Portland Cement Concrete Pavement Best Practices Summary Report

WA-RD 744.1

Stephen T. Muench

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PCCP Best Practices

Portland Cement Concrete Pavement Best Practices Summary Report

By
Stephen T. Muench
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

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16. ABSTRACT

This report summarizes the work and findings from WA-RD 744. This work consisted of four separate efforts related to best practices for portland cement concrete (PCC) pavement design and construction: (1) a review of past and current PCC pavement, (2) an analysis of PCC pavement studded tire wear on the WSDOT network, (3) a life cycle assessment (LCA) of PCC pavement rehabilitation options and (4) an analysis of the effects of loop detector installation on PCC pavement life. Key findings are: (1) outstanding issues to resolve with PCC pavement include the impact of smaller maximum aggregate size, new dowel bar materials, and shorter joint spacing, (2) there is no effective means to mitigate studded tire wear, (3) stud wear is typically in the range of 0.04-0.09 mm/yr but tends to occur more quickly early on in pavement life, (4) excessive stud wear problems are limited and not a widespread issue, (5) an aggregate hardness program like Alaska's can help ensure stud wear does not become a major issue on newly constructed pavements, (6) life cycle assessment (LCA) can be a useful information tool and tends to show that crack, seat and overlay rehabilitation of aged PCC pavement provides many environmental advantages; and (7) current loop embedment practices do not seem to affect pavement life however previous practices may have.

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

1 INTRODUCTION

WSDOT is responsible for over 2,300 lane-miles (3,700 lane-km) of concrete pavement. Of this, about 38 percent is over 35 years old including most of the heavily traveled Interstate 5 urban corridor through the Tacoma-Seattle-Everett area. These older pavements have lasted far beyond their original 20-year design life and have endured perhaps an order of magnitude more traffic loading than their original design anticipated while remaining in serviceable condition with little to no maintenance or rehabilitation. However, as the age of concrete pavements placed largely during the Interstate construction era (1950s through 1980s) continues to increase it is worthwhile to consider how the next generation of concrete pavements will be evaluated, designed, constructed, maintained and (ultimately) disposed. The WA-RD 744 series of reports (WA-RD 744.1 through WA-RD 744.5) discusses the most relevant issues in these areas to include:

1. A review of past and current PCC pavements to include design and construction parameters, performance, issues encountered that are largely solved and issues encountered that have yet to be solved (WA-RD 744.2).
2. Studded tire wear on PCC pavements including its effects, extent and severity across the WSDOT PCC pavement network and potential opportunities for improvement (WA-RD 744.3).
3. Life cycle assessment of PCC pavements including a discussion of the utility of such a technique, its limitations and an example on I-5 in King County (WA-RD 744.4).

4. A review of the impact of loop detector installation on PCC pavement to include effects on pavement life, life cycle costs of loop detectors and trends in the I-5 King County area (WA-RD 744.5).

2 REVIEW OF PAST AND CURRENT PCC PAVEMENTS

WSDOT is responsible for over 2,300 lane-miles (3,700 lane-km) of concrete pavement. Much of that pavement is on the major highways within the state (I-5, I-82, I-90, I-182, US 195, I-205 and I-405). Table 1 shows conditions as of 2004 on these major routes.

Table 1. Concrete Pavement Condition as of 2004 on the Major Routes

SR	Total ln-miles (ln-km)	Weighted IRI Avg. inches/mile (m/km)	Weighted Wear Avg. inches (mm)	Percent of Panels Cracked (cracks/panel)			Percent Panels Faulted inches (mm)		
				1	2 – 3	4+	0.1-0.2 (3-6)	0.2-0.5 (6-13)	0.5+ (13+)
5	502 (808)	138.7 (2.19)	0.19 (4.8)	7	1	0	5	2	0
82	366 (589)	97.5 (1.54)	0.23 (5.8)	1	0	0	1	0	0
90	331 (533)	125.4 (1.98)	0.20 (5.1)	6	1	0	2	0	0
182	60 (96)	86.7 (1.37)	0.22 (5.6)	1	0	0	0	0	0
195	59 (95)	146.9 (2.32)	0.21 (5.3)	4	2	0	9	2	0
205	39 (62)	125.4 (1.98)	0.22 (5.6)	3	0	0	3	0	0
405	30 (48)	157.0 (2.48)	0.21 (5.3)	5	1	0	4	1	0
Total or Avg.	1,386 (2,231)	122.85 (1.94)	0.21 (5.2)	3.9	0.7	0.0	3.4	0.7	0.0

Of note, average IRI, wear depth, cracking and faulting are generally quite good. However, specific sections of these routes can exhibit significantly different conditions.

2.1 Past and Current Pavement Findings from WA-RD 744.2

Lessons learned from these pavements are both positive and negative and have shaped the WSDOT state-of-the-practice for PCC pavements:

- **Design life**. While 20 years was deemed adequate 50 years ago, past actions demonstrate that most pavements are asked to perform 40 plus years with little or no rehabilitation. The current 50-year design life practice reflects this experience and is appropriate. However longer design lives do not avoid an eventual end-of-life condition.
- **Thickness design**. Original pavements were on the order of 8-9 inches (200-225 mm) of concrete over of 4-6 inches (100-150 mm) of crushed aggregate base. More accurate traffic projections and more advanced design tools have led to designs of up to 12 inches (300 mm) of concrete plus an additional 1 inch (25 mm) expected to be removed during a future diamond grinding to restore smoothness. However, this approach does not, fundamentally, eliminate studded tire wear.
- **Base material**. The original pavements generally used crushed aggregate bases 4-6 inches (100-150 mm) thick. Currently, 0.35 ft (105 mm) of HMA over 0.35 ft (105 mm) of aggregate base is used to limit base deflection and pumping. To date, this has been successful and should be continued.
- **Mix design**. Older PCC pavements contained maximum aggregate sizes of up to 2.5 inches (62.5 mm). Although not mandated by specification, recent maximum aggregate size has been as small as 0.75 inches (19 mm) for new pavements. Cement fineness has increased and more variation in mixes is typical because mix

design is done by contractors rather than centrally by WSDOT. These changes may or may not affect long-term pavement performance items such as load transfer and ultimate strength. To date, no adverse effects have been seen.

- **Joints**. Transverse joint spacing remains consistent near 15 ft (4.6 m), as does the basic joint formation technique of single sawing and filling with hot poured sealant.
- **Dowel bars.** Original concrete pavements omitted dowel bars; however they are now consistently used to minimize faulting potential. Dowel bar use should be continued. While new dowel bar materials (e.g., stainless steel) look promising, they still lack long-term field performance data.
- **Surface considerations**. Studded tire wear has been an issue in Washington and it is likely to remain so. Elimination of studded tires is not likely so research to mitigate their effects continues but has, to date, met little success.

2.2 Significant Remaining PCC Pavement Issues from WA-RD 744.2

- The impact of smaller maximum aggregate size on pavement life is unknown.
- Long-term field performance of new dowel bar materials is unknown.
- A shorter joint spacing (i.e., 12 ft (3.7 m)) may help reduce the risk of early age (first 72 hours) cracking and reduce long-term slab stresses.
- WSDOT does not yet have a “quiet” (i.e., less than 100 dBA by on-board sound intensity measurement) PCC pavement surface.
- Rapid PCC construction contracting is not yet standard practice.

- The end-of-life remove-and-replace practice for PCC pavement may not be the best use of materials or money.
- Knowledge of concrete rehabilitation techniques and new construction is probably at an all time low, primarily due to the infrequent work on concrete pavements over the last 25 to 30 years. Training must continue to address this.
- The durability and long-term performance of current cements (including fast setting hydraulic cements) is not well understood.
- There is no effective mitigation strategy for studded tire wear.

3 STUDDED TIRE WEAR

Studded tire wear on PCC pavements is an issue for WSDOT but its extent is perhaps less than thought. Even so, studded tire wear is a significant contributor to pavement condition deterioration and noise. Short of a political ban, there is currently no feasible way to eliminated it.

3.1 Studded Tire Wear Conclusions from WA-RD 744.3

Studded tire use

- **Studs cause PCC wheelpath wear**. Studs are likely responsible for nearly 100% of wheelpath wear on WSDOT 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.

Washington PCC Pavement

- **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 (Figure 1). 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.

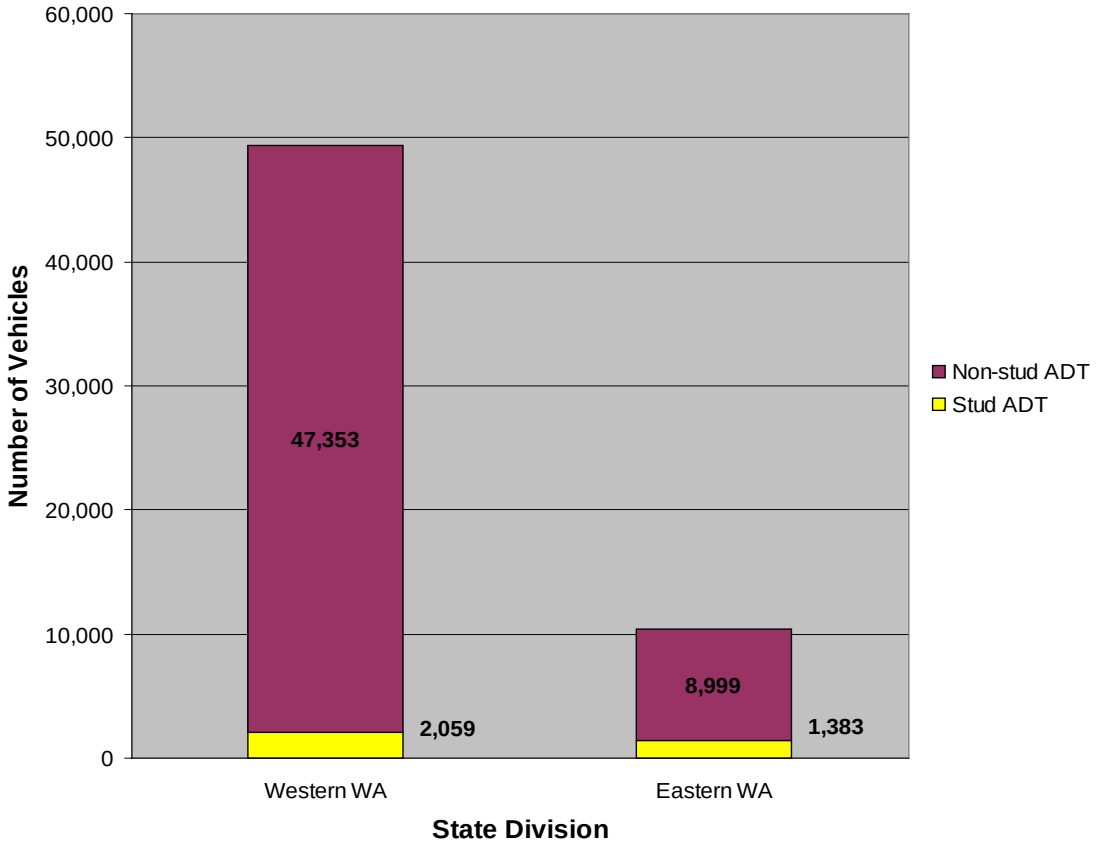

Figure 1: Average traffic levels in western Washington and eastern Washington showing non-stud ADT (top) and stud ADT (bottom).

- **Higher stud volumes generally correlate with lower wear depth ratings (Figures 2 and 3)**. 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.

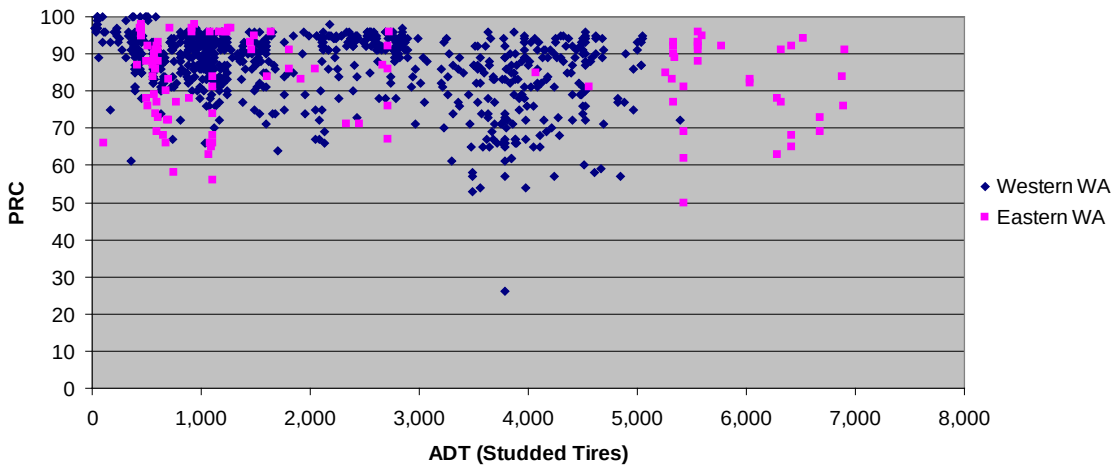

Figure 2: PRC vs. stud ADT.

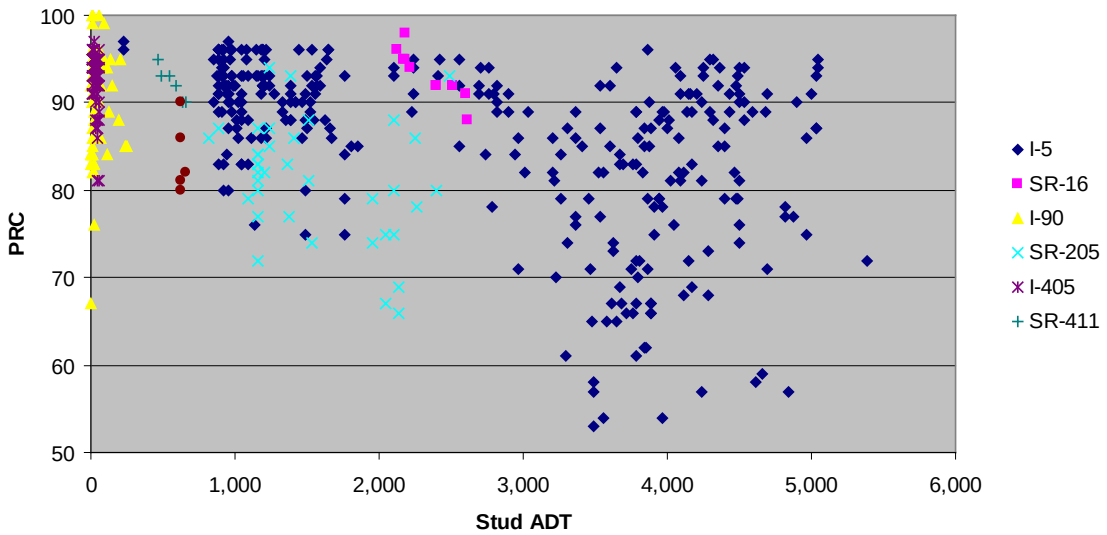

Figure 3: Distribution of PRC vs. stud ADT by western highway.

- **The average PCC pavement wear rate across Washington State is about 0.01 inches per 1 million studded vehicle passes (Figures 4 and 5)**. This holds true for both western and eastern Washington with few exceptions.

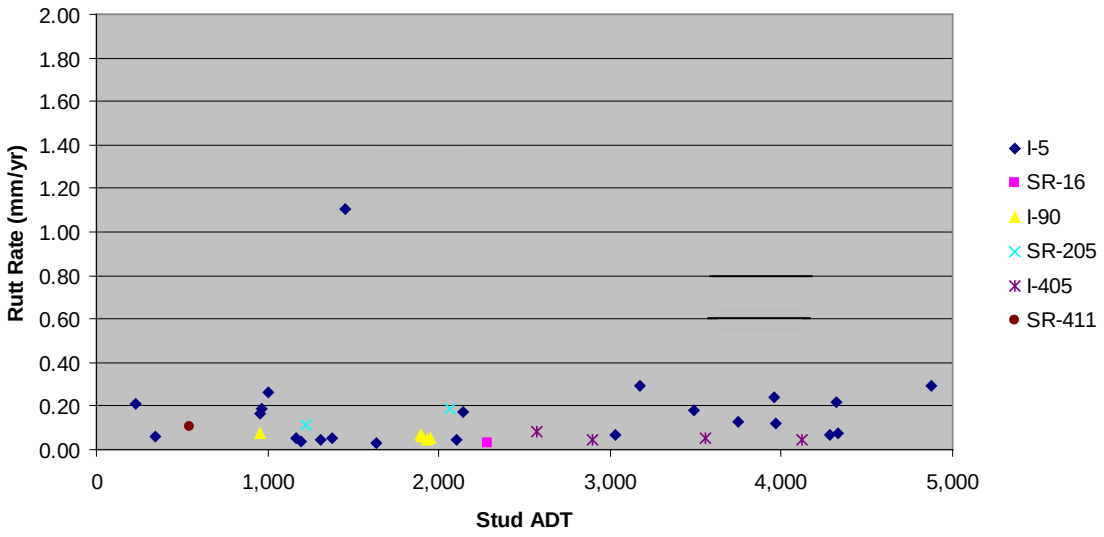

Figure 4: Western stud ADT vs. wear rate.

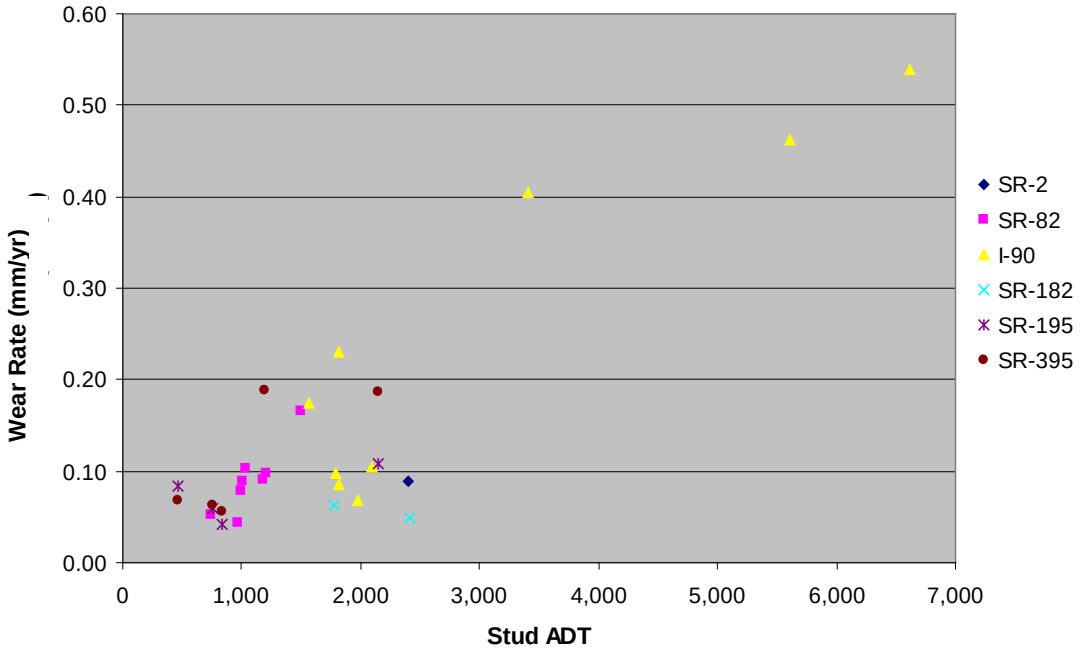

Figure 5: Eastern stud ADT vs. rut rate.

- **The highest stud wear rates are near 0.50 mm/yr according to 2004 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 2004 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.

Paving Practices to Mitigate Stud Wear

- **Diamond grinding is the most cost effective measure**. Of the three main ways to rehabilitate damaged PCC pavement (diamond grinding, HMA overlays, PCC

overlays) diamond grinding is the most cost effective measure to correct stud wear in Washington. HMA overlays are also a viable option, although they are just as susceptible to stud wear as PCC.

- **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.

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.

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.

3.2 Studded Tire Recommendations from WA-RD 744.3

- 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.

4 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) is a tool used to summarize the inputs and outputs of a system or process, usually in an environmental context. It identifies all "cradle to grave" inputs and outputs of a system that are relevant to the environment. The collection of all processes from cradle to grave allows LCA to provide a cumulative total of inputs and outputs for that final product and the environmental impacts associated with those inputs and outputs. These environmental flows can include, but are not limited to, raw materials input, energy input, solid waste output, air emissions, water emissions, and any final products or co-products.

4.1 Pavements Compared Using LCA in WA-RD 744.4

WA-RD 744.4 compares the environmental impact of three different options for replacing an existing PCC pavement (Figure 6) over an analysis period of 50 years. This existing pavement section was chosen to represent typical conditions on I-5 in the greater Seattle area. Replacement options are:

- **Remove and replace with new PCC pavement**. Remove the existing 9 inches of PCC and replace with 13 inches of doweled PCC (Figure 7).
- **Remove and replace with new HMA pavement**. Remove the existing 9 inches of PCC and replace with 13 inches of HMA placed in five lifts (Figure 8).
- **Crack, seat and overlay (CSOL)**. Crack seat and overlay the existing pavement with 5 inches of HMA placed in two lifts (Figure 9).

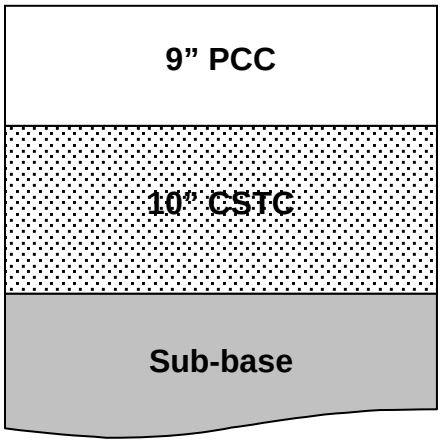

Figure 6. Cross-section of Existing PCC Highway.

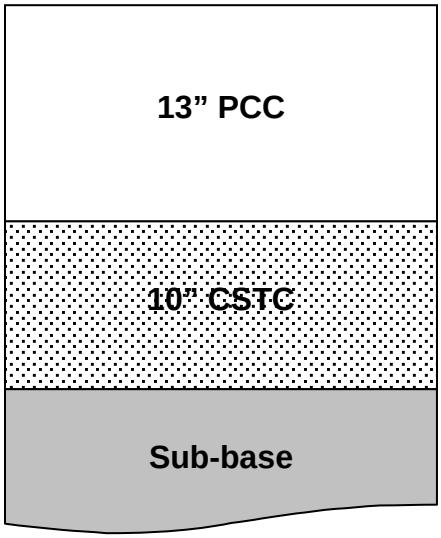

Figure 7. Cross-section of PCC replacement option.

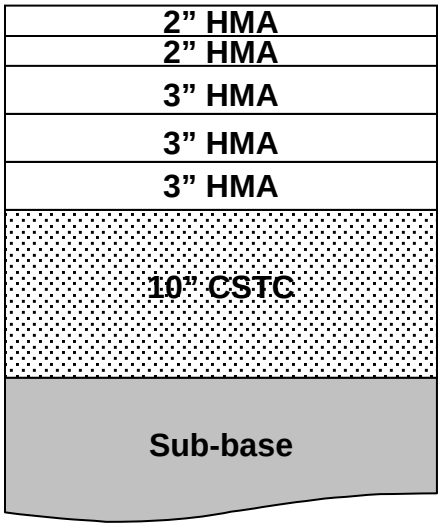

Figure 8. Cross-section of HMA replacement option.

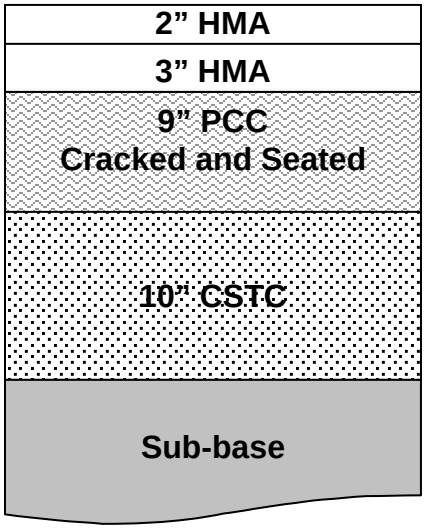

Figure 9. Cross-section of CSOL option.

Table 2 shows the assumed rehabilitation schedule for each option over the 50-year analysis period.

Table 2. Pavement Preservation Schedule

Scenario	Maintenance	Year
PCC Replace	Diamond Grind 1	20
	Diamond Grind 2	40
	Diamond Grind 3	50
HMA Replace	Mill and Fill 1	16
	Mill and Fill 2	32
	Mill and Fill 3	48
CSOL	Mill and Fill 1	16
	Mill and Fill 2	32
	Mill and Fill 3	48

These options are not meant to comprehensively evaluate current WSDOT design standards with LCA. Rather, they were chosen as representative of potential pavement designs for a new pavement on I-5. Even if the ultimate pavement replacement options do not exactly match those analyzed in WA-RD 744.4, the relative relationship between the options is unlikely to change. In general, the LCA considered the processes associated with paving as shown in Figure 10.

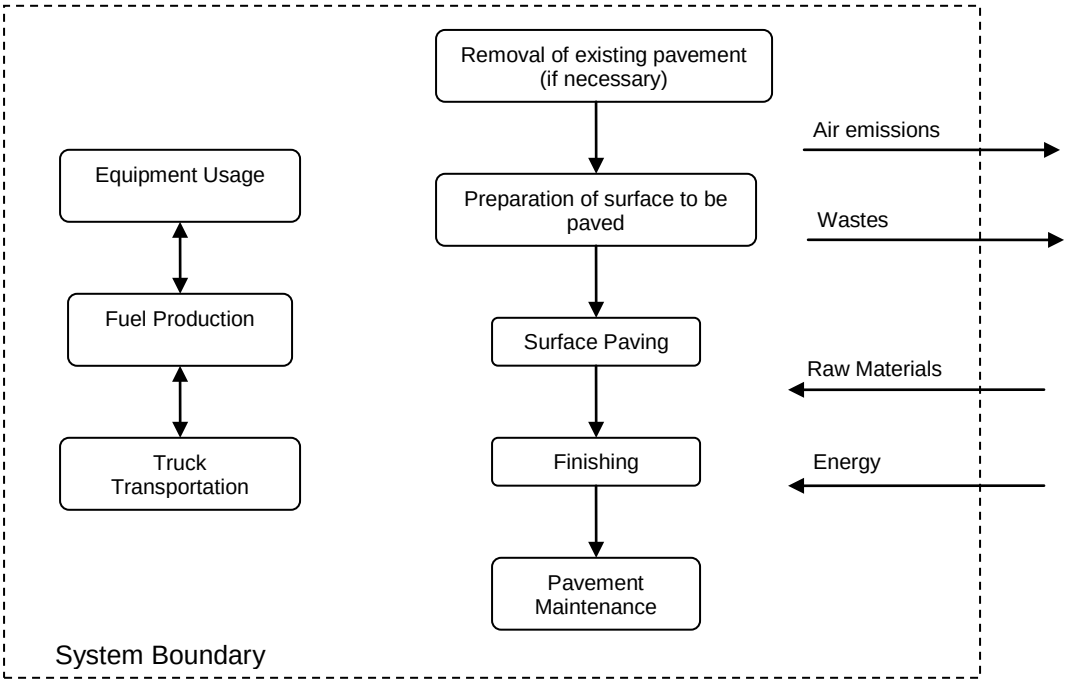

Figure 10. Sequence of main activities and scope included in LCA.

4.2 LCA Results from WA-RD 744.4

General LCA results are usually presented in the following order:

1. **Life cycle inventory (LCI)**. All environmental flows are evaluated and the results are compiled in terms of amounts associated with each process.

2. **Impact assessment**. Information is used to help interpret LCI amounts by determining the relative environmental impacts of those amounts. For instance, total SO_2 emissions may come from the LCI and the acid rain potential resulting from those emissions may be determined in the impact assessment.

3. **Interpretation**. Formulation of any conclusions or recommendations that help achieve the goal of the LCA. The interpretation should include limitations of the

study and descriptions of what additionally could be done to improve or expand the LCA.

Life cycle inventory (LCI). Table 3 shows the results.

Table 3. Life Cycle Inventory Results of New Highway Options

Input or Output	Units	PCC Replace	HMA Replace	CSOL
Total Energy	BTU	-3.84E+09	-5.90E+09	-3.28E+09
Fossil Fuels	BTU	-2.64E+09	-5.26E+09	-2.92E+09
Coal	BTU	-1.42E+09	-2.40E+08	-1.34E+08
Natural Gas	BTU	-5.09E+08	-3.10E+09	-1.75E+09
Petroleum	BTU	-7.19E+08	-1.92E+09	-1.03E+09
CO_2	g	5.25E+08	3.43E+08	1.91E+08
CO	g	1.31E+06	7.91E+05	4.47E+05
NO_x	g	1.41E+06	1.55E+06	8.66E+05
SO_x	g	1.20E+05	1.26E+05	6.98E+04
CH_4	g	3.31E+05	7.95E+05	4.45E+05
$PM_{2.5}$	g	9.02E+04	7.30E+04	4.13E+04
PM_{10}	g	1.32E+06	2.26E+05	1.28E+05
SO_2	g	5.62E+05	6.43E+05	3.66E+05
N_2O	g	1.58E+03	6.13E+03	3.39E+03
VOC	g	6.73E+04	1.74E+05	9.71E+04

*The red numbers illustrate the highest fuel use/emissions.

From this table it appears that in no case does CSOL give the highest fuel use or emissions. HMA and PCC are the largest contributors in several categories.

Impact Assessment. Impacts were tabulated for total energy use, global warming potential (GWP), acidification, human health criteria for air pollution, eutrophication, and photochemical smog. Table 4 shows the impact assessment and highlights the largest value for each impact in red text.

Table 4. Impact Category Results

Environmental Impact Category	Equivalence Unit	PCC Replace	HMA Replace	CSOL
Total Energy Usage	BTU	3.84E+09	5.90E+09	3.28E+09
Global Warming Potential	kg CO_2	5.32E+05	3.61E+05	2.01E+05
Acidification	moles H+	9.12E+04	1.01E+05	5.68E+04
HH Criteria Air	milli - DALYs	1.33E+02	4.13E+01	2.34E+01
Eutrophication	kg N	6.26E+01	6.84E+01	3.84E+01
Photochemical Smog	g NO_x	1.48E+03	1.69E+03	9.49E+02

These impact categories indicate that the CSOL option is the best all-around for the environment and that HMA and PCC might be equally impactful, with different environmental consequences for each. The HMA replacement option uses more energy but the PCC replacement option contributes much more to global warming.

Interpretation. An effort was made to determine the relative contribution of each process within an option to the overall inventory and impact of that option. Figures 11 and 12 show that the overwhelming contributor to all three rehabilitation options is materials production (i.e., production of asphalt, cement, HMA and PCC). This suggests that efforts to reduce environmental impact could be focused on the materials production or higher use of recycled products in order to have the biggest impact.

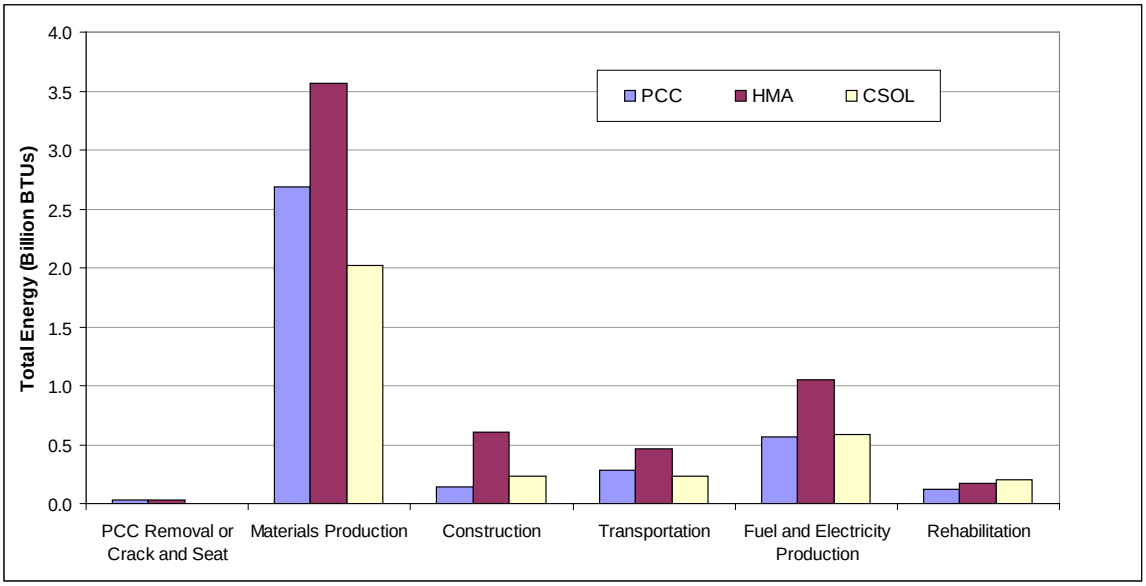

Figure 11. Total energy contribution analysis.

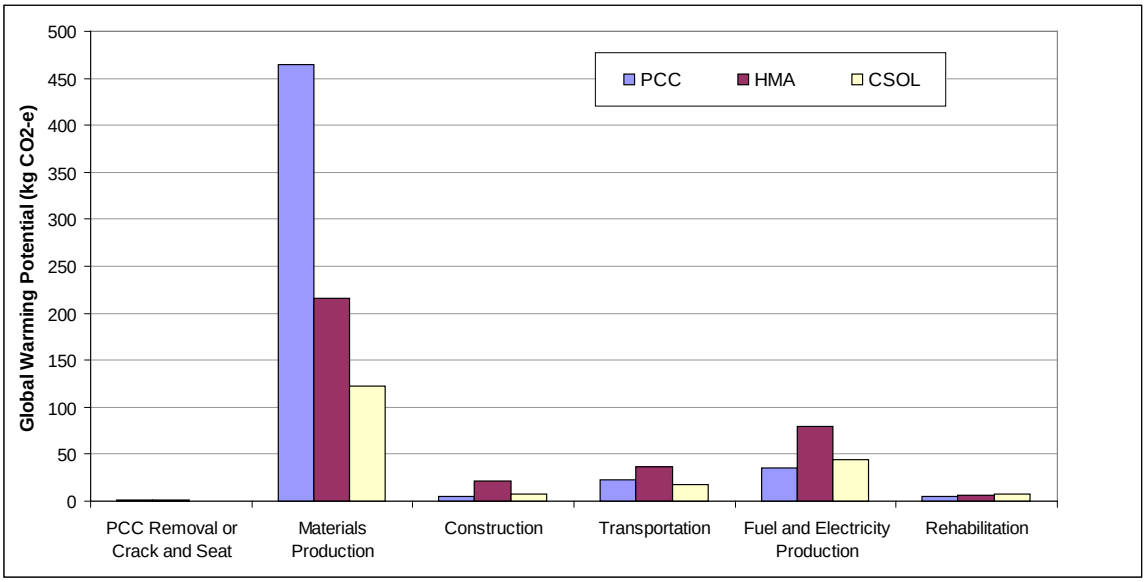

Figure 12. Global warming potential contribution analysis.

4.3 Recommendations Based on LCA from WA-RD 744.4

Overall it appears that CSOL uses the least amount of energy and contributes the least to the environmental impacts studied in this LCA. This is the case because it requires the least amount of paving material and because the existing pavement does not have to be

removed. The contribution analysis showed that the largest contributors to all of the environmental impacts were the production of the paving materials (bitumen, HMA, PCC). That being said, CSOL will not necessarily always be the best option for a situation like this. The existing pavement has to still be on a solid base and the pavement surface has to be raised by the thickness of the overlay, which could create extra work at bridge overpasses and with shoulder work. CSOL used 44% less energy than the HMA option and 15% less energy than the PCC option and contributed 62% less than PCC to global warming and 44% less than HMA to global warming. Not only this, but the CSOL would likely be the least expensive option as well because it requires the least amount of labor and materials. A big assumption that was made in this study was that the CSOL pavement would have the same structural integrity and useful life as the other two options. This is still unknown because this practice is relatively recent having been done extensively in only the last 20 years or so. The best recommendation for WSDOT or another agency may be to investigate the legitimacy of CSOL as a long-life pavement.

It is more difficult to make an environmentally friendly decision when deciding between the remaining two new pavement options. The PCC replacement option was a greater contributor to global warming potential and human health criteria air pollutants, whereas the HMA replacement option was the largest contributor to acidification, eutrophication, and photochemical smog, as well as the largest consumer of energy. These differences seem driven by PCC's larger contribution to CO_2 and particulate emissions and by HMA's larger contribution to nitrogen and sulfur oxides. It is up to the decision-making authority to decide which of these impacts are more important. It may be that the environmental impacts attributed to each pavement type may not be

differentiated enough to warrant one choice over another. The contribution analysis did show however, for all three options, that the largest contributor to each of the impacts was the production of materials. WSDOT or other agencies may want to focus their attention on reducing the impact of material production processes in order to reduce environmental impact.

5 EFFECTS OF LOOP DETECTOR INSTALLATION

WA-RD 744.5 attempts to determine whether or not loop detector installation methods significantly affect long-term PCC pavement performance by assessing the PCC pavement condition surrounding over 800 loop detectors on Interstate 5 (I-5) in King County, and comparing that condition with the general pavement condition in the same area. Condition data is used in combination with workzone traffic delay data associated with loop detector installation to estimate the life-cycle cost of embedded loop detectors.

5.1 Loop Detector Findings from WA-RD 744.5

Major findings were as follows:

- **Results may not be transferrable**. Since there are few (if any) studies on loop embedded PCC pavement panel (LEPs) condition it was not possible to verify results of this study with others. It may be that different study corridors show different results.
- **Comparison by cracking**. LEPs show poorer performance than loop-free panels (LFPs) in terms of cracking except on the small section of I-5 that has been dowel bar retrofitted and diamond ground.

- **Comparison by loop type**. LEPs with circle loops have fewer cracks than those with rectangular loops. This effect is pronounced in panels with two or more cracks. This may not be a reasonable comparison because circle loops were installed much later than the rectangular ones.
- **Cost attributable to shorter panel life from loop detector installation**. Using non-rehabilitated PCCP for calculations, the cost due to shorter panel lifetime because of loop installation is estimated at $560 per loop detector, which is about 25% of the installation cost (this excludes the user cost associated with traffic delay).
- **Cost attributable to traffic delay (user cost)**. The user cost due to traffic delay caused by lane closures can be a significant part of the overall cost of loop installation (around 60% for a 4 lane freeway and about 40% for a 5 lane freeway) if loop installation is the only reason for closing lanes. However, loop detectors are typically installed when lanes are closed for other reasons.
- **Cost comparison between loop and video detectors**. When compared for a 4-lane freeway the inclusion of user costs for loop detector installation makes total lifecycle costs between loop and video detectors comparable and, in situations with high traffic and inexpensive video detectors, can sometimes result in video lifecycle costs being less. While this does not suggest video detectors are universally less expensive (in fact, they are usually more expensive), it does indicate that user costs are important to include in comparing detector costs.

5.2 Loop Detector Recommendations from WA-RD 744.5

The following recommendations are made:

- **Continue using circle loop detectors**. The shape of loop detectors matters for performance of the pavement, and even though the comparison between various shapes may not be accurate because of different installation times, the results indicate that circle loops have less impact on the panel cracking than rectangular shapes. WSDOT has realized this and now only uses circle loops for new installations.
- **Even considering potential PCC damage, loop detectors are still a cost competitive means of traffic detection**. The cost comparison between loop and video detection shows loop detectors are still a more economical solution for traffic detection than video detectors in most situations.
- **Reevaluate user cost**. The simulation to determine user cost for this study used evening traffic volumes (8 p.m. to midnight) but it may be more reasonable to use early morning volumes (say, midnight to 5 a.m.). This could potentially result in lower estimated user costs.
- **Compare loop detection to other detection methods beyond video**. Other traffic detection systems may compare differently to loop detectors.