Life Cycle Assessment of Interstate Highway Pavement Reconstruction Options in Seattle, Washington

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ABSTRACT

Life Cycle Assessment (LCA) is a tool that can be used to identify the environmental impact of a product or process. This paper compares three different replacement options for an aging portland cement concrete (PCC) pavement using LCA process-based protocol. Those options are: remove and replace with PCC pavement, remove and replace with hot mix asphalt (HMA) pavement, and crack-and-seat the existing pavement followed by a HMA overlay. Each option investigated includes a detailed construction and rehabilitation schedule and is analyzed over 50 years. Results show that materials production (e.g., cement, asphalt, PCC, HMA) dominates the energy use, emissions and impacts for all three options. In general, HMA production tends to cause the HMA option to have the highest energy use while cement production tends to cause the PCC option to have the highest global warming potential (GWP). Of significant note, the crack, seat and overlay option was the lowest energy and GWP option and produced the least emissions in more measured categories than the other two options. In the future this may become a strong argument for expansion of the crack, seat and overlay method of rehabilitation.

INTRODUCTION

While still not a common decision metric, life cycle assessments (LCAs) are becoming more common in the transportation community. A LCA is a protocol for quantifying the impacts of an industrial system, such as a road, for all life cycle stages including materials acquisition and processing, construction, maintenance, rehabilitation and ultimate retirement. As such it can quantify items associated with the system such as energy consumption, pollutant emissions and their ecological and human health impacts. These quantifications are becoming more important as decision makers and the general public begin to demand they be accounted for in transportation infrastructure decisions.

Currently, the Washington State Department of Transportation (WSDOT) is analyzing options to ultimately replace 76.5 centerline miles (123 km) of the aging, 40+ year-old portland cement concrete (PCC) pavement on I-5 in the greater Seattle metropolitan area to include all of King County (*1*). This paper seeks to quantify some of the basic energy, environmental and ecological/human health impacts of the three most likely options for reconstructing this segment of I-5 by using LCA protocol. These three options are:

- Remove and replace the existing PCC pavement with new PCC pavement.
- Remove and replace the existing PCC pavement with new hot mix asphalt (HMA) pavement.
- Crack and seat the existing PCC pavement then overlay it with HMA.

Ultimately, LCA results can be used as a decision support tool in making both large and small decisions regarding transportation infrastructure construction.

LIFE CYCLE ASSESSMENT OVERVIEW

A Life Cycle Assessment (LCA) is tool for identifying all “cradle to grave” inputs and outputs of a system that are relevant to the environment. This means that an LCA includes everything from gathering raw materials to the point at which those materials are returned to the environment (*2*). This collection of all processes from “cradle to grave” allows LCA to provide a cumulative total of inputs and outputs for a 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. An inventory of these environmental flows is built upon by assessing the environmental impacts that result, and then using the results to improve the system.

There are two broadly accepted means for conducting LCAs: the process-based approach and an economic input-output approach (see *5* for a comparison). This paper follows ISO 14040 (*3*) and ISO 14044 (*4*) standards for a process-based LCA approach. ISO outlines a systematic four phased approach (*6*):

1. **Goal and scope**. Define the reasons for carrying out the LCA, the intended audience, geographic and temporal considerations, system functions and boundaries, impact assessment and interpretation methods.
2. **Inventory assessment**. Quantify life cycle energy use, emissions, and land and water use for technology use in each life cycle stage.
3. **Impact assessment**. Estimate the impacts of inventory results...
4. **Interpretation**. Investigate the contribution of each life cycle stage, technology use throughout the life cycle and include data quality, sensitivity and uncertainty analyses.

GOAL AND SCOPE

This paper develops a general feel for the energy and emissions involved (and their impacts) associated with three different options for reconstructing I-5 through the Seattle metropolitan area by conducting a LCA that compares these options. Of note, it does not attempt to quantify life-cycle costs or any other metric associated with option comparison. The intended audience includes transportation and pavement professionals including agencies, consultants and contractors. Impact assessment will be done for several standard measures: global warming, acidification, human health (HH) criteria, eutrophication and photochemical smog. Also, the data will be examined in order to determine where ecologically friendly initiatives in transportation infrastructure could have the greatest impact.

Functional Unit

In an LCA, the compared options should perform the same utility for the same duration. In terms of pavement, this is interpreted to mean they should serve the same traffic over the same time with the same performance. A “functional unit” quantifies a standard amount to be compared between options that serve this function. For this paper, the functional unit is one lane-mile, 12 ft wide, (1.61 lane-km, 3.66 m wide) of reconstructed highway that will perform satisfactorily for 50 years with periodic rehabilitation. It is assumed that I-5 will continue to function as it does now with similar truck traffic and axle loading and a reasonable amount of traffic growth. The exact amount of traffic growth is not critical as the designs selected for each alternative are for the highest traffic levels available in current WSDOT design and will suffice for even substantially higher traffic volumes. Currently, traffic volumes vary along I-5 in the Seattle area average about 105,000 AADT (in each direction) and about 3.5 million Equivalent Single Axle Loads (ESALs) per year (in each direction). Figure 1 shows the relationship of the main activities considered in this study.

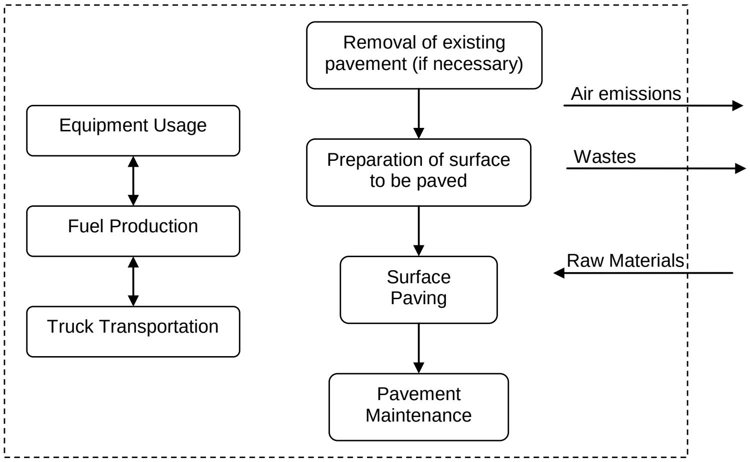

FIGURE 1 Sequence of main activities and scope included in LCA.

Replacement Options

Three main replacement options are considered:

- **Remove and replace with PCC (called “PCC” hereafter)**. Remove the existing PCC, keep the existing base and subgrade in place and repave with new PCC. Use diamond grinding as a periodic rehabilitation strategy.

- **Remove and replace with HMA (called "HMA" hereafter)**. Remove the existing PCC, keep the existing base and subgrade in place and repave with new HMA. Use a mill-and-fill (remove of the HMA surface with a cold planer and replace with the same depth of new HMA) as a periodic rehabilitation strategy.
- **Crack, seat and overlay (called "CSOL" hereafter)**. Crack and seat (*7*) the existing PCC then overlay it with HMA. Use a mill-and-fill as a periodic rehabilitation strategy.

The structural designs are taken directly from the current WSDOT design catalog in (*8*). Table 1 shows details for these options. There are several assumptions built into these options:

- There are no problems with the existing subgrade or base material; they provide the support required by WSDOT (*8*) and they can remain in place.
- It is acceptable for the final new pavement structure to have a higher elevation than the existing pavement structure. Although this may not be true in reality, it is assumed efforts to maintain elevation will affect all three options similarly and thus not be a differentiating factor.
- The existing pavement is 9 inches (225 mm) of PCC. Examination of Washington State Pavement Management System (WSPMS) records indicates this is true of over 99% of the study area.
- The existing base material is 10 inches (250 mm) of crushed aggregate. This is a general approximation of the base layer throughout the area and is consistent with that seen in WSPMS.
- Methods for the new construction and subsequent rehabilitation options remain essentially the same as current WSDOT standard practice.

Shortcomings

This comparison is neither complete nor ideal, however relative results should be dependable as the major construction and design items have been considered. The following is a brief list of known shortcomings of this LCA:

- User delay and the resultant emissions and materials usage are not considered. While these items are significant, this paper focuses on construction activities only.
- Smoothness (usually measured by International Roughness Index or IRI) differences between options is only accounted for in only a general manner. Rehabilitation schedules were chosen to maintain the same relative smoothness over time but this similarity is only assumed and only true on a 50-year time scale.
- Noise and safety as well as less quantifiable factors (e.g., scenic views, water quality) are not considered.
- Maintenance between rehabilitation actions (e.g., patching, joint repair, etc.) is not considered. This is reasonable as maintenance activities are generally small and isolated.

TABLE 1 Structural Design and Rehabilitation Schedules for Each Option

PCC	**HMA**	**CSOL**
13 inches (330 mm) Portland Cement Concrete 10 inches (250 mm) Existing Crushed Aggregate Existing Subgrade	2 inches (50 mm) HMA 3 inches (75 mm) HMA 4 inches (100 mm) HMA 4 inches (100 mm) HMA 10 inches (250 mm) Existing Crushed Aggregate Existing Subgrade	2 inches (50 mm) HMA 3 inches (75 mm) HMA 9 inches (225 mm) Cracked and Seated Existing PCC 10 inches (250 mm) Existing Crushed Aggregate Existing Subgrade
Structural Design: WSDOT (*8*) • 95% reliability • 100-200 million ESALs • Doweled joints (steel) o 1.5 inch (37.5 mm) diameter o 18 inches (457 mm) long • Crushed surfacing base course • J = 3.2 • E_c = 4,000,000 psi (27,579 MPa) • ΔPSI = 1.5 • S_c' = 650 psi (4.5 MPa) • S_0 = 0.40 • C_d = 1.0 • k = 200 pci (0.54 MPa/cm)	Structural Design: WSDOT (*8*) • 95% reliability • 100-200 million ESALs • Crushed surfacing base course • Average Subgrade o M_R = 10,000 psi (69 MPa) • ΔPSI = 1.5 • S_0 = 0.40 • m = 1.0 • a_{HMA} = 0.44 • a_{HMAB} = 0.44 • a_{base} = 0.13	Structural Design: average of typical California crack-and-seat overlay thickness of 4- 6 inches (100-150 mm) as observed in (*1*).
Rehabilitation		
Diamond grind to restore surface smoothness. Diamond grinding has not been done on a large scale in Washington but a 20 year life is slightly longer than the 16-17 year estimate provided by (*9*).	Remove and replace (mill-and-fill) the top 1.8 inches (45 mm) every 16 years. This corresponds to average HMA surface life in Western Washington (unpublished 2008 document from Washington State Pavement Engineer)	Remove and replace (mill-and-fill) the top 1.8 inches (45 mm) every 16 years. This corresponds to average HMA surface life in Western Washington (unpublished 2008 document from Washington State Pavement Engineer)
Schedule		
year 0: reconstruction year 20: diamond grind year 40: diamond grind year 50: diamond grind	year 0: reconstruction year 16: mill-and-fill year 32: mill-and-fill year 48: mill-and-fill	year 0: crack, seat, overlay year 16: mill-and-fill year 32: mill-and-fill year 48: mill-and-fill

INVENTORY ASSESSMENT

The inventory analysis is used to determine, both qualitatively and quantitatively, the material and energy inputs and the environmental releases to be associated with each unit process. It was done in accordance with Section 5.3 of ISO 14040 (*3*) and Section 4.3 of ISO 14044 (*4*). One important exception to the ISO standard is that bitumen feedstock energy is not included in the energy usage data. Typically, this can add about 30% to the energy use total.

Primary Data Sources

The main sources of energy usage and air emissions data were the U.S. Environmental Protection Agency's NONROAD2005 model for nonroad engines, equipment, and vehicles and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET). This section gives a brief description of how each source was used.

EPA NONROAD2005

Emissions data for all non-road construction and vehicular equipment was obtained from the EPA NONROAD2005 model (*10*). Non-road diesel fuel has recently seen new regulation that will decrease its negative impact on the environment by requiring lower sulfur levels in non-road fuels. In 2007, this fuel was required to have less than 500 ppm of sulfur and starting in 2010 the limit will be reduced to 15 ppm (*11*). These changes are reflected in the GREET fuel data, where an average sulfur content of 163 ppm is used. This sulfur content was used as a NONROAD input for consistency. The default NONROAD2005 value of 55.16 kPa Reid Vapor Pressure (RVP) was used. NONROAD2005 only includes fuel usage and air emissions of vehicles. It does not include the production or maintenance of the machine. Vehicle production is outside of the scope of this paper.

For each piece of construction equipment an estimate of the engine horsepower was made based on one or two typical machines. NONROAD2005 provides emissions factors for ranges of horsepower. All data is presented in BTUs per operating hour for energy flows and in grams per operating hour for material flows. For all cases NONROAD2005 data was specific to Washington State for a year-long average and all equipment used non-road diesel fuel. NONROAD2005 uses a mix of engine types to come up with the average emissions; for this 2009 analysis it assumes 90 percent meeting Tier 3 EPA engine standards and 10 percent meeting only Tier 1. NONROAD2005 uses brake-specific fuel consumption (BSFC) to calculate the air emissions that it presents. This BSFC is in units of pounds lbs/hp-hr so the BSFC had to be multiplied by the horsepower to get a fuel usage in pounds per hour.

GREET

The GREET model was developed as a tool for researchers to analyze the environmental impact of different combinations of vehicles and fuels (*12*). GREET was used as a source of data for fuel and electricity production, truck transportation, tie and dowel bar production, and natural gas burned in the HMA tack truck. GREET versions 1.7 and 2.7 (for steel production) were used. All relevant GREET assumptions are discussed by process in the following sections.

PCC Life Cycle Inventory

Emissions data and energy usage for PCC production were obtained from Marceau et al. (*13*). This LCI covers seven different PCC mixes of different strengths and with different amounts of fly ash and slag. For mixes including fly ash or slag, the production of these materials was also included in the LCI. Most of this data was collected via an anonymous survey of PCA member plants around the United States and from EPA emissions factors. Data from this document represent national averages; application to a specific region may be less representative.

Asphalt Life Cycle Inventory

Asphalt (bitumen) production emissions data and energy usage were obtained from Stripple (*14*). This is a European LCI and is likely to introduce some data quality issues. Stripple (*14*) uses the European averages of 70% Middle Eastern and 30% Venezuelan origin for crude oil, which is substantially different than the 2007 U.S. average of 63% from the Middle East, 11% from Venezuela and 26% from Canada, Mexico and elsewhere (*15*). The bitumen documented is a B60 or 50/70 pen by straight-run distillation.

Processes

This section describes the processes modeled. Three basic processes were shared by all options: fuel production, electricity production and truck transport. Tables 2 through 4 then show the processes for each option beyond these three common ones. In many cases, details involved in calculating quantities are not included due to space constraints.

TABLE 2 Remove and Replace with PCC Process and Data

No.	Task	Data Source	Item	Quantity/lane-mile
Remove and Replace with PCC				
1	Break up existing PCC	NONROAD2005	300 hp off-road truck 175 hp crushing/processing	0.74 hrs
2	Load broken PCC	NONROAD2005	300 hp excavator	15.8 hrs
3	Waste PCC truck transp.[a]	GREET v1.7	Heavy-heavy trucks	53,460 ton-miles
4	Utility excavator[b]	NONROAD2005	300 hp excavator	4.0 hrs
5	Base grading	NONROAD2005	175 hp grader	1.1 hrs
6	Base compaction	NONROAD2005	300 hp roller	0.9 hrs
7	PCC production	PCA LCI (*13*)	3,000 psi (287 MPa) mix no fly ash, no slag	2,542 yd^3
8	PCC mix transport[a]	GREET v1.7	Heavy-heavy truck	77,220 ton-miles
9	PCC placing and spreading	NONROAD2005	300 hp surfacing equipment	26.8 hrs
10	Dowel/tie bar production[c]	GREET v2.7	Low grade steel	18.3 tons
10	Dowel/tie bar transport	GREET v1.7	Heavy-heavy	914 ton-miles
11	PCC paving/bar placement	NONROAD2005	300 hp paver	26.8 hrs
12	Texturing/curing	NONROAD2005	75 hp surfacing equipment	26.8 hrs
13	PCC saw cutting	NONROAD2005	75 hp concrete/ind. saw	7.8 hrs
Diamond Grinding (to be accomplished at year 20, 40 and 50)				
1	Diamond grinder[d]	NONROAD2005	600 hp surfacing equipment 100 hp surfacing equipment	8.6 hrs
2	Grinder transport[d]	GREET v1.7	Heavy-heavy	96 ton-miles

Notes:

a. Distance from the workzone to the PCC recycling facility or the PCC plant is 15 miles.
b. Assumed to accomplish small work items at about 4.0 hrs per lane-mile.
c. Epoxy, stainless or other coating/cladding is not included.
d. Must travel 15 miles to the workzone. Needs 3 passes per lane. Weight is 32 tons.

TABLE 3 Remove and Replace with HMA Process and Data

No.	Task	Data Source	Item	Quantity/lane-mile
Remove and Replace with HMA				
1-6	Same as Table 2			
7	Bitumen production	Stripple (*14*)	Grade B60, 60/70 pen	281 tons
	Bitumen transport	GREET v1.7	Heavy-heavy truck	14,050 ton-miles
8	Crushed aggregate prod.[a]	Stripple (*14*)	½-inch dense gradation	4,930 tons
9	HMA production[b]	EPA AP-42 Stripple (*14*)	½-inch Superpave	5,211 tons
10	HMA transport[c]	GREET v1.7	Heavy-heavy truck	78,173 ton-miles
11	Emulsifier production	Stripple (*14*)	Emulsifier (water+chemicals)	3.5 tons
12	Emulsion production	Stripple (*14*)	CSS-1 emulsion tack coat	7.0 tons
13	Material transfer vehicle[d]	NONROAD2005	300 hp surfacing equipment	23.5 hrs
14	HMA paver[d]	NONROAD2005	300 hp paver	23.5 hrs
15	Breakdown rolling[d]	NONROAD2005	Two 300 hp rollers	47.0 hrs
16	Finish rolling[d]	NONROAD2005	100 hp roller	23.5 hrs
17	Tack coat application	GREET v1.7	Medium-heavy truck	161 ton-miles
18	Tack coat truck heater	GREET v1.7	Small natural gas turbine	232 MJ of propane
1.8-inch (45 mm) HMA Mill-and-Fill (to be accomplished at year 16, 32 and 48)				
1	Milling machine	NONROAD2005	750 hp surfacing equipment	7.0 hrs
2	RAP transport[c]	GREET v1.7	Heavy-heavy truck	10,824 ton-miles
3	Street sweeping	GREET v1.7	Medium-heavy truck	24.0 ton-miles
4	Sweeper aux. engine	NONROAD2005	100 hp cement/mortar mixer	0.4 hrs
5	Emulsifier production	Stripple (*14*)	Emulsifier	1.7 tons
6	Emulsion production	Stripple (*14*)	CSS-1 emulsion tack coat	3.4 tons
7	Material transfer vehicle	NONROAD2005	300 hp surfacing equipment	5.9 hrs
8	HMA paver	NONROAD2005	300 hp paver	5.9 hrs
9	Breakdown rolling	NONROAD2005	Two 300 hp rollers	11.7 hrs
10	Finish rolling	NONROAD2005	100 hp roller	5.9 hrs
11	Tack coat application	GREET v1.7	Medium-heavy truck	54.4 ton-miles
12	Tack coat truck heater	GREET v1.7	Small natural gas turbine	58 MJ of propane

Notes:

a. 100% crushed aggregate was used, which is common for Superpave mix designs.
b. 5.4% binder, counter flow drum mixer, natural gas, baghouse, no reclaimed asphalt pavement (RAP)
c. Distance from workzone to the PCC recycling facility, HMA plant or RAP storage area is 15 miles.
d. The paving train must travel traverse the entire lane-mile for each HMA lift.

TABLE 4 Crack, Seat and Overlay (CSOL) Process and Data

No.	Task	Data Source	Item	Quantity/lane-mile
Crack, Seat and Overlay				
1	Break up existing PCC	NONROAD2005	300 hp off-road truck 175 hp crushing/processing	0.74 hrs
2	Seating broken PCC	NONROAD2005	300 hp roller	0.9 hrs
3	Street sweeping	GREET v1.7	Medium-heavy truck	24.0 ton-miles
4	Sweeper aux. engine	NONROAD2005	100 hp cement/mortar mixer	0.4 hrs
5	Bitumen production	Stripple (*14*)	Grade B60, 60/70 pen	108 tons
6	Bitumen transport	GREET v1.7	Heavy-heavy truck	5,411 ton-miles
7	Crushed aggregate prod.[a]	Stripple (*14*)	½-inch dense gradation	1,896 tons
8	HMA production[b]	EPA AP-42 Stripple (*14*)	½-inch Superpave	2,004 tons
9	HMA transport[c]	GREET v1.7	Heavy-heavy truck	30,067 ton-miles
10	Emulsifier production	Stripple (*14*)	Emulsifier (water+chemicals)	2.2 tons
11	Emulsion production	Stripple (*14*)	CSS-1 emulsion tack coat	4.3 tons
12	Material transfer vehicle[d]	NONROAD2005	300 hp surfacing equipment	11.7 hrs
13	HMA paver[d]	NONROAD2005	300 hp paver	11.7 hrs
14	Breakdown rolling[d]	NONROAD2005	Two 300 hp rollers	23.4 hrs
15	Finish rolling[d]	NONROAD2005	100 hp roller	11.7 hrs
16	Tack coat application	GREET v1.7	Medium-heavy truck	77 ton-miles
17	Tack coat truck heater	GREET v1.7	Small natural gas turbine	116 MJ of propane
1.8-inch (45 mm) HMA Mill-and-Fill (to be accomplished at year 16, 32 and 48)				
Same as Table 3.				

Notes are the same as for Table 3.

Fuel Production

Data was obtained from GREET. The fuels included in this analysis are conventional diesel at fueling station, diesel for nonroad engines at fueling station, natural gas as a stationary fuel at point of use, natural gas for electricity generation at point of use, coal to power plant, coal at point of use, liquefied petroleum gas at point of use, and residual oil at point of use. These data sets include any processes required from extraction through transportation to the point of use.

Electricity Production

GREET was modified to represent electricity production in Washington State. Washington State's electricity fuel mix was input into the GREET 1.7 model to obtain the energy usage and air emissions of electricity production (*16*). Of significance, over 68 percent of Washington State's electricity comes from hydropower with its associated low emissions. Electricity transmission and distribution losses were assumed to be 7.2% based on the U.S. average in 1995 (*17*).

Truck Transport

All on-road vehicular transport data (e.g., dump trucks) was obtained from GREET. Medium-heavy and heavy-heavy diesel trucks were the only categories from GREET used in this LCA. The heavy-heavy truck class can haul up to 20 tons (18 tonnes) of cargo, while the medium-heavy truck can haul up to 8 tons (7.3 tonnes) of cargo. For both it was assumed that travel would include a 100% full front-haul and an empty back-haul.

Computational Structure

The inventory analyses and all calculations associated with them were performed according to the computational structure described by Heijungs and Suh (*18*).

Results

Table 5 shows the results for each reconstruction option and each of the two rehabilitation strategies. Of significant note, the feedstock energy of the asphalt that is not being combusted is not being included in the energy usage data. While it may be appropriate to track this feedstock value (which typically adds about 30% to the energy use data) such tracking is largely an accounting tool and does not represent any realistic intent to use the feedstock for fuel.

TABLE 5 Life Cycle Inventory Results per Lane-Mile

	Reconstruction Options[a]			Rehabilitation Actions[b]	
Input/Output	**PCC**	**HMA**	**CSOL**	**Diamond Grind**	**Mill-and-Fill**
Total Energy	4.05 TJ	5.86 TJ	3.42 TJ	0.052 TJ	0.631 TJ
CO_2	525 Mg	328 Mg	189 Mg	2.20 Mg	35.0 Mg
CO	1.31Mg	0.758 Mg	0.441 Mg	0.010 Mg	0.084 Mg
NO_x	1.41 Mg	1.45 Mg	0.853 Mg	0.019 Mg	0.164 Mg
SO_x	120 kg	120 kg	69.0 kg	0.878 kg	12.7 kg
CH_4	331 kg	765 kg	442 kg	4.31 kg	79.8 kg
$PM_{2.5}$	90.3 kg	66.6 kg	40.3 kg	1.43 kg	7.84 kg
PM_{10}	1318 kg	217 kg	126 kg	1.69 kg	23.0 kg
SO_2	562 kg	641 kg	366 kg	0.158 kg	64.1 kg
N_2O	1.59 kg	6.06 kg	3.38 kg	0.011 kg	0.615 kg
VOC	67.4 kg	165 kg	95.8 kg	1.72 kg	17.9 kg

Notes:

a. Each reconstruction option includes all items listed in Tables 2 through 4.
b. Numbers are for each occurrence of that rehabilitation option. These items are included in the Reconstruction Options but are listed separately here for comparison.

IMPACT ASSESSMENT

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (*19*) was used to determine impacts in the following categories: global warming, acidification, human health (HH) criteria, eutrophication and photochemical smog (Table 6). Further, a contribution analysis shows the relative contribution of each process within the three options considered to the total input and output. Table 7 shows the largest contributor in each category, while Figures 2 and 3 show the relative contribution of major components to the total energy used and global warming potential.

TABLE 6 Impact Category Results from TRACI (*19*).

Impact Category	**PCC**	**HMA**	**CSOL**
Total energy use	2.78 TJ	3.75 TJ	2.04 TJ
Global warming potential	533 kg CO_2-e	346 kg CO_2-e	199 kg CO_2-e
Acidification	91 moles H+/kg	96 moles H+/kg	56 moles H+/kg
Human health criteria air	0.133 milli-DALYs/kg	0.040 milli-DALYs/kg	0.023 milli-DALYs/kg
Eutrophication	0.063 kg N	0.064 kg N	0.038 kg N
Photochemical smog	1.48 kg NO_x	1.59 kg NO_x	0.94 kg NO_x

TABLE 7 Largest Contributor for Each Option[a]

	PCC + 3 diamond grinds		HMA + 3 mill-and-fills		CSOL + 3 mill-and-fills	
Item	**Largest Cont.**	**Percent**	**Largest Cont.**	**Percent**	**Largest Cont.**	**Percent**
Total energy	PCC prod.	56.1%	HMA prod.	31.4%	HMA prod.	30.6%
CO_2	PCC prod.	79.3%	HMA prod.	33.6%	HMA prod.	33.1%
CO	Steel prod.	48.5%	HMA prod.	58.5%	HMA prod.	56.8%
NO_x	PCC prod.	79.4%	Asphalt prod.	52.0%	Asphalt prod.	50.5%
SO_x	Steel prod.	38.0%	Electricity prod.	42.2%	Electricity prod.	41.5%
CH_4	Coal prod.	37.6%	Natural gas prod.	70.0%	Natural gas prod.	68.9%
$PM_{2.5}$	Coal prod.	49.1%	HMA prod.	55.5%	HMA prod.	52.1%
PM_{10}	PCC prod.	76.9%	HMA prod.	35.3%	HMA prod.	34.4%
SO_2	PCC prod.	99.8%	Asphalt prod.	97.4%	Asphalt prod.	97.4%
N_2O	Steel prod.	33.2%	Aggregate prod.	69.2%	Aggregate prod.	70.0%
VOC	PCC prod.	45.4%	HMA prod.	64.7%	HMA prod.	63.1%
GWP	PCC prod.	78.3%	HMA prod.	32.1%	HMA prod.	31.6%
Acidification	PCC prod.	81.1%	Asphalt prod.	64.0%	Asphalt prod.	62.9%
HH criteria air	PCC prod.	71.3%	Asphalt prod.	41.4%	Asphalt prod.	40.4%
Eutrophication	PCC prod.	79.4%	Asphalt prod.	52.0%	Asphalt prod.	50.5%
Photochem. smog	PCC prod.	77.7%	Asphalt prod.	47.4%	Asphalt prod.	46.2%

Notes:

a. Data includes both initial reconstruction and complete rehabilitation schedule.

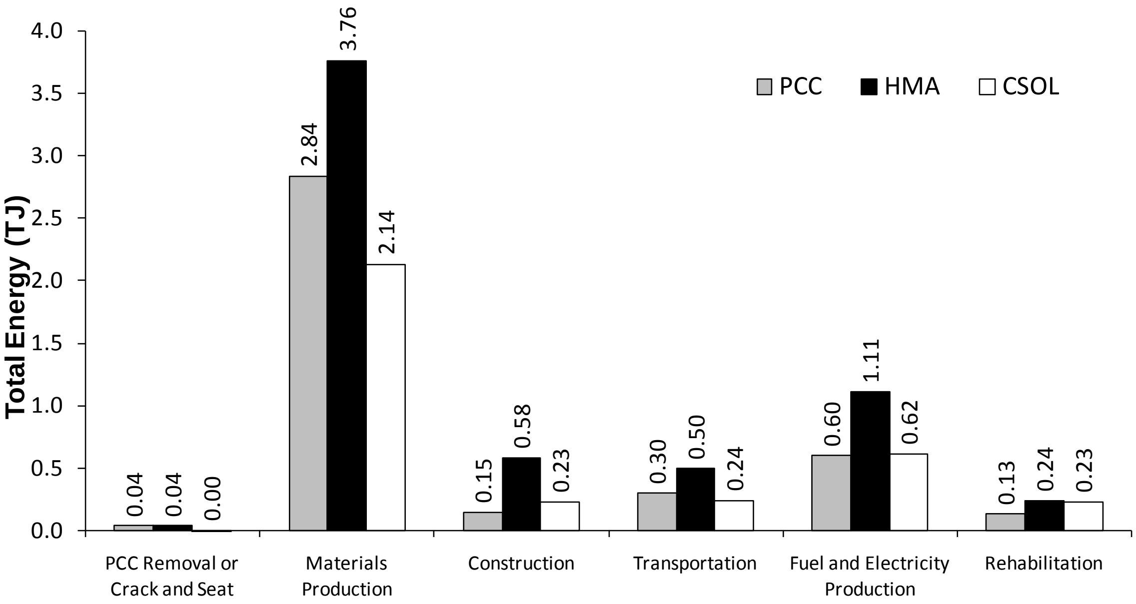

FIGURE 2 Contribution of each component to total energy use.

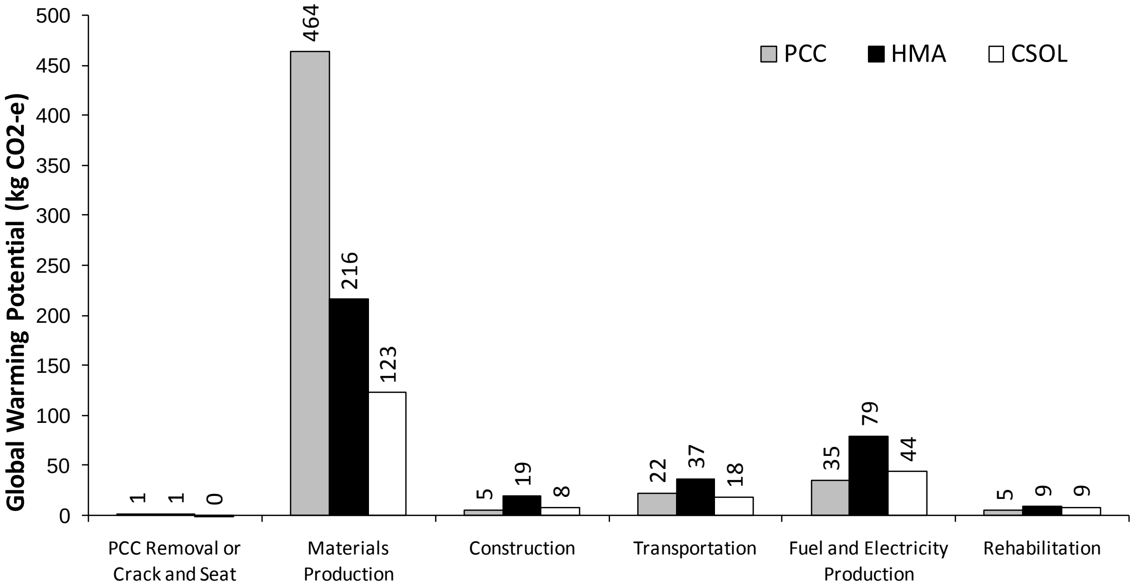

FIGURE 3 Contribution of each component to global warming potential.

Observations

This LCA leads to several observations about the type of data modeled and not modeled, the age and relevance of some key data sources, the relative contributions of different processes and an overall comparison between options.

Data Quality and Completeness

There are many pieces of data that comprise the entire environmental picture that are not adequately modeled or are simply excluded from this effort. Typically in pavement LCAs items such as user delay, emissions due to reduced speeds or stop-and-go traffic through workzones, construction dust, and fugitive emissions are excluded because there is no reliable information on their quantities or no simple way to include it in the analysis. Of note, Huang et al. (*20*) included user delay and found it significant. Other exclusions, such as the manufacture of equipment used in road construction, are done so as a matter of routine to make the conduct of a LCA reasonable and appropriate for the stated goal and scope.

Second, some key sources, namely the Stripple (*14*) document, are dated and are notably Eurocentric. While asphalt production is similar worldwide, items noted previously such as crude oil mix, asphalt grade and production methods only loosely translate to the U.S. in general and Seattle specifically. As better U.S. data sources become available they can be readily substituted for those used in this study, however the general order-of-magnitude results are not likely to change.

Process Contributions

Table 7 and Figures 2 and 3 show convincingly that materials production dominates energy use, emissions output and impacts for all three options. Specifically, PCC production (which includes cement production), HMA and asphalt production are the most influential in total energy use as well as all reported impact categories.

- PCC: PCC and cement production together account for 56.1% of total energy use and 78.3% of GWP

- HMA: HMA and asphalt production together account for 59.8% of total energy use and 59.4% of GWP
- CSOL: HMA and asphalt production together account for 58.4% of total energy use and 58.7% of GWP

Given these contributions, efforts to reduce the ecological footprint of pavements may be most impactful if they focus on PCC/cement production and HMA/asphalt production. Efforts to reduce the ecological footprint of construction activities and vehicles, while important, will have much less influence overall as seen in Figures 2 and 3.

A Comparison of Options

It is striking to note that in no case is the CSOL option the highest value in Table 5 and in many cases (10 out of 15) it is the lowest. In productivity analyses (*21*) CSOL has also been shown to be faster than the HMA or PCC options. Given that it leaves the old PCC in place and requires less material it is also likely to be the lowest first-cost option. Therefore, it may be preferable to choose CSOL as a viable reconstruction option if it meets two additional criteria:

- It can be shown to have a similar life expectancy as the PCC and HMA options. To date, CSOL has performed well in the short and medium term but there is little performance evidence over about 20 years.
- The increase in pavement profile elevation associated with CSOL is not so cost prohibitive (e.g., bridge clearance and drainage and safety adjustment issues) that it forces the CSOL life cycle cost to be greater than either the PCC or HMA option.

These two criteria are significant and warrant thorough investigation. They will be addressed in a follow-on to this study.

Future Use

The LCA computations described in this paper are likely too complicated for routine application, however a more user-friendly software-based version may be suitable. Such applications already exist, e.g., PaLATE (*22*), ROAD RES (*23*) and an upcoming release from the International Road Federation (*24*), although their availability and the reliability of their calculations are questionable. More are being developed including an effort based on methods used in this paper. Given the growing emphasis on quantifying carbon dioxide (CO_2) emissions in the National Environmental Policy Act (NEPA) process (*25*) and various emission reduction efforts (e.g., *26*) LCA use in project evaluation is likely to grow creating a small but definable market space for more user-friendly straightforward LCA-type calculators.

SUMMARY

This paper performed a LCA on three options for replacing the existing PCC pavement on 16 centerline miles (26 km) of I-5 in the Seattle metropolitan area. These options were: remove and replace with a new 13-inch (330-mm) PCC pavement, remove and replace with a 13-inch (330-mm) HMA pavement and crack-and-seat overlaid by a 5-inch (125-mm) HMA pavement.

Data sources for these LCAs varied in quality. While NONROAD and GREET were fairly recent and detailed, data sources for asphalt production, HMA production and aggregate production were somewhat dated (about 8 years old) and were not based on U.S. data, let alone Washington State or Seattle area data. This likely affected the results but not significantly enough to alter general order-of-magnitude observations. Observations are based solely on LCA results and are not a comprehensive comparison of options; other comparisons such as a life cycle cost analysis (LCCA), while important, are outside the scope of this paper.

Observation of the results showed that depending upon the item measured either the PCC or HMA option was higher. However, in no case did the CSOL option use the most energy, create the most emissions or have the greatest impact. In fact, the CSOL option was actually the lowest of the three investigated in 10 of the 15 categories analyzed. Also, materials production, and specifically PCC/cement production and HMA/asphalt production, tend to dominate energy use and GWP as well as other categories. Therefore, efforts to improve the ecological footprint of pavements should focus on these areas in order to have the largest impact. To date, this is happening in the cement and concrete industries with current trends towards reducing cement's clinker factor (the percentage of clinker in cement), thermal energy efficiency in clinker production, thermal substitution (substitution of alternate waste-derived fuels for fossil fuels in clinker production) and use of recycled PCC and cement kiln dust. It is also happening in the HMA industry with the advent of warm mix asphalt (WMA) and increased use of reclaimed asphalt pavement (RAP) in new HMA mixtures. As these advances occur it is important to keep LCIs such as Marceau (*13*) and Stripple (*14*) current so these advances can be properly captured in environmental accounting procedures.

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