that increasing the fly ash content could have a correlation to stud resistance, however no specific data exists.

4.4.4 Silica Fume (Microsilica)

Silica fume has been recognized as effective in resisting abrasion (FHWA 1999). Composed of particles approximately 100 times smaller than the average cement particle, Silica fume is a byproduct of producing silicon metal. These extremely fine particles increase the durability of the mix and are added to the concrete during production. Normal proportions used are 7% to 10% by weight of cement, while up to 15% may make the PCC too brittle (FHWA 1999).

4.4.5 Combined Gradation

A study by WSDOT (2006) examined the effects of traffic and stud wear on combined gradation concrete. The study compared the rutting on standard near gap graded PCC with a more uniform combined gradation PCC. WSDOT monitored the wear on both pavements and made analytical adjustments based on traffic volumes and the 2 year age difference of the pavements. The combined gradation mix produced a higher average compressive strength with less deviation and less failed specimens than the standard mix, however ultimately the wear rates on both road sections were the same (Anderson et al. 2007a). It was noted however that there were a few points for consideration in this study. First, traffic estimates were rough, and second, since both pavements are very young, having been constructed less than ten years ago and monitored for only three years, the long term effects still need to be monitored.

4.4.6 Cement Content

A number of field investigations conducted on a Strategic Highway Research Program Special Pavement Study (SPS-2) site that was constructed in 1995 show that cement content may have some effect in *initial* stud wear rates (Figure 22).

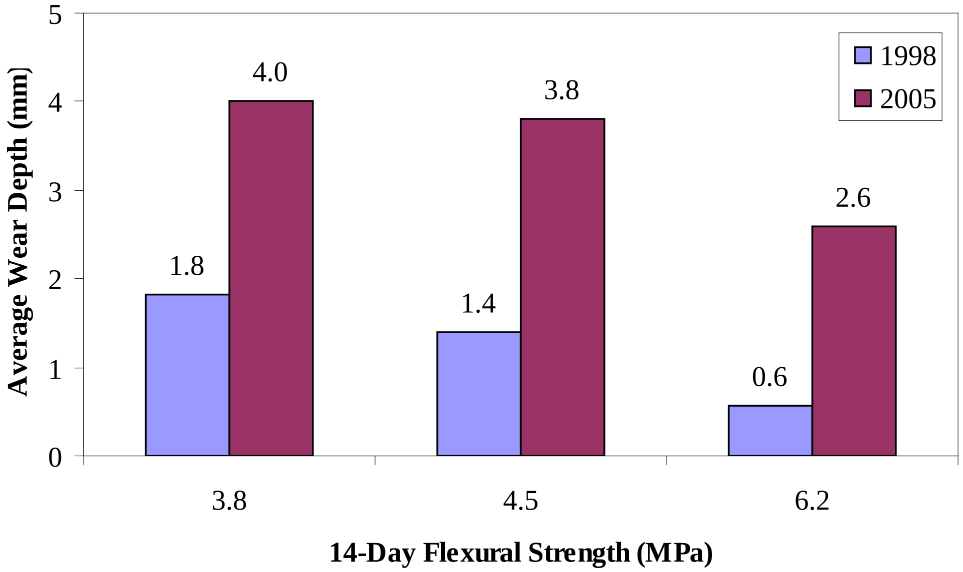


Figure 22: Pavement wear rates by flexural strength on SR-395 SPS-2 pavement sections.

It seems that wear rates in the first 3 years (1995-1998) were affected by cement content. Wear rates since then (as measured in 2005) appear to be quite similar for all 3 sections. This suggests that perhaps the weaker paste material at the surface benefited from the higher cement content (and thus strength) but once it wore away, wear rates in all sections equalized.

4.4.7 Engineered Cementitious Composites, ECC

A fairly new fiber-reinforced bendable concrete called Engineered Cementitious Composites (ECC) is being explored by the U.S. as a durable paving material that may perform well against studs. Although it has been used in other countries like Japan, Korea, Switzerland, and Australia, one of the first major applications in the states was not until 2005 by the Michigan DOT (Kuennen 2006). ECC differs from regular fiber-reinforced concrete because in addition to microscale fibers which bond the concrete more tightly, the ingredients in the actual concrete make the pavement more flexible (see Figure 23). This technique specifically looks to reduce early age cracking however a study conducted on this material by the University of Michigan in 1997 estimates that this pavement will be durable enough to last twice as long as regular concrete (Li 1997). To this point there are no conclusions regarding performance of this pavement with respect to cracking or stud wear resistance. Test projects in Kansas, Missouri, South Dakota, and Maryland concluded that adding fibers to strengthen the mix is not cost effective and should be reserved for special circumstances (FHWA 2006b).

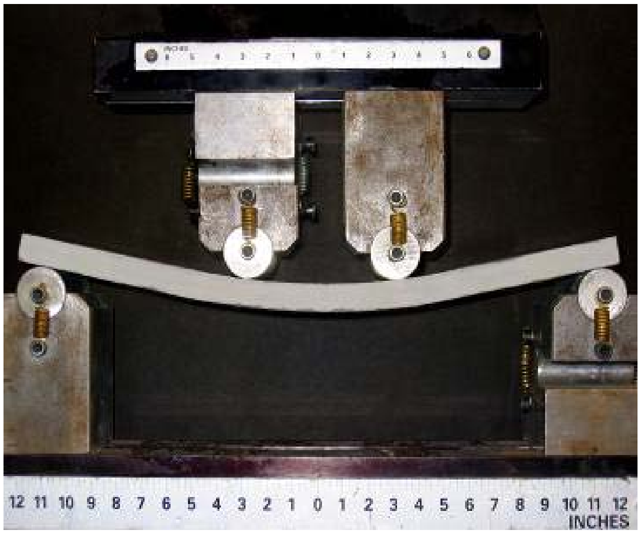


Figure 23: Bendable concrete (Bailey 2005).

4.4.8 Hard-Cem

As part of an experimental study on preventing studded tire wear (WSDOT 2006) a concrete hardening additive called Hard-Cem was trialed in 2004. Manufactured by Cementec Industries, Inc. this additive is a fine powder handled similar to cement which is added during the batching process, thus affecting the entire mix, not just the surface of the pavement. It reportedly does not affect any concrete qualities such as air-entrainment and is claimed to improve the abrasion resistance of concrete by 35%. For the Washington test section the mix was prepared to 650 psi flexural strength, which is the standard for state PCC pavements. After testing the performance in 2006, the Hard-Cem test section had an average wear of 2mm, and a wear rate of 1.3mm per year which was the lowest compared to the other test sections. In this study the sections that had the worst wear rates were an 800 psi flexural strength with carpet drag section, and a section with 925 lbs/cy of cement content. The overall results of the study were somewhat inconclusive as mixes of equal flexural strength had different wear rates, and some of the sections with higher strengths, 800 psi, performed worse than those of lower strength, 650 psi (Anderson et al. 2007). Because all of the sections are still very young, the study also recommended further performance monitoring, however this does suggest that flexural strength is not a good proxy for wear resistance.

4.4.9 Recycled Concrete Material, RCM

A final PCC paving material to consider with respect to studded tire resistance is recycled concrete. The practice of recycling concrete involves breaking up and removing the old concrete, crushing to reach desired particle size, removing any reinforced steel or embedded items, and stockpiling. As of 2004 38 states were identified as using recycled concrete for aggregate as a base material and 11 used recycled concrete for aggregate in PCC (FHWA 2004). One potential way to mitigate stud wear would be to create a grading system specifically for recycled concrete materials that was based on its wear condition prior to removal. Then the higher rated RCM could be used for reconstruction or rehabilitation in areas with high stud usage.

4.4.10 Summary: Materials & Additives

Overall it appears that there are some paving materials and additives that could potentially aid in reducing studded tire wear, the problem remains that testing has not identified any specific recipes. Though the link between aggregate strength and abrasion resistance is debatable, there is an increasing need for hard aggregate in many areas. Alaska has proposed an idea where premium aggregate would be reserved for roadways with the highest volumes. Altering the amount of specific PCC materials such as fly ash and silica fume is another idea that has been noted to potentially aid in abrasion resistance. In Washington, a combined gradation experiment showed that higher compressive strength did not result in slower wear rates. The use of ECC is projected to improve the abrasion resistance of concrete by 35% however these results have not actually been achieved in the field and ECC is an expensive option. Finally air entraining admixtures and recycled concrete materials are areas where more investigation is needed with respect to stud wear, however a special grading system for the use of RCM could aid in stronger pavements. Table 14 shows a summary of the materials and additives examined in this section.

Table 14: Summary of Relative Materials and Additives

Material or Additive	Current Use	Correlation to Stud Wear	General Cost	Potential with Further Research
Hard Aggregate	Throughout the country depending on geographic location	Used specifically in Alaska to prevent stud wear	Average but increases with transportation cost	Yes
Fly Ash	Commonly used in mixes, but content varies	Undetermined	Average	Yes
Silica Fume	Not commonly used in mixes, but growing	Used in Maine for stud resistance	Relatively expensive	Yes
Combined Gradation	Some experimental use	Slows wear insignificantly	Average	Maybe
Engineered Cementious Composites	Used abroad and recently in the U.S.	Undermined	Expensive	Yes
Hard-Cem	Trialed in Washington	Inconclusive	Slightly expensive	Unlikely
Recycled Concrete Materials	Used in various states for base and surface courses	Undermined	Average	Maybe

5 TEST METHODS

Since soft aggregate may be to blame for excessive studded tire wear rates, it may be prudent to test aggregate sources before paving PCC to ensure, or at least lower the risk, of excessive stud wear. This section looks at the methods that either are or could be used to evaluate PCC pavements and their constituent materials for stud wear resistance.

5.1 PCC Testing

There are several tests that have been used over the years to examine PCC pavements characteristics however the link to stud resistance is not always definite. While studded tire wear is often associated with the strength of the PCC it is durability, abrasion, and wear resistance that appear to be most related to stud resistance. .

5.1.1 Nordic Abrasion Test (Ball Mill Test)

This is one of the main aggregate tests used throughout the world and the main test in countries with high stud use, such as Finland (Zubeck et al. 2004). Generally this test takes a 1000-g aggregate sample and rotates it in a standard mill with 7 kg of 15-mm diameter steel balls and 2 liters of water for one hour at 90 RPM (Zubeck et al. 2004). As further described in the Zubeck et al. (2004) report on studded tires, the particle size of the aggregate tested is from 11.2 mm to 16 mm. The ball mill value is defined as the particle size percentage that is finer than 2 mm after the test. The general consensus is that the smaller the Nordic Abrasion value, the better the wearing resistance.

Alaska is one state which uses the Nordic Abrasion test to predict the pavements resistance to studded tire wear. Researchers in Alaska have seen a correlation between the hardness of aggregates used resulting in better stud resistance (Frith et al. 2004).

5.1.2 LA Abrasion

The Los Angeles (L.A.) abrasion test is a common test method used to indicate aggregate toughness and abrasion characteristics. The standard L.A. abrasion test subjects a coarse aggregate sample (retained on the No. 12 sieve) to abrasion, impact, and grinding in a rotating steel drum containing a specified number of steel spheres. After being subjected to the rotating drum, the percentage of the total aggregate weight that has broken down and passed through the No. 12 sieve is calculated. Therefore, an L.A. abrasion loss value of 40 indicates that 40% of the original sample passed through the No. 12 sieve. The standard Los Angeles abrasion test is AASHTO T 96 or ASTM C 131. Figure 24 is an example of the LA Abrasion machine.

Figure 24: LA Abrasion machine (Qualitest International, Inc. 2009).

Studies of the LA Abrasion tend to conclude that it has little relationship with field performance (Rangaraju et al. 2005; Mokwa, et al. 2007; Folliard, et al. 2003).

5.1.3 Micro-Deval Test

The Micro-Deval test (Figure 25) is another test used to evaluate the performed of an aggregates resistance to wear, and is similar to the LA Abrasion test. There are two versions of the test available. The test is described as placing the sample in a steel jar with steel balls (9.5 mm in diameter) and water, then rotating the jar at 100 rpm for 2 h for coarse aggregates, as previously described, or 15 min for fine aggregates (Land et al. 2006). Then the aggregate damage is assessed by mass loss using a 1.25-mm sieve for coarse aggregates and a 75-µm sieve for fine aggregates (Lang et al. 2006).

Figure 25: A Micro-Deval test machine (Inopave 2003).

Unlike the LA Abrasion test, this test method is unique in that the aggregates are tested in saturated conditions rather than dry-conditions. According to the South Carolina DOT, analysis indicated that Micro-Deval test method is a better test in characterizing aggregate's field performance. The SCDOT found that for any given source of aggregate, finer gradation consistently yielded higher losses compared to coarser gradations (Rangaraju et al. 2005). Further, a Micro-Deval loss limit of 17% identified nearly all of the aggregates that were rated as being "fair" or "poor" in field performance.

To this point the vast majority of in-depth research on the Micro-Deval Test method comes from Ontario, however there have been U.S. reports examining the accuracy of the test. After studying 19 test samples, the Colorado DOT concluded the test to be accurate for field performance, and a similar report from the Oklahoma DOT reported field conditions corresponded "exactly" with the Micro-Deval results (Lang et al. 2006). Lang et al. (2006), looking at over 100 samples from various locations across the U.S., concluded that Micro-Deval provided good prediction of performance for base materials. It was also noted however that as far as open-graded friction course aggregates the Micro-Deval, LA Abrasion, and Magnesium Sulfate tests all produced the same "fairly good" results, though the LA Abrasion was mentioned to be the least consistent.

Despite many reports suggesting that the Micro-Deval predicts pavement performance accurately, there are a still a few which take the opposite position. In comparing the Micro-Deval, LA Abrasion and Nordic Ball tests, Hunt (2001) concluded the Micro-Deval was not better at testing aggregate resistance than the LA Abrasion test. Further, the Nordic Abrasion Ball Test was the test ultimately recommended to best predict resistance to abrasion (Hunt, 2001). One other report (Cooley et al. 2002) looked at 72 different aggregates and ultimately found the results of the Micro-Deval Test to be variable at best.

5.1.4 Sodium Sulfate & Magnesium Sulfate Soundness Tests

This is a durability test for which there are two main styles involving cycles of soaking and drying samples of aggregate in chemical solutions (Sodium Sulfate or Magnesium Sulfate) at varying temperatures. After multiple cycles of drying and re-sieving samples, the losses are weighed and aggregate performance can be predicted (Lang et al. 2006). One study from the SCDOT found the Magnesium Sulfate test to be the more valid predictor of durability, however results across other SC projects found the two tests to produce similar results (Rangaraju et al. 2005). It was noted that with a maximum allowable loss criterion of 15%, sodium sulfate soundness test was not able to identify any aggregates that were rated as being “fair” or “poor” in field performance.

5.1.5 British Tests: AIV and ACV

Two tests that specifically test abrasion resistance are the aggregate impact value (AIV), and the aggregate crushing value (ACV) tests. Developed and used throughout Britain, these tests are performed on aggregate fractions between 10 mm and 14 mm. The process for the AIV test, as explained in Saeed et al. (2001), involves placing aggregate particles in a cylindrical rigid mold and subjecting15 blows using a 30-lb drop hammer dropped from a height of 15 in. The ACV test is similar, except a 4.4 lb of aggregate is placed in a specially designed apparatus with a load of 90,000 lb which is increased gradually over ten minutes. In both tests the percentage of fines created that pass the No. 8 sieve are determined to be the AIV or ACV (Saeed et al. 2001). No significant use in the U.S. supports the validity of these tests.

5.1.6 Summary: PCC Testing

At this point the best predictors of PCC performance against studded tires is seen in aggregate tests, despite many conflicting opinions. It appears that the Nordic Abrasion, LA Abrasion, and Mico-Deval are the leading tests and there seems to be most potential with the Micro-Deval due to its incorporation of wet conditions. A number of other abrasion tests exist, but none that are necessarily related to stud wear resistance. Some of these test however, may have the potential to be modified to better predict stud wear.

5.2 Summary: Test Methods

- The three main tests for aggregate durability which have a debatable link to studded tire resistance are the Nordic Abrasion, LA Abrasion, and Micro-Deval tests.
- There appears to be some consensus on the Micro-Deval test however, there are detractors (e.g., Hunt 2001) and also reports that the Micro-Deval is not all that accurate either (Cooley et al. 2002).

6 CONCLUSIONS AND RECOMMENDATIONS

The information presented in this report describes the negative implications of studded tire use and some of the measures that can be taken to reduce these effects. Based on this information the following conclusions and recommendations are presented regarding stud wear in Washington state and the measures to correct and minimize stud damage, deter use, and predict wear.

6.1 Conclusions

6.1.1 Studded Tire Use

- **Studs cause PCC wheelpath wear**. Studs are likely responsible for nearly 100% of wheelpath wear on Washington PCC pavement.
- **Stud use rates are difficult to quantify**. The best estimation for stud use in Washington is about 10% in western Washington and 32% in eastern Washington.

6.1.2 Washington PCC Pavement

Note that these conclusions are based on an analysis of WSPMS 2004 only. Project-specific measurements have shown different wear rates in some cases.

- **Stud volumes across Washington State are comparable**. In general, western Washington has higher AADTs and lower stud use, while eastern Washington has lower AADTs and higher stud use. Given the existing data, there does not seem to be much merit to the argument that stud traffic is significantly higher in eastern Washington with the possible exception of I-90 through Spokane.
- **Higher stud volumes generally correlate with lower PRC ratings**. This is a weak conclusion because most PCC pavement in eastern Washington has similar low stud traffic making it difficult to spot a general trend.
- **The average PCC pavement wear rate across Washington State is about 0.25 mm per 1 million studded vehicle passes according to WSPMS data**. This holds true for both western and eastern Washington with few exceptions.

- **The highest stud wear rates are near 0.50 mm/yr according to WSPMS data**. These occur on I-90 in the Spokane area.
- **The lowest stud wear rates are in the range of 0.04 to 0.09 mm/yr according to WSPMS data**. These rates occur in many locations. It is likely that this wear rate over the life of a pavement is about as low as can be expected in Washington State.
- **Stud wear is quicker at the beginning of a PCC pavement's surface life.** It is fairly clear that PCC pavement surfaces wear more quickly during the first 5 years of existence and then wears more slowly after that. The general assumption is that the initial high wear rate occurs as the paste on the pavement surface from finishing is worn off, and the lower ultimate wear rate occurs as the underlying aggregate becomes the controlling factor. This phenomenon occurs in new pavements as well as those rehabilitated with diamond grinding.
- **Excessive stud wear problems are limited and not a widespread issue in Washington State.** Most pavement sections showed reasonably small wear rates. It is likely that excessive wear rates are driven by a project-specific factor rather than general wear issues. The most plausible explanation is that some projects have knowingly or unknowingly used a softer aggregate. Since all three sections showing excessive wear rates beyond their first year are near Spokane, aggregate sources there may be the culprit. In some cases lane specific wear rates as high as 45 mm in 15 years have been reported but not in all lanes of a multi-lane section.

6.1.3 Paving Practices to Mitigate Stud Wear

- **Diamond grinding is the most cost effective measure**. Of the three main ways to rehabilitate damaged PCC pavement it appears as though diamond grinding is the most cost effective measure, especially to correct stud wear in Washington. HMA overlays are also a viable option, although they are just as susceptible to stud wear as PCC and thus are likely to suffer a recurrence of the same stud wear problem.
- **Some new research shows potential for reducing stud wear**. Based on some of the newer PCC research and experiments, practices that have potential to reduce stud wear include resin modified pavements and surface texture techniques such as carpet drag that expose less surface area.

6.1.4 Stud Alternatives

There are alternatives to the current design for studded tires that offer at least some improved winter traction on compacted snow and ice. These include: all season tires, retractable studs, and lighter-weight studs, GoClaw and Green Diamond Tires. Alternatively, concentration can be turned away from tire technology and focused on anti-icing measures to improve winter traction.

6.1.5 Testing Measures

- **There are no tests that accurately predict studded tire wear on PCC pavement**. There are three main tests that are sometimes used to estimate wear: Nordic Ball Mill, LA Abrasion, and Micro-Deval. Among research on these tests there is significant conflicting evidence as to the accuracy and ability to predict stud wear. The Micro-Deval test has been the most favorably rated test however it too has detractors.

6.2 Recommendations

- The mix designs and construction practices of the highest and lowest performing pavements discussed should be investigated for further insight, specifically sections with high stud traffic and low wear rates.

- Some of the newer constructed and reconstructed pavements with low wear rates should also be looked at in more detail (especially in western Washington) as they are actually out-performing many of the older pavements due to the increase in traffic over time.

- Based on both cost and performance, diamond grinding should be considered to extend PCC pavement life when studded tire wear is the primary distress. The current practice of building in an extra sacrificial inch of PCC pavement thickness to account for future diamond grinding is a sound policy and should be continued.

- For older thin PCC pavements (typically 8 or 9 inches thick) an additional HMA lift or wearing course is a sound option to extend pavement life.

- Further experimental practices should be conducted targeting some of the ideas suggested in this report, specifically resin-modified surface courses.

- A hardness specification program, such as Alaska’s, should be investigated in order to ensure that future PCC pavement does not use aggregate that is susceptible to excessive studded tire wear. Similarly, a grading system for the use of recycled concrete could also improve new mixes.

REFERENCES

AFCESA/CES. (2001). Engineering Technical Letter (ETL) 01-8: Resin Modified Pavement (RMP) Design and Application Criteria. Department of the Air Force, Headquarters, Air Force Civil Engineer Support Agency, Tyndall AFB, FL. http://www.alyancorp.com/ETL_2001-8.pdf. Accessed 8 September 2007.

American Concrete Pavement Association (ACPA). (1998). Rubblizing of Concrete Pavements: A Discussion of its Use. American Concrete Pavement Association. http://www.pavement.com/Downloads/Rubblization.pdf.

American Concrete Pavement Association (ACPA). (2006). R&T Update Concrete Pavement Research and Technology: Diamond Grinding Shines in California and Missouri. American Concrete Pavement Association. http://www.pavement.com/Downloads/RT/RT7.01.pdf.

Anderson, K.W.; Uhlmeyer, J. and Pierce, L.M. (2007b). Studded Tire Wear Resistance of PCC Pavements. Washington State Department of Transportation, Olympia, WA. http://www.wsdot.wa.gov/biz/mats/pavement/Argonne_SullivanDraftReport.pdf.

Angerinos, M.J.; Mahoney, J.P.; Moore, R. (1999). A Synthesis on Studded Tires. Washington State Department Transportation, Olympia, WA. http://www.wsdot.wa.gov/research/reports/fullreports/471.1.pdf.

Ansari, F.; Maher, A. Luke, A.; Zhang, G.Y. and Szary, P. (2000). Recycled Materials in Portland Cement Concrete. FHWA 2000-03. New Jersey Department of Transporation and Federal Highway Administration, Trenton NJ and Washington D.C. http://cait.rutgers.edu/files/FHWA-NJ-2000-003.pdf. Accessed 11 February 2010.

Bailey, L. (2005). U-M professor's work will bend, but not break. The University Record Online. University of Michigan. http://www.umich.edu/~urecord/0405/May09_05/02.shtml. Accessed 11 February 2010.

Battey, R.L. and Whittington, J.S. (2007). Construction, Testing and Performance Report, State Study No. 137 Resin Modified Pavement Demonstration Project. Mississippi Department of Transportation & Federal Highway Administration, Washington, DC. http://www.gomdot.com/research/pdf/SS137.pdf. Accessed November 2007.

Concrete Paving Association of Minnesota. (2002). The True Cost of Unbonded PCC Overlays. Concrete Conveyor, Volume 2002, Issue 3. http://www.concreteisbetter.com/conveyor_newsletters/vol_2002_issue3_oct.pdf.

Concut Diamond Products. (no date given). Aggregate Classification Map of the United States. Concut website. http://www.concutusa.com/aggmap.html. Accessed 6 April 2009.

Cooley, L.A.; Huner, M.S. and James, R.H. (2002). Micro-Deval Testing of Aggregates in the Southeast. NCAT Report No. 02-09. National Center for Asphalt Technology, Auburn, AL. http://www.eng.auburn.edu/center/ncat/reports/rep02-09.pdf. Accessed 11 February 2010.

Federal Highway Administration (FHWA). (1999). Silica Fume. FHWA, Washington, D.C. http://www.fhwa.dot.gov/infrastructure/materialsgrp/silica.htm. Accessed 11 February 2010.

Federal Highway Administration (FHWA). (2004). Transportation Applications of Recycled Concrete Aggregate: FHWA State of the Practice National Review. FHWA, Washington, D.C. http://www.recycledmaterials.org/Research/tools/RCAREPORT.pdf. Accessed September 2007.

Federal Highway Administration (FHWA). (2006a). Concrete Pavement Rehabilitation Guide for Diamond Grinding. FHWA, Washington, D.C. http://www.fhwa.dot.gov/pavement/concrete/diamond.cfm. Accessed 13 September 2007.

Federal Highway Administration (FHWA). (2006b). High Performance Concrete Pavements Technical Summary of Results from Test and Evaluation Project 30. Publication No: FHWA-IF-06-032. FHWA, Washington, D.C. http://www.fhwa.dot.gov/pavement/concrete/hpcp/techsumm.pdf. Accessed 18 September 2007.

Federal Highway Administration (FHWA). (2007b). Portland Cement Concrete Overlays. Publication No: FHWA-RC-BAL-04-0015. Federal Highway Administration, Washington, D.C. http://www.fhwa.dot.gov/pavement/concrete/overlays.pdf. Accessed 19 September 2007.

Federal Highway Administration (FHWA).(2007a). Long-Life Concrete Pavements in Europe and Canada. FHWA, Washington, D.C. http://international.fhwa.dot.gov/pubs/pl07027/index.cfm. Accessed 20 September 2007.

Frith, D.J.; Morian, D.A.; Stoffels, S.M. and Saboundjian, S. (2004). Hard Aggregate Resistance to Studded Tires: Alaskan Experience. Transportation Research Record 1874. TRB, National Research Council, Washington, D.C., pp. 19-28.

Hunt, E.A. (2001). Mirco-Deval Coarse Aggregate Test Evaluation. Oregon Department of Transportation, Salem, OR. http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/MicroDeval.pdf. Accessed September 2007.

Idaho Transportation Department (ITD). (2001). Preventative Maintenance – Section 524. ITD, Boise, ID. https://www.itd.idaho.gov/manuals/Online_Manuals/Current_Manuals/Materials/Sec%20542.pdf. Accessed 2 October 2007.

Kay, R.K., Mahoney, J.P. and Jackson, N.C. (1993). The WSDOT Pavement Management System – A 1993 Update. Report No. WA-RD 274.1. Washington State Department of Transportation, Olympia, WA.

Kuennen, T. (2004). America's Quest for Premium Aggregates. Better Roads 74(8), pp. 24-34.

Kuennen, T. (2006). Concrete Update: FHWA’s Major Concrete Initiative Only Part of Dynamic Change. Expressways Online. http://www.expresswaysonline.com/expwys/concrete%2004.html. Accessed 19 September 2007.

Lang, A.P.; Range, P.H.; Fowler, D.W. and Allen, J.J. (2006). The Prediction of Coarse Aggregate Performance by Micro-Deval and Other Aggregate Tests. Research Report ICAR 507-1F. Aggregates Foundation for Technology, Research and Education. http://www.icar.utexas.edu/reports/507-1F.pdf. Accessed September 2007.

Li, V. (1997). Engineering Cementitious Composites (ECC) – Tailored Composites Through Micromechanical Modeling. Fiber Reinforced Concrete: Present and the Future, Eds: N. Banthia, A. Bentur, and A. Mufti, Canadian Society of Civil Engineers. http://www.engineeredcomposites.com/publications/csce_tailoredecc_98.pdf.

Malik, M.G. (2000). Studded Tires in Oregon: Analysis of Pavement Wear and Cost of Mitigation. Oregon Department of Transportation, Salem, OR. http://www.oregon.gov/ODOT/CS/FS/docs/other/STUDDED_TIRES.pdf.

Muench, S.T.; Mahoney, J.P.; Pierce, L.M.; Uhlmeyer, J. and Anderson, K. (2006). The Evolution of Long-Life Concrete Pavements in Washington State. Proceedings of the International Conference on Long-Life Concrete Pavements, 24-27 October 2006, Chicago, IL.

North Dakota Department of Transportation (NDDOT). (2007). Project Cost History. North Dakota Department of Transportation. http://www.dot.nd.gov/manuals/designmanual/wordfiles_design/cost-history.pdf. Accessed October 2007.

Oregon Department of Transportation Road User Fee Task Force (ODOT Task Force). (2003). Road User Fee Task Force Meeting Minutes for 3 May 2002. Report to the 72nd Oregon Legislative Assembly. http://www.oregon.gov/ODOT/HWY/OIPP/docs/FinalReportKK2003march.pdf.

Qualitest International, Inc. (2009). Los Angeles Abrasion Tester - LA Abraser / Abrader for Concrete. http://www.qualitestinc.com/losangelesabrasion.htm. Accessed 17 October 2007.

Rangaraju, P.R.; Edlinski, J. and Amirkhanian, S. (2005). Evaluation of South Carolina Aggregate Durability Properties – Executive Summary. . FHWA-SC-05-01. Federal Highway Administration, Washington, D.C. http://www.clemson.edu/t3s/scdot/pdf/projects/SPR%20636.pdf.

Saeed, A.; Hall, J.W. and Barker, W. (2001). NCHRP Report 453: Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers. Transportation Research Board, National Research Council, Washington, D.C.

Stubstad, R.; Darter, M.; Rao, C.; Pyle, T. and Tabet, W. (2005). Report on the Effectiveness of Diamond Grinding Concrete Pavements in California. Caltrans, Sacramento, CA. http://www.igga.net/downloads/rehab/CaltransGrindingReportMay2005.pdf. Access 11 February 2010.

Washington State Department of Transportation (WSDOT). (2003). Studded Tire Use in Washington State. WSDOT webpage from 2003 archived on the Green Diamond Tire website. http://greendiamondtire.com/wsdot.pdf. Acccessed 10 September 2007.

Washington State Department of Transportation (WSDOT). (2006). Pavements and Studded Tire Damage. http://www.wsdot.wa.gov/biz/mats/pavement/PavementsStuddedTiresFinalv2.pdf. Accessed 8 September 2007.

Washington State Department of Transportation (WSDOT). (2007). Studded Tire Information. WSDOT web page. http://www.wsdot.wa.gov/winter/studtire. Accessed 6 September 2007.

Zubeck, H.; Aleshire, L.; Harvey, S.; Porhola, S. and Larson, E. (2004). Socio-Economic Effects of Studded Tire Use in Alaska. University of Alaska Anchorage, Anchorage, AK. http://www.engr.uaa.alaska.edu/research/upload/StuddedTiresInAlaska.pdf.