Determining Changes in Greenhouse Gas Emissions (1990-2010) due to Pavement Technology

WA-RD 838.1

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Determining Changes in Greenhouse Gas Emissions (1990-2010) due to Pavement Technology

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16. ABSTRACT

This research quantifies the changes in greenhouse gas (GHG) emissions and energy consumption from WSDOT between 1990 and 2010 associated with (1) using warm mix asphalt (WMA), reclaimed asphalt pavement (RAP), fly ash and slag in pavement materials, (2) use of the dowel bar retrofit (DBR) as a portland cement concrete pavement (PCCP) rehabilitation practice, (3) improvements in WSDOT pavement network roughness, and (4) adoption of a long-life asphalt concrete pavement (ACP) strategy. Findings show:

- Use of WMA, RAP, fly ash and slag can result in GHG emissions and energy consumption savings of 4-44% depending upon the scenario.
- DBR use can save on the order of 15% in GHG emissions and energy consumption if it extends the life of existing PCCP by 15 years.
- WSDOT's overall pavement network has actually gotten rougher from 1990 to 2010; therefore no savings associated with GHG emissions or energy consumption has been realized. Reducing WSDOT pavement network roughness as a means to reduce GHG emissions may cost on the order of \$44/MTCO$_2$e, which is quite expensive by any measure.
- There is no discernible trend towards long-life asphalt ACP from 1990 to 2010. Therefore, no savings associated with GHG emissions or energy consumption can be identified.

In context with the GHG emissions and energy consumption associated with WSDOT fleet operations and vehicles driving on WSDOT pavement, total savings is on the order of 0.2-0.3%.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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1 INTRODUCTION

Greenhouse gas (GHG) emissions are a growing national and international concern (IPCC 2013). While heightened global concern has not necessarily translated to political action everywhere, it has sparked scientific interest in a broad array of fields including pavements. In the U.S. pavement life cycle assessment (LCA) is growing in popularity as a means for pavements to show relevance in GHG emissions reductions strategies. To date, most efforts regarding pavement impacts on GHG emissions have focused on a single project or several projects and have used custom-made analysis models that generally conform to international standards. There are comparatively few efforts aimed at quantifying impacts based on an entire road-owning agency's programmatic efforts such as this one.

1.1 Scope

This research quantifies the change in GHG emissions and energy consumption for the Washington State Department of Transportation (WSDOT) between 1990 and 2010 due to the following pavement practices:

a. **Paving materials**. Four basic pavement materials practices at the Washington State Department of Transportation (WSDOT) that have evolved over the past 20 years:
    a. Use of warm mix asphalt (WMA) in place of conventional hot mix asphalt (HMA).
    b. Incorporation of reclaimed asphalt pavement (RAP) in HMA pavement mixtures.
    c. Use of fly ash as portland cement substitutes in portland cement concrete (PCC) pavements.
    d. Use of slag as portland cement substitutes in portland cement concrete (PCC) pavements.

b. **Use of dowel bar retrofitting as a PCC pavement rehabilitation practice**. Retrofitting older PCC pavements (that lack dowel bars) with dowel bars is generally thought to prolong service life at minimal cost. GHG emissions and fuel consumption may also be reduced because one net benefit of extending service life is less materials consumption over time.

c. **Improvements in WSDOT pavement network roughness**. Changes in roughness affect fuel consumption in those vehicles traversing WSDOT pavements, which affects GHG emissions and energy consumption of those vehicles. Given the high traffic levels associated with WSDOT roads (31.76 billion vehicle-miles travelled (VMT) in 2010) even moderate improvements in roughness could have large GHG and energy consequences.

d. **Adoption of a long-life asphalt pavement strategy**. Although not a formally documented strategy, common sentiment in WSDOT is that the agency has progressed from a substantial fraction of structural overlays to inadequate pavement structures towards more routine minimum thickness (i.e., 0.15 ft.) resurfacings. This concerted effort is thought to have built up pavement structure over time. Overall this strategy could serve to increase the area of the pavement network capable of being adequately addressed by the same amount of material; effectively a reduction in the amount of material and a savings in GHG emissions and energy consumption.

These specific pavement practices were chosen for analysis because:

- **They were specifically requested by the WSDOT Materials Laboratory**. This includes the pavement practices of WMA, RAP, fly ash, slag, and dowel bar retrofit rehabilitation.
- **Their effects are potentially large and WSDOT has appropriate data for analysis**. This includes the effects of roughness changes, and the adoption of a long-life pavement strategy.

These pavement practices only represent a small fraction of those items in the generally recognized pavement life cycle that may contribute to GHG emissions but do represent some of the most prominent items associated with materials and pavement policy. Figure 1 shows a comprehensive view of the pavement life cycle and highlights which items are considered by this research. Findings from this research are used to (1) provide rough rules-of-thumb for the savings potential of these common processes, and (2) provide WSDOT with guidance.

1.2 Choice of 1990 and 2010 as Comparison Years

In general, to describe the impacts of these items, they are quantified in 1990 and 2010 and changes between these two years are quantified as savings. 1990 is a convenient baseline date because (1) none of these practices were in wide use then, and (2) it was the baseline year for the United Nations Kyoto Protocol in setting emissions reduction targets (UNFCCC 1998) and thus, has served as a baseline date for GHG reductions for a number of global and national initiatives. 2010 provides a convenient 20-year analysis period and represents a point in time when these practices have become more-or-less standard.

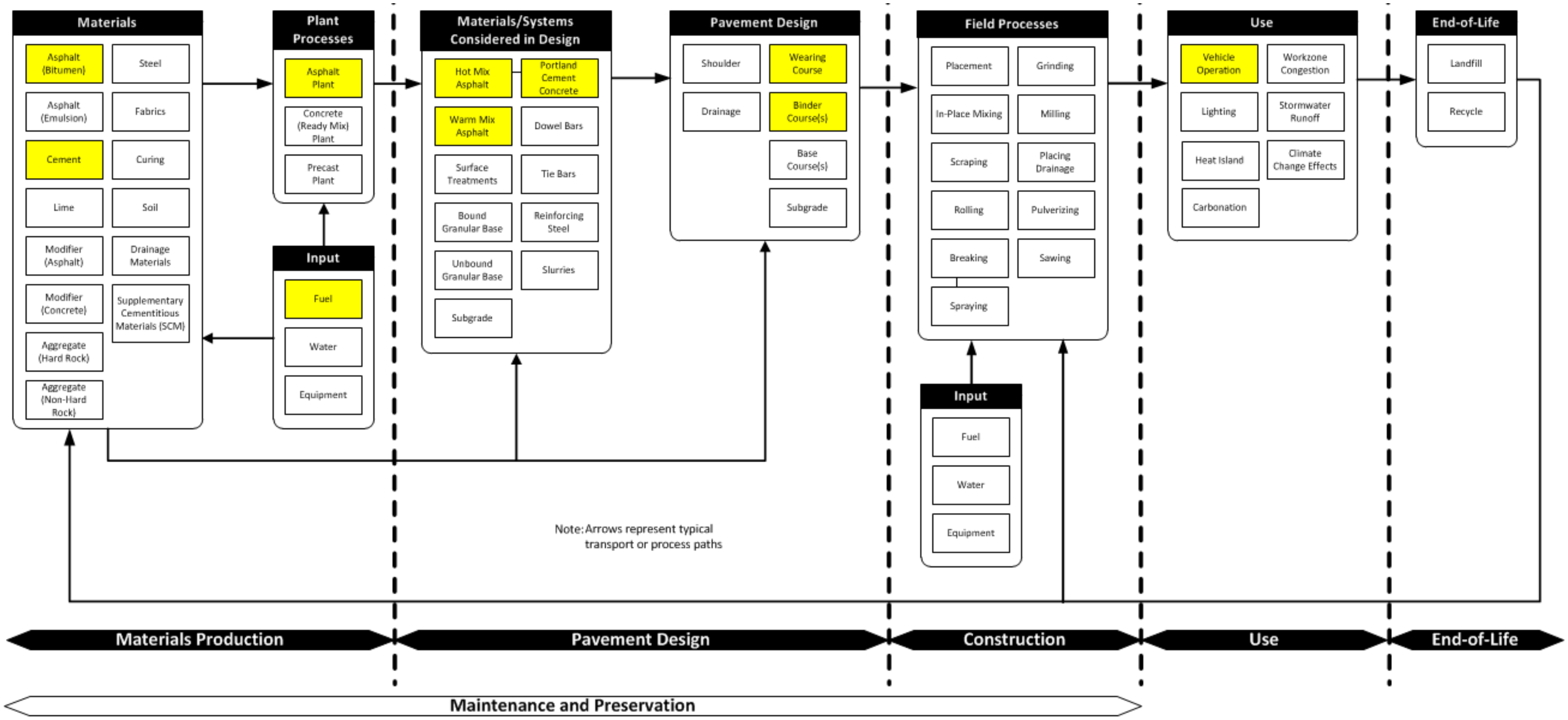

Figure 1. The pavement life cycle showing major processes contributing to GHG emissions (after Santero 2009; UCPRC 2010). Those addressed in this research are highlighted in yellow.

1.3 Context

GHG emissions and energy consumption from pavement construction represent a small fraction of worldwide, U.S., or even Washington State GHG emissions and energy consumption. This section provides estimates of relevant GHG emissions and energy consumption totals in order to provide context for this research. Note that reported emissions and energy consumption in the literature can vary significantly depending upon scope and reporting method.

1.3.1 GHG Emissions

- **Global**. In 2010, the world emitted 30.3 billion $MgCO_2e$ (Mega-grams of carbon dioxide equivalents – a standard measure of GHG emissions) from fuel combustion (OECD/IEA 2012). Of this, 6.8 billion $MgCO_2e$ (22.4%) are attributable to transportation (OECD/IEA 2012).
- **U.S**. the US accounts for 5.4 billion $MgCO_2e$ (17.8% of the world's emissions), of which 1.6 billion $MgCO_2e$ (29.6% of U.S. total) is attributable to transportation (OECD/IEA 2012).
- **Washington State**. In 2010, Washington State emitted 95.1 million $MgCO_2e$ (1.7% of U.S. total), of which 42.2 million $MgCO_2e$ (44.4% of the State total) is attributable to transportation (WSDOE 2012). Note that WSDOE emission inventories differ from IEA.
- **WSDOT**. 2007 WSDOT fleet and facilities emissions were reported as 0.26 million $MgCO_2e$ (Landsberg 2009). Using 2010 VMT on WSDOT roads of 31.764 billion (WSDOT 2012), 17.4 miles/gallon average fuel economy (BTS 2013), and the standard CO_2 emission factor for gasoline of 8.78 $kgCO_2$/gallon (EPA 2012), vehicles driving on WSDOT pavements in 2010 emitted 16 million $MgCO_2e$. These emissions together constitute 17% of Washington State GHG emissions.

1.3.2 Energy Consumption

- **Global**. In 2010, the world consumed 363 million TJ (terra-joules, or one trillion, 10^{12}, joules) of energy, of which 99 million TJ (36.6%) are attributable to transportation (IEA 2012).
- **U.S**. The U.S. consumed 103 million TJ of energy, of which 29 million TJ (28.1%) is attributable to transportation (EIA 2012).
- **Washington State**. In 2011, Washington State consumed 2.2 million TJ of energy, of which 0.6 million TJ (29%) is attributable to transportation (EIA 2013).
- **WSDOT**. Although specific data are not readily available, energy consumption can be roughly estimated from fuel consumption and therefore would follow the same trend as GHG emissions. If so, at 17% of state energy consumption, this would mean 0.37 million TJ of energy consumed by WSDOT and vehicles operating on WSDOT pavements each year.

1.4 Organization of this Report

The remainder of this report is organized into the following major sections:

a. Paving materials.
b. Dowel-bar retrofit.
c. Roughness.

d. Long-life pavement.

2 PAVING MATERIALS

This section estimates the change in GHG emissions and energy from WSDOT use of WMA, RAP, fly ash and slag in paving materials. These practices are generally thought to reduce GHG emissions and energy use associated with the paving process.

This section provides a general background on WSDOT paving materials use from 1990 to 2010, the specific method used to estimate changes in WMA, RAP, fly ash, and slag use from 1990 to 2010 and the result changes in GHG emissions and energy use.

2.1 Hypothesis

The use of the WMA, RAP, fly ash, and slag in paving materials leads to reduced GHG emissions and energy consumption associated with pavement construction.

2.2 WSDOT Paving 1990-2010

Over the 20-year period from 1990-2010 WSDOT annual paving quantities have averaged 1,625,200 tons/year (ranging from a low of 1,061,000 in 2006 to a high of 2,611,000 in 1999) for HMA and 73,400 yd^3/year (ranging from a low of 3,000 in 1997 to a high of 242,000 in 1999) for PCC. Overall, paving quantities in recent years have been trending down for HMA towards the 1,000,000 tons/year mark and up for PCC towards the 100,000 yd^3/year mark, but remain volatile year-to-year.

Table 1. WSDOT HMA and PCC Paving Quantities 1990-2010

	HMA		PCC	
Year	Mass in tons	Lane-miles	Volume in yd^3	Lane-miles
1990[a]	Incomplete data	Incomplete data	No data	No data
1991	1,385,000	629	24,000	36
1992	1,687,000	495	82,000	122
1993	2,669,000	877	130,000	193
1994	1,695,000	893	179,000	265
1995	1,485,000	1.055	17,000	25
1996	1,694,000	702	26,000	39
1997	2,300,000	997	3,000	4
1998	1,434,000	1,319	61,000	91
1999	2,611,000	1,276	242,000	359
2000	1,454,000	948	49,000	73
2001	2,031,000	776	27,000	40
2002	1,227,000	1,211	14,000	21
2003	1,852,000	740	134,000	199
2004	1,379,000	802	19,000	28
2005	1,591,000	700	111,000	165
2006	1,061,000	334	13,000	19
2007	1,232,000	708	69,000	102
2008	1,280,000	757	39,000	58
2009	1,256,000	597	61,000	91
2010	1,181,000	532	168,000	249
Total[b]	32,504,000	15,294	1,468,000	2,179
Avg./yr[b]	1,625,200	765	73,400	109

Year	HMA		PCC	
	Mass in tons	Lane-miles	Volume in yd^3	Lane-miles

a. 1990 information is incomplete or not available and is not included in this table.
b. Excludes 1990

2.3 Method

2.3.1 Changes in Paving Practices from 1990 – 2010

This section describes the overall average WSDOT paving practices associated with WMA, RAP, fly ash, and slag that existed, or were assumed to exist, for the years 1990 and 2010. It also describes for each what could be considered a reasonable “ultimate” amount (highest practical amount given current technology and specifications) that could be used by WSDOT either now or in the near future (i.e., less than 10 years into the future). It is assumed that none of the paving practices existed in 1990 to any significant degree. 2010 and “ultimate” values were not measured directly, but rather best values were taken from the literature or from reasonable estimates by WSDOT and industry personnel.

Warm Mix Asphalt (WMA). WMA refers to plant mix asphalt produced by any number of methods used to reduce the mixing temperature below that of equivalent HMA while maintaining adequate aggregate coating. Within the U.S., about 95% of WMA is produced by the plant foaming technique (Hansen and Copeland 2013). Benefits have been expressed many ways but generally involve some combination of lower emissions, less fuel/energy use, and better compaction (Kristjansdottir et al., 2007). The following levels of use were selected for this study:

- 1990 = 0. WMA was not used in 1990.
- 2010 = 66% of all HMA. This represents reported fraction of WSDOT mixes from Hansen and Copeland (2013). Current specifications are permissive only (they allow the contractor to substitute WMA for HMA if they meet certain minimum criteria) so there is not yet an accounting system in place to capture actual WMA use. This is likely an overestimation of WMA *used to reduce mixing temperature* as anecdotal evidence suggests that plant foaming techniques are sometimes used without any associated mixing temperature reduction.
- Ultimate = 100% of all HMA. It is possible to produce all HMA as WMA, and given current trends in outfitting HMA plants in Washington State, this could be achievable in the future.

Reclaimed Asphalt Pavement (RAP). RAP refers to old pavement reclaimed for use. Typically old pavement is either milled up or removed in bulk from the old pavement surface. It is then processed (usually crushed and often sorted) then used as a constituent in new HMA mixtures. Benefits include less waste to landfill (Hansen and Copeland 2013) report recycling rates of over 99%), and less virgin material used. The following levels of use were selected for this study:

- 1990 = 0. RAP was likely used in small quantities in 1990 however records of its use are sparse. Therefore, overall use was assumed to be essentially zero.
- 2010 = 18% of all HMA. This represents reported numbers for WSDOT mixes (Hansen and Newcomb 2011). Current WSDOT standards limit RAP inclusion to 20% by total weight of mix (WSDOT 2014). The fraction of RAP use in non-WSDOT mixes is unknown but likely higher.

- Ultimate = 40% of all HMA. It is possible to use RAP successfully at higher fractions (e.g., Valdes et al. 2011; West et al. 2013), however, issues with supply, mixture quality control, RAP processing, and plant tuning will likely prevent routine usage at higher fractions for the near future.

Fly Ash. Fly ash is a byproduct of electric power generating plants that burn coal. In concrete mixtures it is common to use fly ash as a cement replacement. Fly ash can impart desirable qualities to the concrete mixture (e.g., improved workability, sulfate and alkali-aggregate resistance, lower permeability) and, when used to reduce the required portland cement content in mixtures, can result in lower cost mixes. The following levels of use were selected for this study:

- 1990 = 0. Fly ash may have been used in a limited manner in 1990 but no records exist so its use was assumed to be essentially zero.
- 2010 = 20% of all cementitious material. This was taken as a reasonable estimate based on 2012 personal phone conversations with Bruce Chattin, Executive Director of the Washington Aggregates and Concrete Association, and Rob Shogren, Technical Service Engineer, Lafarge North America.
- Ultimate = 25% of all cementitious material. This is a result of the limitations with the LCA tool used for analysis (called "Roadprint.") Roadprint takes its concrete data from Marceau et al. (2007), which provides data based on a number of pre-defined mixes. The highest fly ash content of any of these mixes was 25%. This is likely an underestimate of what is ultimately achievable given that current WSDOT specifications allow for up to 35% by weight of total cementitious material.

Slag. Slag is the non-metallic byproduct of iron production that can be processed into a hydraulic cement known as ground granulated blast furnace slag (GGBFS), or "slag." Slag can impart desirable qualities to the concrete mixture (e.g., reducing permeability, mitigating sulfate attack and alkali-silica reaction) and, when used to reduce the required portland cement content in mixtures, can result in lower cost mixes. The following levels of use were selected for this study:

- 1990 = 0. Slag may have been used in a limited manner in 1990 but no records exist so its use was assumed to be essentially zero.
- 2010 = 25% of all cementitious material. This was taken as a reasonable estimate based on personal phone conversations with Bruce Chattin, Executive Director of the Washington Aggregates and Concrete Association, and
- Ultimate = 50% of all cementitious material. This is result of the general specifications limitations in progressive jurisdictions such as California. This is currently more than the 35% by weight of total cementitious material currently allowed by WSDOT.

This section summarizes Roadprint inputs for both the unit mass/volume scenarios and the 1-lane mile new construction scenarios.

2.3.2 Quantification

Quantification is done in two manners, which provide useful but different perspectives. First, the scope of assessment is limited to just materials production of HMA and PCC. In this way, the total materials production impact for any year can be reported by multiplying these results on a per-ton basis by reported or predicted annual WSDOT paving quantities. Second, the scope of assessment is enlarged to consider one lane-mile of new construction pavement that includes materials production, materials transport, construction equipment, and underlying structural layers (e.g., crushed aggregate). This perspective provides insight into how much the rest of pavement construction processes and structure can impact potential savings.

Quantification was done using Roadprint, a pavement life cycle assessment (LCA) tool (Lin, 2012). Roadprint is currently available in an online version for use free of charge at http://clients.paviasystems.com/wfl.

2.3.3 Interpretation of Results

Because of the current limitations of LCA in terms of data and scope (Lin 2012; Muench et al. 2014), results are best interpreted as rules-of-thumb or orders of magnitude, and are intended to provide perspective and agency guidance only. They should not be compared to results of other LCA efforts using different tools or materials. Quantification for the purposes of official GHG or energy consumption inventory should adhere to specific inventory rules, which, for pavements, have not yet been developed at any level in the U.S.

2.3.4 LCA Steps Associated with this Research

The standard framework for conducting a LCA is articulated in the International Organization for Standardization (ISO) 14000 series of documents. As typically described, there are five basic steps in the standardized LCA approach (ISO 14040/14044:2006). This section describes this portion of the research in relation to these five steps:

Goal. Quantify the change in GHG emissions and energy consumption between 1990 and 2010 due to the following paving practices: (1) use of warm mix asphalt (WMA) in place of conventional hot mix asphalt (HMA), (2) incorporation of reclaimed asphalt pavement (RAP) in HMA pavement mixtures, and (3) use of fly ash and slag as portland cement substitutes in portland cement concrete (PCC) pavements.

Scope Definition. The functional unit (item to be analyzed) is as follows:

- HMA and PCC materials production cases: one ton of HMA or PCC.
- One lane-mile of new construction pavement cases: one lane-mile of pavement according to WSDOT standard design (WSDOT, 2011) for (1) 25-50 million ESALs, and (2) 100-200 million ESALs.

Impacts outside the scope of Roadprint (e.g., changes in equipment technology) are estimated for this research but are outside the scope of this paper. The LCA scope for Roadprint is described in Lin (2012) and Muench et al., (2014). In general it includes the standard pavement life cycle phases (UCPRC 2010) of materials production, pavement design, construction, maintenance and preservation, and end-of-life. Pavement use is not included. This seems a valid scope for LCA conducted for inventory purposes (e.g., inventory total GHG emissions from construction in a given year).

Life Cycle Inventory Analysis (LCIA). Roadprint inputs and outputs are described in Section 2.4. Data sources and quality are described by Lin (2012).

Impact Assessment. Impact assessment is limited to global warming potential (GWP, as defined by EcoSense, Inc. and Five Winds International, 2000) and energy consumption. Other impacts were calculated but are not reported in this paper.

Interpretation. Interpretation of results is done in the Discussion and Conclusions/Recommendations sections.

2.3.5 General Inputs

For all scenarios the following Roadprint inputs were used for all analysis scenarios:

- Project location: Washington State
- Project analysis period: 50 years
- WMA is modeled as a process that reduces energy use and emissions by a fixed amount of 15%. This amount represents the low end range of reported fuel savings in (Frank et al. 2011). Higher savings are often reported (e.g., Kristjansdottir et al. 2007; Prowell et al. 2012), but contractors often use WMA plant foaming techniques purely as an aid for coating aggregate particles in the HMA plant and do not lower mix temperature, so the true impact of WMA technologies is unknown but likely is between zero and 15%.
- Feedstock energy is taken as 40.20 MJ/kg in accordance with the International Panel on Climate Change (IPCC 2006).
- RAP production and processing are included in the LCA scope.
- Densities: HMA = 2.05 tons/yd^3, PCC = 2.03 tons/yd^3

2.3.6 Roadprint Inputs

The following Roadprint inputs were used for the 1 lane-mile new construction pavement scenarios only:

- Maintenance actions:
  - HMA: 1.8-inch thick mill-and-fill every 15 years (WSDOT 2011) resulting in 2.33 maintenance activities over the 50 year analysis period. The maintenance activity in year 45 is counted as only 1/3 of the entire activity since it will last 15 years but only 5 years is needed to complete the 50-year analysis period. This is an artifact of not using a GHG or energy salvage value for value beyond the analysis period.
  - PCC: none. Roadprint does not model diamond grinding, which is the standard WSDOT maintenance activity for PCC pavement (WSDOT 2011). Because diamond grinding does not involve a significant amount of materials (which are responsible for the majority of GHG emissions and energy consumption) this omission is considered acceptable but not ideal.

2.3.6.1 Pavement Structural Design

For the 1 lane-mile new construction pavement scenarios, Figure 2 shows the standard WSDOT structural sections used (WSDOT 2011).

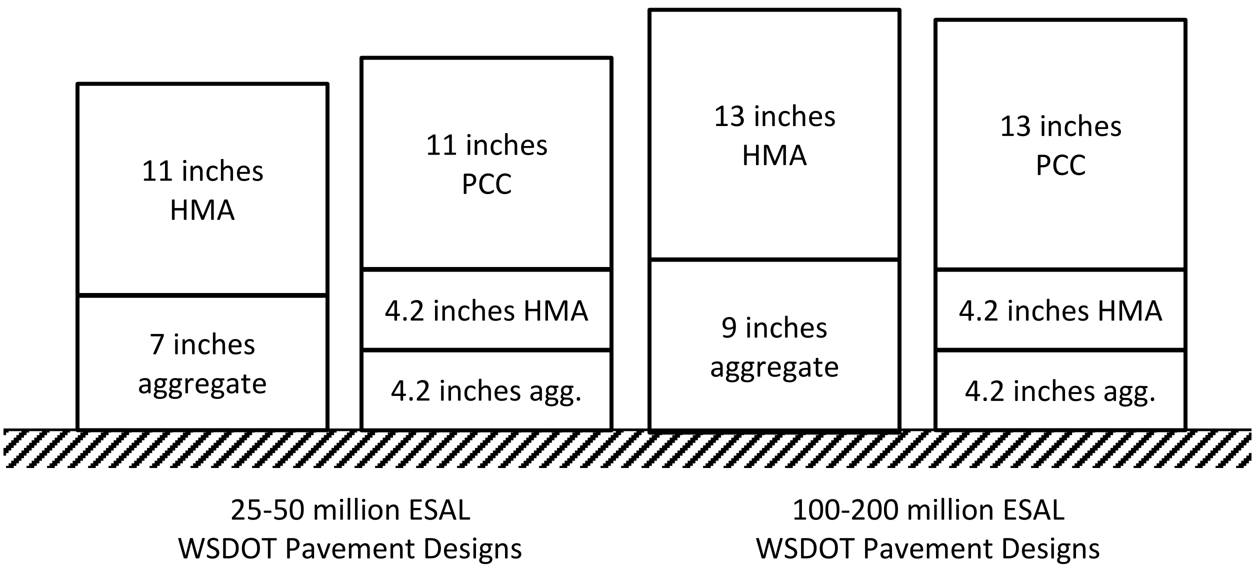

Figure 2. Pavement dimensions used for the pavement structure results (note: ESAL = equivalent single axle load).

2.3.6.2 Materials

For all scenarios materials data were entered into Roadprint according to Table 2.

Table 2. Roadprint Material Inputs

Case	Type	Material	Fraction	Associated Transport[a]	
				Mode[b]	Distance[c] (miles)
HMA Cases					
1990 Baseline 0% WMA 0% RAP	% of HMA/WMA	HMA	100%	HH Truck	20
		WMA	0%	-	-
	Mix design (by weight)	Virgin Aggregate	95%	-	-
		Bitumen	5%	HH Truck	50
		RAP[d]	0%	-	-
	Base material[a]	Virgin Aggregate	100%	HH Truck	20
2010 WMA 66% WMA	% of HMA/WMA	HMA	34%	HH Truck	20
		WMA	66%	HH Truck	20
	Mix design	Virgin Aggregate	95%	-	-

Case	Type	Material	Fraction	Associated Transport[a]	
				Mode[b]	Distance[c] (miles)
	(by weight)	Bitumen	5%	HH Truck	50
		RAP[d]	0%	-	-
	Base material[a]	Virgin Aggregate	100%	HH Truck	20
Ultimate WMA 100% WMA	% of HMA/WMA	HMA	0%	HH Truck	20
		WMA	100%	HH Truck	20
	Mix design (by weight)	Virgin Aggregate	95%	-	-
		Bitumen	5%	HH Truck	50
		RAP[d]	0%	-	-
	Base material[a]	Virgin Aggregate	100%	HH Truck	20
2010 RAP 18% RAP	% of HMA/WMA	HMA	100%	HH Truck	20
		WMA	0%	HH Truck	20
	Mix design (by weight)	Virgin Aggregate	95%	-	-
		Bitumen	5%	HH Truck	50
		RAP[c]	18%	HH Truck	20
	Base material[a]	Virgin Aggregate	100%	HH Truck	20
Ultimate RAP 40% RAP	% of HMA/WMA	HMA	100%	HH Truck	20
		WMA	0%	-	-
	Mix design (by weight)	Virgin Aggregate	95%	-	-
		Bitumen	5%	HH Truck	50
		RAP[d]	40%	HH Truck	20
	Base material[a]	Virgin Aggregate	100%	HH Truck	20
PCC Cases					
1990 Baseline 0% Fly Ash 0% Slag	PCC	3,000 psi PCC	100%	HH Truck	20
	Base Course	HMA (1990)[e]	50%	Note f	Note f
		Virgin aggregate	50%	HH Truck	20
2010 Fly Ash 20% Fly Ash	PCC	3,000 psi PCC (20% fly ash)	100%	HH Truck	20
	Base Course	HMA (1990)[e]	50%	Note f	Note f
		Virgin aggregate	50%	HH Truck	20
Ultimate Fly Ash 25% Fly Ash	PCC	3,000 psi PCC (25% fly ash)	100%	HH Truck	20
	Base Course	HMA (1990)[e]	50%	Note f	Note f
		Virgin aggregate	50%	HH Truck	20
2010 Slag 25% Slag	PCC	3,000 psi PCC	50%	HH Truck	20
		3,000 psi PCC (50%	50%	HH Truck	20

Case	Type	Material	Fraction	Associated Transport[a]	
				Mode[b]	Distance[c] (miles)
		slag)			
	Base Course	HMA (1990)[e]	50%	Note f	Note f
		Virgin aggregate	50%	HH Truck	20
Ultimate Slag 50% Slag	PCC	3,000 psi PCC (50% slag)	100%	HH Truck	20
	Base Course	HMA (1990)[e]	50%	Note f	Note f
		Virgin aggregate	50%	HH Truck	20

Notes:

a. Used with the 1 lane-mile new construction pavement scenarios only.

b. "HH truck" is a 20-ton capacity truck with a fuel economy of 5 miles/gallon.

c. Transport distance is for both fronthaul (loaded) and backhaul (assumed empty).

d. In cases where RAP is present, the sum of mix design percentages will exceed 100%. This is because in Roadprint the RAP fraction is input as a fraction of the total mixture weight. Roadprint then calculates reduced virgin aggregate and bitumen quantities based on the input RAP percentage.

e. Data for the HMA mixture used is identical to that of the "1990 HMA baseline" mixture.

f. See data from the 1990 HMA baseline row.

2.3.6.3 Construction Equipment

For the 1-lane mile new construction pavement scenarios construction equipment used for initial construction and maintenance were entered into Roadprint according to Table 3.

Table 3. Equipment Used for Initial Construction and Maintenance

Machine	Number	Engine Horsepower
Earthwork (Initial Construction Only)		
Grader 1	2	175
Backhoe 1	1	100
Excavator 1	1	175
Loader 1	1	175
HMA Paving (both Initial Construction and Maintenance)		
HMA Paver 1	1	175
HMA Paver 2	1	100
HMA MTV 1	1	300
Breakdown Roller 1	2	100
Breakdown Roller 2	1	25
Finish Roller 1	1	100
Dump Trucks	11 or 12	-
Surface Preparation (Initial Construction and Maintenance)		
Milling Machine	1	750

Machine	Number	Engine Horsepower
Guillotine Breaker	1	300
PCC Paving (Initial Construction Only)		
PCC Paver 1	1	175
PCC Spreader 1	1	300
PCC Spreader 2	1	300

2.4 Results

2.4.1 Materials Production Scenarios

Table 4 and Table 5 show the calculated GWP and energy consumption for materials production only scenarios and resultant savings over the 1990 baseline case. These scenarios only consider materials production for HMA and PCC mixtures.

Table 4. GWP and Energy Consumption for Materials Production Scenarios

Scenario	Global Warming Potential GWP ($KgCO_2e/ton$)	Energy Consumption (MJ/ton)[a]	Feedstock Energy (MJ/ton)
HMA			
1990 (Baseline, 0% WMA, 0% RAP)	36.98	817.50	2,035.81
WMA Scenarios			
2010 (66% WMA)	32.76	701.97	2,035.81
Ultimate (100% WMA)	30.59	642.45	2,035.81
RAP Scenarios			
2010 (18% RAP)	34.06	772.82	1,669.36
Ultimate (40% RAP)	30.49	718.21	1,221.49
PCC			
1990 (Baseline, 0% fly ash, 0% slag)	86.23	551.57	0.00
Fly Ash Scenarios			
2010 (20% Fly Ash)	69.98	452.53	0.00
Ultimate (25% Fly Ash)	65.92	427.18	0.00
Slag Scenarios			
2010 (25% Slag)	67.07	463.37	0.00
Ultimate (50% Slag)	47.91	375.19	0.00

Notes:
a. Does not include feedstock energy.

Table 5. Savings Over 1990 Baseline Case for GWP and Energy Consumption for Materials Production Scenarios

	GWP Reduction		Energy Consumption Reduction[a]	
Scenario	**$KgCO_2e$/ton**	**Percent**	**(MJ/ton)**	**Percent**
HMA				
1990 (Baseline, 0% WMA, 0% RAP)	0.00	0%	0.00	0%
WMA Scenarios				
2010 (66% WMA)	4.22	11%	115.53	14%
Ultimate (100% WMA)	6.39	17%	175.05	21%
RAP Scenarios				
2010 (18% RAP)	2.92	8%	44.68	5%
Ultimate (40% RAP)	6.49	18%	99.29	12%
PCC				
1990 (Baseline, 0% fly ash, 0% slag)	0.00	0%	0.00	0%
Fly Ash Scenarios				
2010 (20% Fly Ash)	16.25	19%	99.04	18%
Ultimate (25% Fly Ash)	20.31	24%	124.39	23%
Slag Scenarios				
2010 (25% Slag)	19.16	22%	88.19	16%
Ultimate (50% Slag)	38.32	44%	176.37	32%

Notes:
a. Does not include feedstock energy.

2.4.2 1 Lane-Mile of New Construction Pavement Scenarios

Table 6 and Table 7 show the calculated GWP and energy consumption for the 1 lane-mile of new construction scenarios and resultant savings over the 1990 baseline case. These scenarios consider materials production, materials transportation, construction equipment, and all materials in the pavement structure.

Table 6. GWP and Energy Consumption for 1 Lane-Mile of New Construction Pavement Scenarios

Scenario	**Global Warming Potential GWP ($MgCO_2e$)**	**Energy Consumption (TJ)[a]**	**Feedstock Energy (TJ)**
HMA (25-50 million ESAL design)			
1990 (Baseline, 0% WMA, 0% RAP)	279	5.7	12.4
WMA Scenarios			
2010 (66% WMA)	266	5.4	12.4

Scenario	Global Warming Potential GWP ($MgCO_2e$)	Energy Consumption (TJ)[a]	Feedstock Energy (TJ)
Ultimate (100% WMA)	260	5.2	12.4
RAP Scenarios			
2010 (18% RAP)	260	5.5	10.2
Ultimate (40% RAP)	238	5.1	7.4
HMA (100-200 million ESAL design)			
1990 (Baseline, 0% WMA, 0% RAP)	318	6.5	14.0
WMA Scenarios			
2010 (66% WMA)	303	6.1	14.0
Ultimate (100% WMA)	296	5.9	14.0
RAP Scenarios			
2010 (18% RAP)	297	6.2	11.5
Ultimate (40% RAP)	271	5.8	8.4
PCC (25-50 million ESAL design)			
1990 (Baseline, 0% fly ash, 0% slag)	523	5.0	3.4
Fly Ash Scenarios			
2010 (20% Fly Ash)	460	4.7	3.4
Ultimate (25% Fly Ash)	434	4.5	3.4
Slag Scenarios			
2010 (25% Slag)	439	4.6	3.4
Ultimate (50% Slag)	355	4.3	3.4
PCC (100-200 million ESAL design)			
1990 (Baseline, 0% fly ash, 0% slag)	593	5.5	3.4
Fly Ash Scenarios			
2010 (20% Fly Ash)	519	5.1	3.4
Ultimate (25% Fly Ash)	488	4.9	3.4
Slag Scenarios			
2010 (25% Slag)	494	5.0	3.4
Ultimate (50% Slag)	395	4.6	3.4

Notes:
a. Does not include feedstock energy.

Table 7. Savings Over 1990 Baseline Case for GWP and Energy Consumption for 1 Lane-Mile of New Construction Pavement Scenarios

	GWP Reduction		Energy Consumption Reduction[a]	
Scenario	**MgCO2e**	**Percent**	**(TJ)**	**Percent**
HMA (25-50 million ESAL design)				
1990 (Baseline, 0% WMA, 0% RAP)	0	0%	0.0	0%
WMA Scenarios				
2010 (66% WMA)	13	5%	0.3	6%
Ultimate (100% WMA)	19	7%	0.5	9%
RAP Scenarios				
2010 (18% RAP)	19	7%	0.2	5%
Ultimate (40% RAP)	41	15%	0.6	11%
HMA (100-200 million ESAL design)				
1990 (Baseline, 0% WMA, 0% RAP)	0	0%	0.0	0%
WMA Scenarios				
2010 (66% WMA)	15	5%	0.4	6%
Ultimate (100% WMA)	22	7%	0.6	9%
RAP Scenarios				
2010 (18% RAP)	21	7%	0.3	5%
Ultimate (40% RAP)	47	15%	0.7	11%
PCC (25-50 million ESAL design)				
1990 (Baseline, 0% fly ash, 0% slag)	0	0%	0.0	0%
Fly Ash Scenarios				
2010 (20% Fly Ash)	63	12%	0.3	7%
Ultimate (25% Fly Ash)	89	17%	0.5	11%
Slag Scenarios				
2010 (25% Slag)	84	16%	0.4	8%
Ultimate (50% Slag)	168	32%	0.7	15%
PCC (100-200 million ESAL design)				
1990 (Baseline, 0% fly ash, 0% slag)	0	0%	0.0	0%
Fly Ash Scenarios				
2010 (20% Fly Ash)	74	12%	0.4	7%
Ultimate (25% Fly Ash)	105	18%	0.6	12%

	GWP Reduction		Energy Consumption Reduction[a]	
Scenario	**MgCO2e**	**Percent**	**(TJ)**	**Percent**
Slag Scenarios				
2010 (25% Slag)	99	17%	0.5	8%
Ultimate (50% Slag)	198	33%	0.9	17%

Notes:

b. Does not include feedstock energy.

2.4.3 Implications for Annual WSDOT HMA and PCC Paving Quantities

From 1991-2010 WSDOT paved an average of 1.625 million tons/year of HMA and 150,000 tons/yr of PCC. However, recent years show a trend more towards 1 million tons/year of HMA and 200,000 tons/yr of PCC. Table 8 shows estimated emissions using these normalized quantities together with the results from the materials production scenarios.

Table 8. Total Annual Emissions and Energy Consumption and Associated Savings for WSDOT HMA and PCC for Materials Production[a]

		2010 (66% WMA, 18% RAP, 20% Fly Ash, 25% Slag)		Ultimate (100% WMA, 40% RAP, 25% Fly Ash, 50% Slag)	
	1990 Baseline	Amount	Savings	Amount	Savings
GHG Emissions ($MgCO_2e$)					
WMA	36,980	32,760	4,220	30,590	6,390
RAP	36,980	34,060	2,920	30,490	6,490
Fly Ash	17,246	13,996	3,250	13,184	4,062
Slag	17,246	13,414	3,832	9,582	7,664
Energy Consumption (TJ)					
WMA	817.5	701.97	115.53	642.45	175.05
RAP	817.5	721.82	44.68	718.21	99.29
Fly Ash	110.3	90.51	19.79	85.44	24.86
Slag	110.3	92.68	17.62	75.04	35.26

Notes:

a. Assuming a typical year of 1,000,000 tons/year of HMA paved and 200,000 tons/year of PCC paved (about 98,500 yd^3/yr using a density of 2.03 tons/yd^3).

For HMA, the use of WMA and RAP can (and has) occur simultaneously. Therefore, a reasonable estimate for the total savings in GHG and energy consumption in the HMA 2010 and ultimate cases can reasonably be assumed as the sum of the savings from WMA and RAP (7,140 $MgCO_2e$). Thus, typical annual GHG emissions from HMA (assuming 1,000,000 tons/year paved) are on the order of 29,840 $MgCO_2e$. Conversely, for the PCC 2010 and ultimate cases the total savings in GHG and energy consumption is likely that associated with a combined 35% use rate since WSDOT currently limits the combination of fly ash and slag to 35% by weight of total cementitious material (5,457 $MgCO_2e$). Thus, typical annual GHG emissions from PCC (assuming 200,000 tons/year paved) are on the order of 11,881 $MgCO_2e$. By similar logic typical annual energy consumption would be 657 TJ (based on a savings of 160 TJ) for HMA) and 86 TJ (based on a savings of 28 TJ) for PCC. So, in a typical year of paving, HMA and PCC materials production emit about 41,721 $MgCO_2e$ and consume about 743 TJ of energy. Given the uncertainty associated with LCA (see Lin, 2012), these number are falsely precise and a better estimate would be in the range of 30,000-50,000 $MgCO_2e$ and 550-950 TJ.

Comparing these results with WSDOT GHG emissions (16.26 million $MgCO_2e$ /year) and energy consumption (0.37 million TJ/year) discussed previously, this would put 2010 HMA and PCC materials production GHG emissions and energy consumption at about 0.2% to 0.3% of these totals.

2.5 Findings

2.5.1 Utility of the Results

Issues with data quality/availability, and LCA scope (e.g., Lin 2012; Santero 2009) almost ensure that results from quantification efforts such as this cannot be repeated unless the exact same information and tools are used. Nonetheless, results from this quantification effort can provide general insight and direction into the impacts of these standard paving materials practices on a programmatic level as discussed in this section.

2.5.2 HMA

- Reductions for 2010 materials production practices when compared to those of 1990 are 5-14% depending upon the scenario.
- If just the materials production of HMA is considered (neglecting the rest of the pavement section, construction, and transport), the best estimates of actual savings for 2010 practices when compared to 1990 is 7,140 $MgCO_2e$ and 160 TJ for HMA (assuming 1,000,000 tons/year paved).
- The "ultimate" materials production scenarios, which represent what is reasonably possible given today's technology and state-of-practice, are significant at 12-21% depending upon the scenario. This means there is still room for improvement and that such practices can have an appreciable influence on GHG emissions and energy consumption associated with pavement construction.
- If the entire pavement structure, materials transportation, and construction equipment are considered, these savings decrease to 5-15% (2010 and ultimate scenarios).
- Reductions based on WMA use are driven by a modeled input of a 15% reduction in energy and emissions. The Roadprint model works this way because at the time of its development there were no extensive environmental product declarations (EPDs) or other databases able to describe energy use and emissions associated with their use. The selected value is a reasonable estimate for the plant foaming technologies that dominate the U.S. WMA market, however more aggressive WMA temperature reductions are claimed by multiple marketplace technologies.
- The inclusion or exclusion of feedstock energy (and its selected value) makes a large difference in reported energy consumption results.
- Using RAP and WMA together (e.g., Copeland et al., 2010 and Timm et al., 2011) can yield greater reductions.
- Limitations for both WMA and RAP exist that were not modeled. WMA generally involves a cost to retrofit a plant (plant foaming technologies) or purchase additives, which also come with their own environmental burden (e.g.,Vidal et al., 2013). RAP, and especially the use of RAP at higher amounts akin to the "ultimate" scenario, would

require added processing equipment to better fractionate the RAP, higher HMA plant operating temperatures (unless WMA is used in conjunction), tuning HMA plants to operate at higher temperatures, and mix design and mixture quality issues associated with RAP (Copeland, 2011).

2.5.3 PCC

- Reductions for 2010 materials production practices when compared to those of 1990 are significant, amounting to 16-22% depending upon the scenario.
- If just the materials production of PCC is considered (neglecting the rest of the pavement section, construction, and transport), the best estimates of actual savings for 2010 practices when compared to 1990 is 5,457 $MgCO_2e$ and 28 TJ for PCC (assuming 200,000 tons/year or 98,500 yd^3/year paved).
- The "ultimate" materials production scenarios, which represent what is reasonably possible given today's technology and state-of-practice, are substantial at 23-44% depending upon the scenario. This means there is still room for improvement and that such practices can have an appreciable influence on GHG emissions and energy consumption associated with pavement construction.
- If the entire pavement structure, materials transportation, and construction equipment are considered, these savings decrease to 7-17% (2010 scenarios) and 11-33% (ultimate scenarios).
- Fly ash and slag are more impactful because they directly remove the most emission and energy intensive process (cement production) from the PCC material. For the scenarios run, portland cement generally constitutes 80-95% of the GHG emissions and energy consumption associated with PCC. This has long been known and is one reason why Europe has expended so much effort to reduce the clinker factor in manufactured cements.
- Using fly ash and slag together can result in greater reductions but most agencies still place either a lower limit on cement content or an upper limit on cement replacement materials somewhere in the 25-50% range.
- Limitations for both fly ash and slag exist that were not modeled. Fly ash and slag generally slow the PCC curing process, which can reduce productivity for a given roadway closure. In some parts of the country fly ash and slag can be scarce. For instance, there is only one coal fired power plant in Washington State and its fly ash can be scarce, forcing the shipping of fly ash by rail from out of state. Also, slag in the Seattle area is generally shipped from Kawasaki, Japan, which adds to GHG emissions and energy consumption associated with its use.

3 DOWEL BAR RETROFIT (DBR)

Since the early 1990s WSDOT has used a PCCP (portland cement concrete pavement) rehabilitation technique that involves retrofitting an existing undoweled PCCP with dowel bars to extend its service life, commonly termed "dowel bar retrofit" or DBR. This technique has been extensively studied (e.g., Pierce and Muench 2009; Pierce et al. 2009; Santero et al. 2009; Anderson et al. 2012) with the general conclusion being that such a technique is financially beneficial if the retrofit can provide some minimum amount of fatigue life extension (Santero et al. 2009) or if it is done earlier in the PCCP life cycle (Pierce and Muench 2009). This section examines DBR to determine its impact on GHG emissions and energy consumption.

3.1 Hypothesis

The use of the PCCP DBR rehabilitation technique leads to reduced GHG emissions and energy consumption associated with the construction of PCCP.

3.2 Method

Two standard PCCP construction and rehabilitation scenarios are developed and compared. Both begin with a WSDOT PCCP typical of what was built in the 1950s and 1960s (Muench et al., 2010) with one scenario involving removal and replacement with a new-construction PCCP and the other scenario involving the extension of the original pavement life through DBR before removal and replacement with a new-construction PCCP. Roadprint (Lin, 2012; Muench et al., 2014) is used in each instance to quantify GHG emissions and results are compared.

3.2.1 PCCP Construction/Rehabilitation Scenarios (Figure 3)

The two scenarios compared are:

- **Baseline**. Consists of an existing 9-inch thick PCCP with no base material that functions for 40 years and then is replaced by a WSDOT standard 50-year PCCP design (WSDOT, 2011). Designs for both 25-50 million ESALs and 100-200 million ESALs were evaluated.

- **DBR**. Consists of an existing 9-inch thick PCCP with no base material that functions for 40 years, then receives a DBR that extends its life another 15 years, then is replaced by a WSDOT standard 50-year PCCP design (WSDOT, 2011). Designs for both 25-50 million ESALs and 100-200 million ESALs were evaluated. The 15-year DBR life extension is consistent with previous WSDOT findings (Pierce and Muench, 2009).

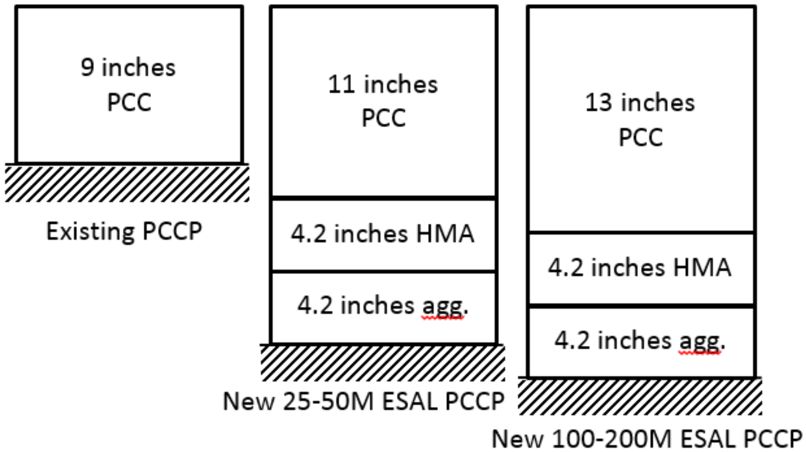

Figure 3. PCCP pavement structures used for Roadprint analysis of DBR.

3.2.2 Analysis Period and Logic (Figure 4)

Scenarios were compared over a 90-year analysis period, which corresponds to the total expected Baseline Scenario :enario. Since the DBR scenario results in a pavement with 15 years of remaining life at the end of the analysis period, and no standard GHG emissions discounting regime exists, the GHG emissions associated with the DBR scenario new pavement was discounted to 70% of its value (35 years / 50 years = 0.70) to account for the remaining life.

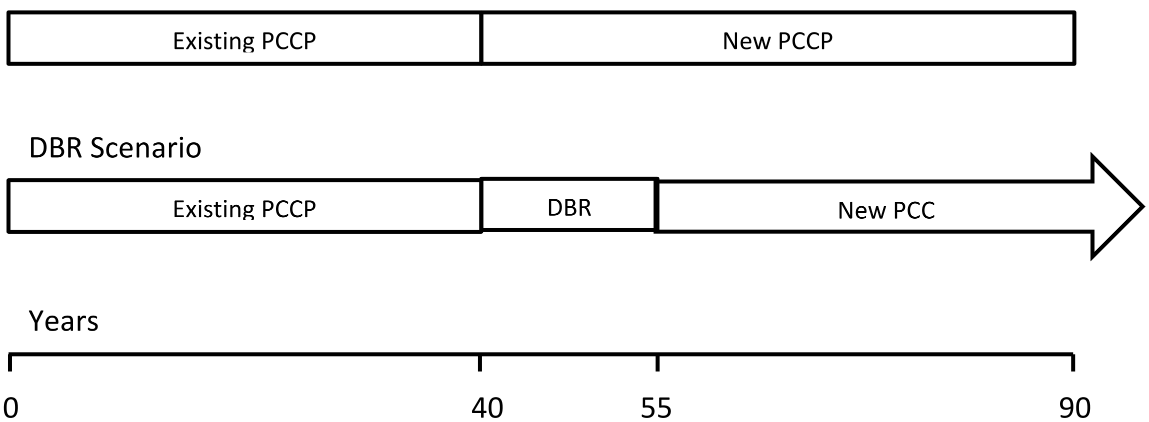

Figure 4. Analysis period and logic.

3.2.3 LCA Steps Associated with this Research

The standard framework for conducting a LCA is articulated in the International Organization for Standardization (ISO) 14000 series of documents. As typically described, there are five basic steps in the standardized LCA approach (ISO 14040/14044:2006). This section describes this portion of the research in relation to these five steps:

Goal. Quantify the change in GHG emissions and energy consumption between baseline and PCCP DBR scenarios.

Scope Definition. The functional unit (item to be analyzed) is as follows:

- One lane-mile of pavement over the 90-year analysis period including replacement pavement options corresponding to the WSDOT standard design (WSDOT, 2011) for (1) 25-50 million ESALs, and (2) 100-200 million ESALs.

Impacts outside the scope of Roadprint are outside the scope of this report. The LCA scope for Roadprint is described by Lin (2012). In general it includes the standard pavement life cycle phases (UCPRC 2010) of materials production, pavement design, construction, maintenance and preservation, and end-of-life. Pavement use is not included. Exclusion of the use phase is reasonable since a typical DBR includes a diamond grinding, which results in pavement smoothness comparable to new PCCP. Thus, vehicle fuel consumption, and resultant GHG emissions, are comparable for both scenarios.

Life Cycle Inventory Analysis (LCIA). Roadprint inputs and outputs are described in the Method and Results sections. Data sources and quality are described by Lin (2012).

Impact Assessment. Impact assessment is limited to GWP and energy consumption. Other impacts were calculated but are not reported.

Interpretation. Interpretation of results is done in Section 3.4.

3.2.4 Roadprint Input Values

Same as listed in Table 3 for PCCP.

3.3 Results

Table 9 shows the GWP and energy consumption associated with each activity show in **Error! Reference source not found.**. Table 10 and Table 11 shows results.

Table 9. GWP and Energy Consumption Associated with PCCP and DBR Activities

Scenario	Activity	Global Warming Potential GWP ($MgCO_2e$)	Energy Consumption (TJ)[a]	Feedstock Energy (TJ)
25-50 million ESALs	Original PCC construction (no dowels)	337	2.35	0
	New PCC construction (with dowels)	509	4.80	1.41
	Dowel Bar Retrofit	33	0.47	0
100-200 million ESALs	Original PCC construction (no dowels)	337	2.35	0
	New PCC construction (with dowels)	581	5.28	1.41
	Dowel Bar Retrofit	33	0.47	0

Notes:

a. Does not include feedstock energy.

Table 10. Comparison of No-DBR and DBR Scenarios for 25-50 Million ESALs

Scenario	Description	Global Warming Potential GWP ($MgCO_2e$)	Energy Consumption (TJ)[a]	Feedstock Energy (TJ)
No DBR	Original PCC construction (no dowels)	337	2.35	0
	New PCC construction (with dowels)	58	4.80	1.41
	90-year total	846	7.15	1.41
DBR	Original PCC construction (no dowels)	337	2.35	0
	Dowel Bar Retrofit	33	0.47	0
	70% of New PCC Construction (with dowels) value due to DBR	356	3.36	0.99
	90-year total	726	6.18	0.99
Savings		120	0.97	0.42
		14%	14%	30%

Notes:

a. Does not include feedstock energy.

Table 11. Comparison of No-DBR and DBR Scenarios for 100-200 Million ESALs

Scenario	Description	Global Warming Potential GWP ($MgCO_2e$)	Energy Consumption (TJ)[a]	Feedstock Energy (TJ)
No DBR	Original PCC construction (no dowels)	337	2.35	0
	New PCC construction (with dowels)	581	5.28	1.41
	90-year total	928	7.63	1.41
DBR	Original PCC construction (no dowels)	337	2.35	0
	Dowel Bar Retrofit	33	0.47	0
	70% of New PCC Construction (with dowels) value due to DBR	407	3.70	0.99
	90-year total	777	6.52	0.99
Savings		151	1.11	0.42
		16%	15%	30%

Notes:

a. Does not include feedstock energy.

3.4 Findings

Added GWP and energy consumption associated with the DBR (33 $MgCO_2e$ and 0.47 TJ) are more than offset by the life extension offered by DBR (represented the reduction in new PCC construction GWP and energy consumption to 70% of the total). The total savings varies depending upon the structural design of the pavement but the fractional savings are consistent at about 15% for both GWP and energy consumption.

3.4.1 Total Savings for WSDOT since the Inception of DBR Method

Since WSDOT undertook the first DBR in 1992, a total of 571 lane-miles have been retrofitted through 2013 (WSDOT 2013). While a calculation of the exact structural section for each project is beyond the scope of this research a quick calculation can be make assuming an average savings in GHG emissions (135 $MgCO_2e$) and energy consumption (1.04 TJ) between the 25-50 million and 100-200 million ESAL designs.

$$\text{Total GHG Savings} = 571 \text{ lane-miles} \times 135 \text{ MgCO2e} = 77{,}085 \text{ MgCO2e}$$
$$\text{Total energy Savings} = 571 \text{ lane-miles} \times 1.04 \text{ TJ} = 593.84 \text{ TJ}$$

Divided evenly per year (although DBR work is not distributed evenly by year), this results in an annual savings of 3,854 $MgCO_2e$ in GHG emissions and 29.69 TJ of energy.

4 IMPROVEMENTS IN NETWORK ROUGHNESS

This section addresses vehicle operations in the use phase. Specifically it estimates the change in GHG emissions from vehicle fuel consumption that can be attributed to pavement roughness. This is considered to be a major contributor to GWP in the use phase and in the total pavement life cycle (Santero 2009). Other use phase items, while potentially significant, are not addressed.

This section provides (1) a general background on how pavement roughness contributes to vehicle fuel consumption and resultant GHG emissions, (2) the specific method used to estimate the change in these emissions for WSDOT pavements from 1990 to 2010, and (3) the results.

4.1 Hypothesis

Improvements in pavement network roughness leads to reduced GHG emissions and energy consumption associated with pavement construction associated with lower fuel consumption of vehicles driving on the network.

4.2 How Roughness Contributes to GHG Emissions

Pavement roughness affects rolling resistance, which affects fuel consumption for vehicles driving on the pavement, which affects GHG emissions resulting from this fuel consumption. Rolling resistance is, in turn, affected by side force, air resistance, surface macrotexture, and (of concern for this study) surface roughness. Figure 5 shows the relationship between major items affecting automotive fuel economy.

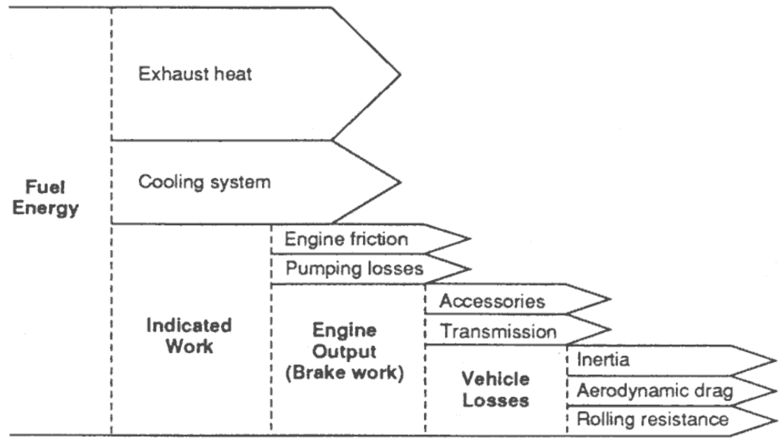

Figure 5. Items affecting automotive fuel economy.
(from Committee on Fuel Economy of Automobiles and Light Trucks, 1992)

4.2.1 Rolling Resistance vs. Fuel Economy

A number of studies have quantified the relationship between changes in rolling resistance and changes in fuel economy (and thus, for this study's purpose, GHG emissions). Shuring (1988) proposed a Return Factor (RF) metric, which is the ratio between fractional improvement in fuel economy (first number) and fractional reduction in rolling resistance (second number). Shuring (1988) found that for passenger cars and light trucks, RF is typically between 1:10 and 2:10 (or 0.1 and 0.2 in decimal form) meaning that a 10% reduction in rolling resistance gives a 1-2% improvement in fuel economy. For heavy trucks, RF can be higher, with a typical range between 1:10 and 3:10 (or 0.1 and 0.3 in decimal form) (LaClair, 2004). Table 9 shows RFs (in decimal form) from a variety of studies.

Table 12. Influence of Rolling Resistance on Fuel Consumption for Various Published Data (modified from Descornet 1990).

Author	Year	Return Factor[a]
Crum and McNall	1974	0.12-0.37
Floyd, C.W.	1976	0.17-0.36
Thompson and Torres	1977	0.2
Knight, R.E.	1979	0.25
Waters and Laker	1980	0.13-0.18
Salerno, P.	1983	0.15
Gerresheim, M.	1983	0.14-0.26
Mathevet	1983	0.27
Schubert, K., et al.	1988	0.28-0.30
Sandberg, U.	1997	0.25

Note:

a. The ratio of change in fuel consumption vs. change in rolling resistance expressed as a decimal. E.g., 0.2 means that for a 1% change in rolling resistance, fuel economy changes by 0.2%.

The relationship between change in rolling resistance and the change in fuel consumption is non-linear with higher rolling resistance changes resulting in larger fuel consumption changes. Table 13 shows this using total energy consumption instead of fuel consumption.

Table 13. Changes in Rolling Resistance vs. Changes in Total Energy Consumed for Vehicles (reproduced from Bendten, 2004)

Change in Rolling Resistance	1%	5%	10%	25%	50%
Change in total energy consumption	0.14%	0.85%	2.33%	6.41%	16.62%

4.2.2 Roughness vs. Fuel Economy

Carrying the relationship one step further, pavement roughness can be related to fuel economy. Several studies have attempted to quantify this relationship (Table 14 and Table 15Table 15) and most have chosen to develop a direct empirical relationship between the two and skip the intermediate theoretical steps. This poses an issue because with the exception of the Epps and Amos studies, all studies in used an extremely high IRI value, which prevents them from forming the basis for further research concerned with typical U.S. roughness values.

Table 14. Roughness Reduction vs. Passenger Car Fuel Savings for Various Studies

Year	Author	IRI (inches/mile)		IRI Decrease	Fuel Saving	Ratio
		Rough	Smooth			
1990	De Plessis et al.	393	76	81%	2.5%	0.03
1997	Motha et al.	362	75	79%	4.0%	0.05
2001	Brown & Powell	75	68	9%	2.0%	0.22

Year	Author	IRI (inches/mile)		IRI Decrease	Fuel Saving	Ratio
		Rough	Smooth			
2004	Jackson et al.	-	-	10%	1.3%	0.13
2006	Amos	130.23	60.99	53%	0.8%	0.01
2010	Zaabar	190	63	67%	1.5%	0.02

Table 15. Roughness Reduction vs. Truck Fuel Savings for Various Studies

Year	Author	IRI (inches/mile)		IRI Decrease	Fuel Saving	Ratio
		Rough	Smooth			
1990	De Plessis et al.	393	95	76%	0.7%	0.01
1997	Motha et al.	362	75	79%	7.0%	0.9
1999	Epps et al.	150	75	50%	4.5%	0.09
2006	Amos	130.23	60.99	53%	2.4%	0.05
2010	Zaabar and Chatti	190	63	53%	1%	0.02

All studies in Table 14 and Table 15 support the general conclusion that smoother pavement results in lower fuel consumption. The exact magnitude of this relationship is not generalizable because results rely on a number of influential but unquantified parameters such as vehicle type/speed/condition, wind and air temperature, roughness, etc.

4.2.3 Summary

Pavement roughness is one factor that can affect vehicle GHG emissions. In general, smoother pavements result in less rolling resistance, which improves fuel economy, which reduces GHG emissions. In general a 1% decrease in roughness (as measured by IRI) can result in a fuel savings of between 0.01% and 0.9%. This relationship is not consistent between studies and is not linear.

4.3 Method

Washington State Pavement Management System (WSPMS) data from 1990 and 2010 were used to determine the trend in IRI from 1990 to 2010 and, using WSDOT aggregate traffic data and generally published fuel economy and GHG emissions constants, an estimate of GHG emissions changes from 1990 to 2010 was made. Estimates were made for (1) the change in GHG emissions resulting from differences in VMT and fuel economy between 1990 and 2010, and (2) the change in GHG emissions attributable to changes in pavement roughness from 1990 to 2010. This section describes the data and methods used for both calculations.

4.3.1 Trend in IRI from 1990 to 2010

WSPMS data from 1990 to 2010 (inclusive) was used to determine the trend in WSDOT pavement system roughness from 1990 to 2010. This entailed (1) determining annual weighted average IRI, (2) correcting for a discontinuity between 1998 and 1999 when WSDOT changed roughness measurement instruments, and (3) creating a straight-line linear regression model that best fit the resulting data.

Step 1: Obtain data from WSPMS roadway segments. WSPMS data was obtained for years 1990 through 2010. Data from the smallest uniform roadway segments, were used for the analysis. The number of usable data points and lane-miles varied slightly from year-to-year, however there were typically 18,500 to 19,000 data points in a year that represented 17,780 lane-miles of pavement (with averages of 11,014 lane-miles surfaced with ACP, 2,004 lane-miles surfaced with PCCP, and 4,496 lane-miles surfaced with BST). For each data point, the following information was used:

- **Surface type**. Classified as either PCCP (portland cement concrete pavement), ACP (asphalt concrete pavement), or BST (bituminous surface treatment).
- **IRI (inches/mile)**. Used as an input into the rolling resistance model.
- **Speed limit**. Used as an input into the rolling resistance model.

Step 2: Account for data discontinuity from 1998 to 1999. Between 1998 and 1999 WSDOT switched from a sonic profiler to a laser profiler, which resulted in a significant reduction in measured IRI for most all segments. To account for this we set the IRI for both years equal and reduced the pre-1999 IRI by an amount equal to the difference between 1998 and 1999 IRI measurements for each pavement type. For instance, if the IRI for an ACP segment in 1998 was 120.54 inches/mile and in 1999 it was 84.22 inches/mile, all pre-1999 IRI measurements for that segment were reduced by the difference between those two measurements, or 36.32 inches/mile.

Step 3: Determine annual weighted average IRI for each pavement type. For each year, an average segment IRI, weighted by segment length, was computed for each pavement type. Adjusted IRI obtained in step 2 was used for all pre-1999 segments.

Step 4: Compute an IRI linear regression model for each pavement type. This was done because annual IRI tended to vary enough from year-to-year enough that we thought a straight comparison of 1990 with 2010 may not be as representative as values taken from a 21-year trend (1990-2010).

4.3.2 Method for the change in GHG emissions resulting from differences in VMT and fuel economy between 1990 and 2010

It was felt that there was possibly a large difference in GHG emissions between 1990 and 2010 that could be attributed to factors other than pavement roughness; most notably differences in VMT and vehicle fuel economy. This difference due to VMT and fuel economy is used to provide an appropriate with which to compare changes in GHG emissions due to pavement roughness. This section describes the method used to determine the difference in GHG emissions attributable to VMT and fuel economy increases between 1990 and 2010.

Step 1: Obtain VMT for 1990 and 2010 for both passenger cars and trucks/buses. Total VMT was obtained from the annual vehicle miles (AVM) summaries in the *1990* and *2010 Annual Traffic Report* (WSDOT). The split between passenger cars and trucks/buses was obtained from WSPMS. 2010 WSPMS data provides the percentage of trucks (as a sum of "single", "double" and "train" percentages) for each roadway segment. This was used to determine a WSDOT pavement network weighted average split of 83.28% cars and 16.72%

trucks and buses. Since no detailed vehicle split was available for 1990 traffic data, the 2010 split was used for 1990 data also.

Step 2: Determine total gallons of fuel consumed. VMT was converted to fuel consumption using fleet average miles traveled per gallon of fuel consumed for both passenger cars and trucks. Data obtained were:

- 1990 (BTS 2014: Table 4-11, 4-13, 4-14)
  - Cars: 20.2 miles traveled per gallon of fuel consumed (Used Table 4-11 value)
  - Trucks: 6.0 miles traveled per gallon of fuel consumed (averaged Table 4-13 and 4-14 values)
- 2010 (FHWA 2012: Table VM-1)
  - Cars: 21.5 miles traveled per gallon of fuel consumed
  - Trucks: 6.4 miles traveled per gallon of fuel consumed

Step 3: Determine total GHG emissions. Fuel consumption was converted to GHG emissions using a standard value of 19.4 lbs. CO_2eq/gallon of fuel consumed (EPA 2005).

4.3.3 Method for the change in GHG emissions attributable to changes in pavement roughness from 1990 to 2010

In order to isolate the effects of pavement roughness, 1990 and 2010 WSDOT network roughnesses were compared using the same 2010 traffic data for each. In this way, differences in VMT and fuel economy (see Section 4.3.2) could be ignored. While this method is useful for estimating the magnitude of roughness's influence on GHG emissions, the output does not represent the actual difference.

Step 1: Determine rolling resistance. Use a model to convert IRI and other input parameters into rolling resistance. A number of models have been proposed for this relationship, however we found the Hammarstrom et al. (2008) model to be the most comprehensive and generalizable. Their model is:

$$Cr = Cr_{01} + Cr_{02} \times V + dCr(IRI) + dCr(MPD)$$

$$dCr(IRI) = C_2 \times IRI + C_3 \times IRI \times (V - 20)$$

$$dCr(\mathrm{MPD}) = C_4 \times \mathrm{MPD} + C_5 \times \mathrm{MPD} \times (V - 20)$$

Variable		Constant Value Car/Van	Constant Value Truck/Bus	Description
Cr	=	-	-	Expression for total rolling resistance coefficient.
Cr_{01}	=	0.00926	0.0057	Parameter for rolling resistance on a smooth surface.
Cr_{02}	=	6.95E-05	0.00008	Parameter for rolling resistance on a smooth surface.
V	=	-	-	Vehicle speed (km/hr). Taken as the speed limit listed in WSPMS for the particular road section in question.
IRI	=	-	-	IRI (m/km). Taken as the modeled IRI for the given year and pavement type.

MPD	=	-	-	Surface macrotexture. Not measured by WSDOT so assigned a value of 1.0 for all road sections.
dCr(IRI)	=	-	-	Additional rolling resistance from roughness.
dCr(MPD)	=	-	-	Additional rolling resistance from surface macrotexture.
C_2	=	0.000380	0.000535	Parameter for rolling resistance from roughness.
C_3	=	0.000035	0	Parameter for rolling resistance from roughness.
C_4	=	0.002210	0.002210	Parameter for rolling resistance from macrotexture.
C_5	=	0.000111	0.000111	Parameter for rolling resistance from macrotexture.

The coefficient of rolling resistance (Cr) calculated from these equations is then multiplied by the vehicle weight to obtain a value for rolling resistance for cars and trucks for each pavement type for both 1990 and 2010.

Step 2: Convert the change in rolling resistance to a change in fuel consumption. The change in rolling resistance from 1990 to 2010 was multiplied by a return factor to obtain a change in fuel consumption from 1990 to 2010 expressed as a percentage. Based on data shown in **Error! Reference source not found.** return factors of 0.25 (for cars) and 0.35 (for trucks/buses) were used.

Step 3: Compute the change in gallons of fuel consumed. Fuel economy numbers from 2010 (FHWA 2012: Table VM-1) were used to determine a baseline amount of fuel consumed for 1990 pavement network roughness. These were:

- Cars: 21.5 miles traveled per gallon of fuel consumed.
- Trucks: 6.4 miles traveled per gallon of fuel consumed.

The fractional fuel savings obtained in Step 2 was then used to adjust the baseline amount of fuel consumed to obtain the fuel consumed for the 2010 pavement network roughness.

Step 4: Compute the change in GHG emissions. 1990 GHG emissions and the 1990-2010 change in GHG emissions were computed from fuel consumption using a standard value of 19.4 lbs. CO_2e/gallon of fuel consumed (EPA 2005).

4.4 Results

Accounting for adjustments, it appears WSDOT pavement network roughness has not changed appreciably between 1990 and 2010 (Figure 6, Figure 7, and Figure 8). While actual changes in GHG emissions for vehicles driving on WSDOT pavements has increased by about 4.5 million tons of CO_2e (a 22.5% increase, see Table 17), most of this change is attributed to a significant increase in VMT (from 23 to 32 billion vehicle-miles traveled) and slight increases in fuel efficiency for both cars and trucks (1.3 miles/gallon and 0.4 miles/gallon, respectively). Changes in GHG emissions due to pavement roughness over the same were between a 0.14% reduction in fuel consumption to a 1.33% increase in fuel consumption depending upon pavement surface type and vehicle type (Table 18 and Table 19).

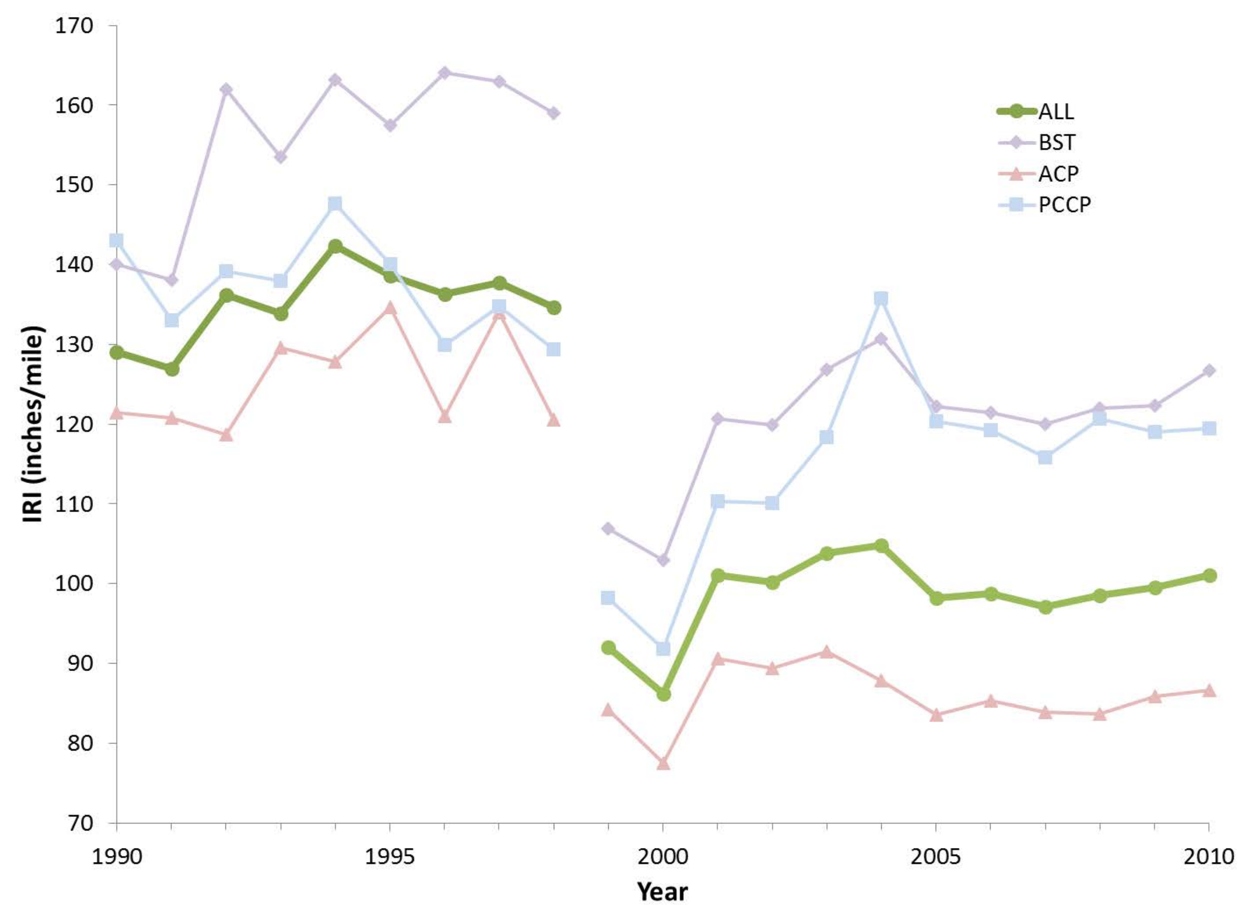

Figure 6. WSDOT annual average roughness by pavement type. See Table 16 for data.

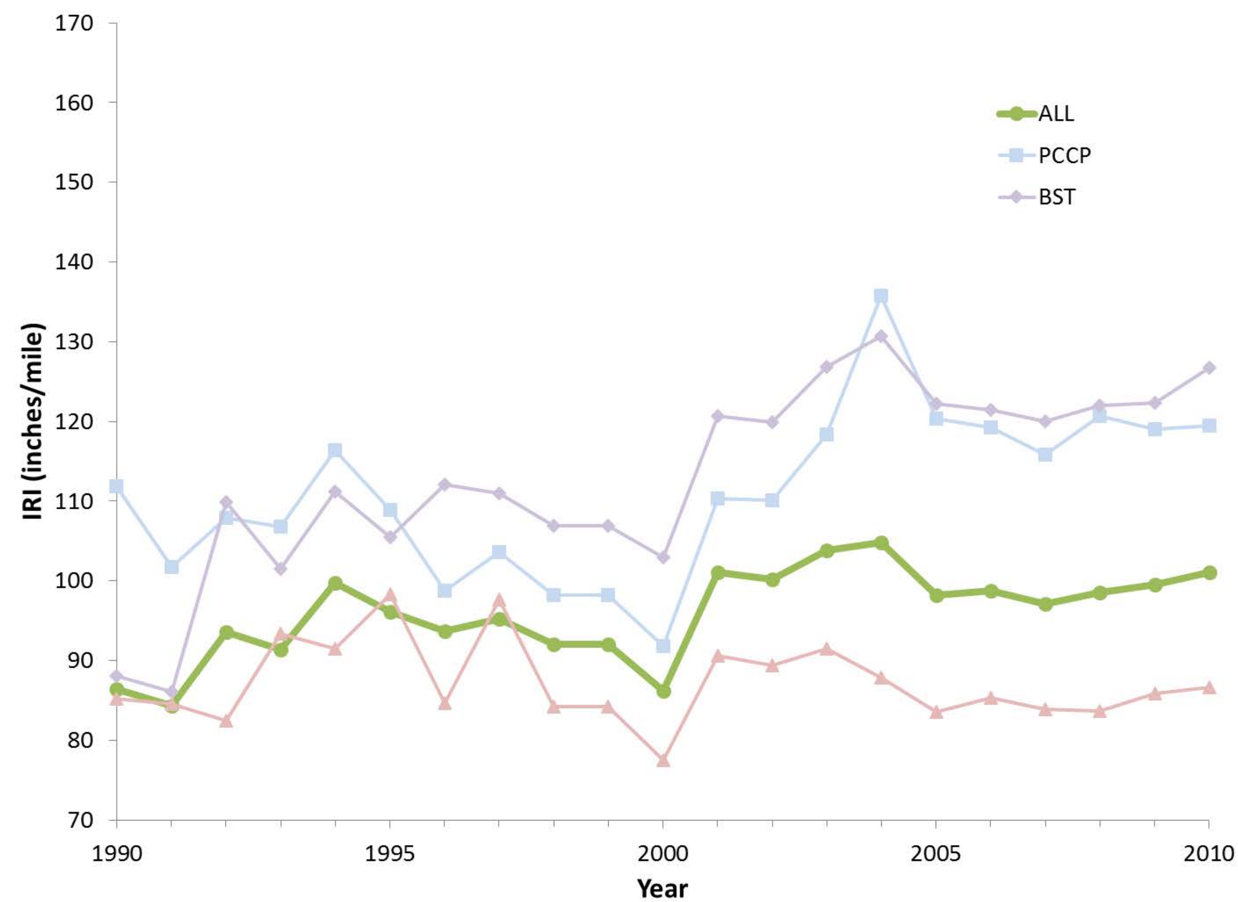

Figure 7. WSDOT annual average roughness by pavement type with 1990-1998 values shifted based on correction for switch from sonic to laser profiler between 1998 and 1999. See Table 16 for data.

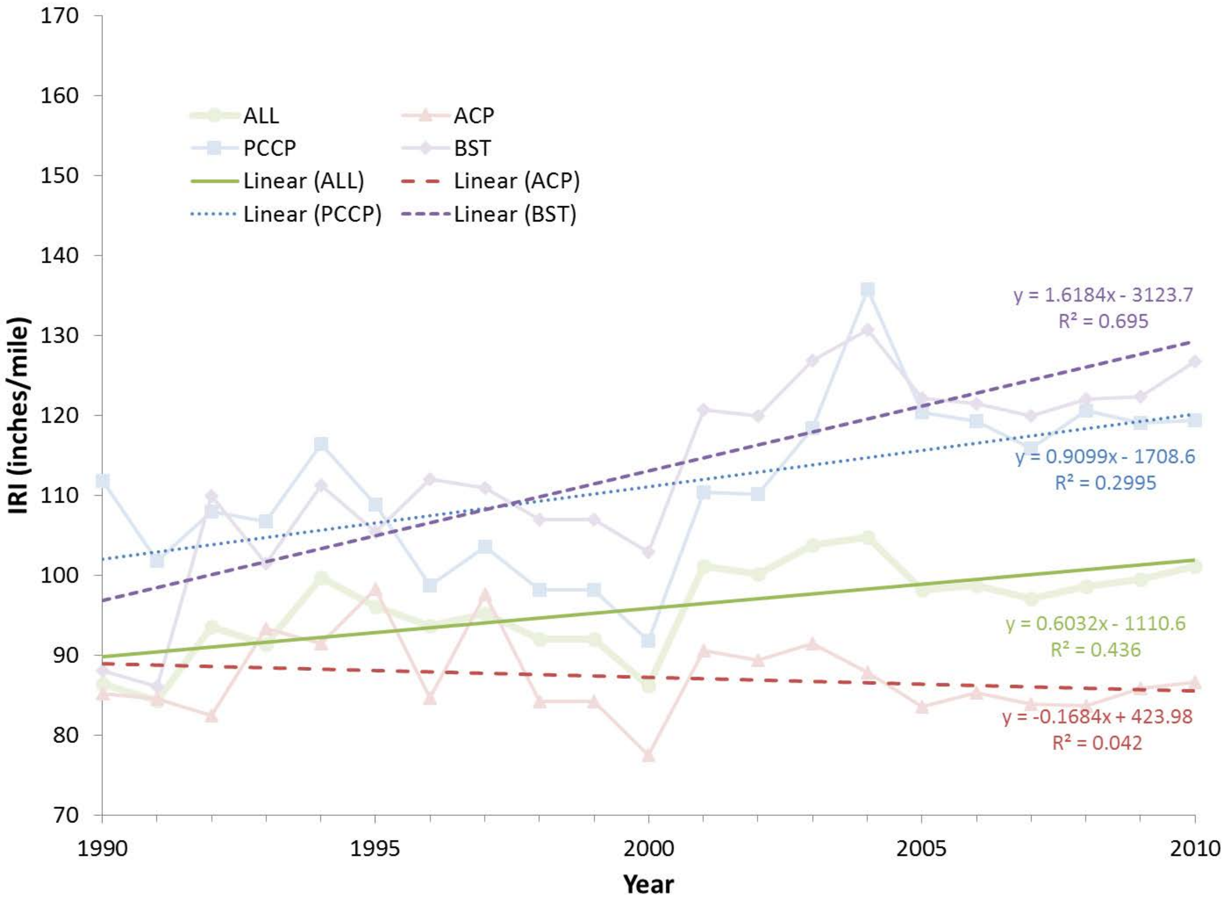

Figure 8. Linear regression models for WSDOT annual average roughness by pavement type. See Table 16 for data.

Table 16. WSDOT Pavement System Roughness Data Used in Analysis

	Overall			Asphalt Concrete Pavement			Portland Cement Concrete Pavement			Bituminous Surface Treatment		
Year	**Actual**	**Shifted**	**Modeled**	**Actual**	**Shifted**	**Modeled**	**Actual**	**Shifted**	**Modeled**	**Actual**	**Shifted**	**Modeled**
1990	129.07	86.47	89.77	121.49	85.18	88.86	143.01	111.81	102.10	140.09	88.10	96.92
1991	126.91	84.31	90.37	120.84	84.52	88.70	132.96	101.76	103.01	138.04	86.05	98.53
1992	136.18	93.58	90.97	118.74	82.42	88.53	139.12	107.92	103.92	161.92	109.93	100.15
1993	133.92	91.32	91.58	129.62	93.31	88.36	137.97	106.78	104.83	153.46	101.46	101.77
1994	142.33	99.73	92.18	127.84	91.53	88.19	147.63	116.43	105.74	163.24	111.25	103.39
1995	138.67	96.07	92.78	134.64	98.32	88.02	140.07	108.87	106.65	157.41	105.42	105.01
1996	136.28	93.68	93.39	121.01	84.69	87.85	129.90	98.70	107.56	164.05	112.06	106.63
1997	137.78	95.18	93.99	134.00	97.69	87.69	134.76	103.56	108.47	162.97	110.98	108.24
1998	134.68	92.09	94.59	120.54	84.22	87.52	129.38	98.18	109.38	158.95	106.95	109.86
1999	92.09	92.09	95.20	84.22	84.22	87.35	98.18	98.18	110.29	106.95	106.95	111.48
2000	86.18	86.18	95.80	77.49	77.49	87.18	91.84	91.84	111.20	102.92	102.92	113.10
2001	101.11	101.11	96.40	90.59	90.59	87.01	110.36	110.36	112.11	120.69	120.69	114.72
2002	100.16	100.16	97.01	89.40	89.40	86.84	110.11	110.11	113.02	119.95	119.95	116.34
2003	103.81	103.81	97.61	91.47	91.47	86.67	118.40	118.40	113.93	126.81	126.81	117.96
2004	104.77	104.77	98.21	87.87	87.87	86.51	135.79	135.79	114.84	130.68	130.68	119.57
2005	98.22	98.22	98.82	83.60	83.60	86.34	120.32	120.32	115.75	122.16	122.16	121.19
2006	98.78	98.78	99.42	85.29	85.29	86.17	119.29	119.29	116.66	121.44	121.44	122.81
2007	97.12	97.12	100.02	83.86	83.86	86.00	115.85	115.85	117.57	119.97	119.97	124.43
2008	98.57	98.57	100.63	83.71	83.71	85.83	120.63	120.63	118.48	122.03	122.03	126.05
2009	99.53	99.53	101.23	85.85	85.85	85.66	119.07	119.07	119.39	122.34	122.34	127.67
2010	101.11	101.11	101.83	86.63	86.63	85.50	119.44	119.44	120.30	126.76	126.76	129.28
Total Lane Miles	17780			11014			2004			4496		

Table 17. GHG Emissions from Vehicles Driving on the WSDOT Pavement Network in 1990 and 2010. Differences are due to changes in (1) VMT, and (2) fuel economy.

		VMT (billion)	VMT-Car (billion) / VMT-Truck (billion)	MPG	Fuel consumed (billion)	GHG emitted ($lbCO_2e/gal$)	Total GHG Emissions (millions of tons CO2e)	GHG-Car (millions of tons CO2e) / GHG-Truck (millions of tons co2e)
2010	Car	31.76	26.45	21.5	1.23	19.4	20.0	11.9
	Truck		5.31	6.4	0.83			8.0
1990	Car	23.12	19.26	20.2	0.95		15.5	9.2
	Truck		3.87	6.0	0.65			6.3

Table 18. Changes in Rolling Resistance and Fuel Consumption from 1990 – 2010

		IRI (inches/mile)		Speed (MPH)	Rolling Resistance (lbs)		ΔRR (%)	ΔFC (%)
		1990	2010		1990	2010		
All	Car	89.77	101.83	56.14	115.38	117.49	1.83%	0.46%
	Truck				202.30	206.36	2.01%	0.50%
ACP	Car	88.86	85.50	54.69	113.13	112.56	-0.50%	-0.13%
	Truck				197.79	196.70	-0.56%	-0.14%
PCCP	Car	102.10	120.30	64.83	130.46	134.19	2.86%	0.72%
	Truck				232.40	239.58	3.09%	0.77%
BST	Car	96.92	129.28	56.40	117.01	122.70	4.86%	1.22%
	Truck				205.47	216.42	5.33%	1.33%

Table 19. Change in GHG Emissions from 1990 – 2010

		Fraction of Traffic (%)	Total VMT (millions of miles)	Car/Truck VMT (million mi)	Baseline MPG for 1990 roughness	Fuel consumed for 1990 network roughness (millions of gal)	GHG emissions attributed to 1990 network roughness (mil. Of MgCO2e)	Change in Fuel Consumption from 1990-2010 (millions of gal)	Change in GHG emissions from 1990-2010 (millions of MgCO2e)	Change in GHG emissions from 1990-2010 (percent)
All	Car	83.28%	31,764	26,453	21.50	1,230	10.97	6	0.050	0.46%
	Truck	16.72%		5,311	6.40	830	7.40	4	0.037	0.50%
ACP	Car	85.36%	20,250	17,285	21.50	804	7.17	-1	-0.009	-0.13%
	Truck	14.64%		2,965	6.40	463	4.13	-1	-0.006	-0.14%
PCCP	Car	84.73%	10,720	9,083	21.50	422	3.77	3	0.027	0.72%
	Truck	15.27%		1,637	6.40	256	2.28	2	0.018	0.77%
BST	Car	79.32%	635	504	21.50	23	0.21	0	0.003	1.22%
	Truck	20.68%		131	6.40	21	0.18	0	0.002	1.33%

4.5 Findings

4.5.1 General Conclusion

Given the variation in year-to-year roughness measurements recorded in WSPMS and the somewhat simplified nature of the roughness-to-rolling resistance models as well as the use of standard universal conversion factors, the general conclusion is that WSDOT pavement network roughness, and GHG emissions attributable to this roughness, have not changed appreciably from 1990 to 2010.

4.5.2 Roughness Observations

Observations on 1990 to 2010 roughness changes are:

- **The overall WSDOT pavement network has gotten about 10% rougher**. The linear model indicates an increase from 89.77 to 101.83 inches/mile (an increase of 13%).
- **ACP surfaces have remained about constant.** The linear model indicates a decrease from 88.86 to 85.50 inches/mile (a decrease of 4%).
- **PCCP surfaces have gotten about 20% rougher.** The linear model indicates an increase from 102.10 to 120.30 inches/mile (an increase of 18%).
- **BST surfaces have gotten about 30% rougher.** The linear model indicates an increase from 96.92 to 129.28 inches/mile (an increase of 33%).

In all instances our simplifying assumptions (i.e., equal roughness values in 1998 and 1999 to account for the change in measurement instrument, and a simple linear model of roughness) and measurement variability makes us choose to limit the precision of our observations to increments of 10%.

4.6 Cost of Reducing GHG Emissions by Improving WSDOT Network Condition

Calculations from this section coupled with previous work from Li et al. (2004) can provide a rough approximation of how much it might cost to reduce GHG emissions by improving WSDOT pavement network smoothness. This value can be compared to various values proposed for GHG emissions as well as costs for other GHG reduction strategies.

4.6.1 Overview of Li et al. (2004) Work

Li et al. (2004) used a program from the World Bank, HDM-4, to model WSDOT pavement network conditions under multiple long-term funding scenarios. Importantly, they were able to relate hypothesized 40-year budgets (i.e., 20 biennial budgets) to annual pavement condition over 40 years using an HDM-4 model calibrated and validated \with actual WSDOT data.

4.6.2 Method

Step 1: Create a regression model

Create a linear regression model from Li et al. (2004) strategic level analysis findings shown in Table 20.

Table 20. Key Findings from Li et al. (2004)

Scenario	WSDOT Annual Budget[a]	WSDOT 40-year Budget[a]	Equilibrium IRI (inches/mile)[b]	Net Present Value[a]
Optimum funding level	$ 105.6	$ 4,224	86	$ 198,052
2004 WSDOT funding	$ 87.1	$ 3,482	317	$ 162,461
75% of optimal	$ 79.2	$ 3,168	380	$ 159,682
50% of optimal	$ 52.8	$ 2,122	570	$ 146,619

Notes:

a. All costs are in millions of present day dollars.
b. The IRI that a given funding level can maintain over time. This level is often reached after several decades.

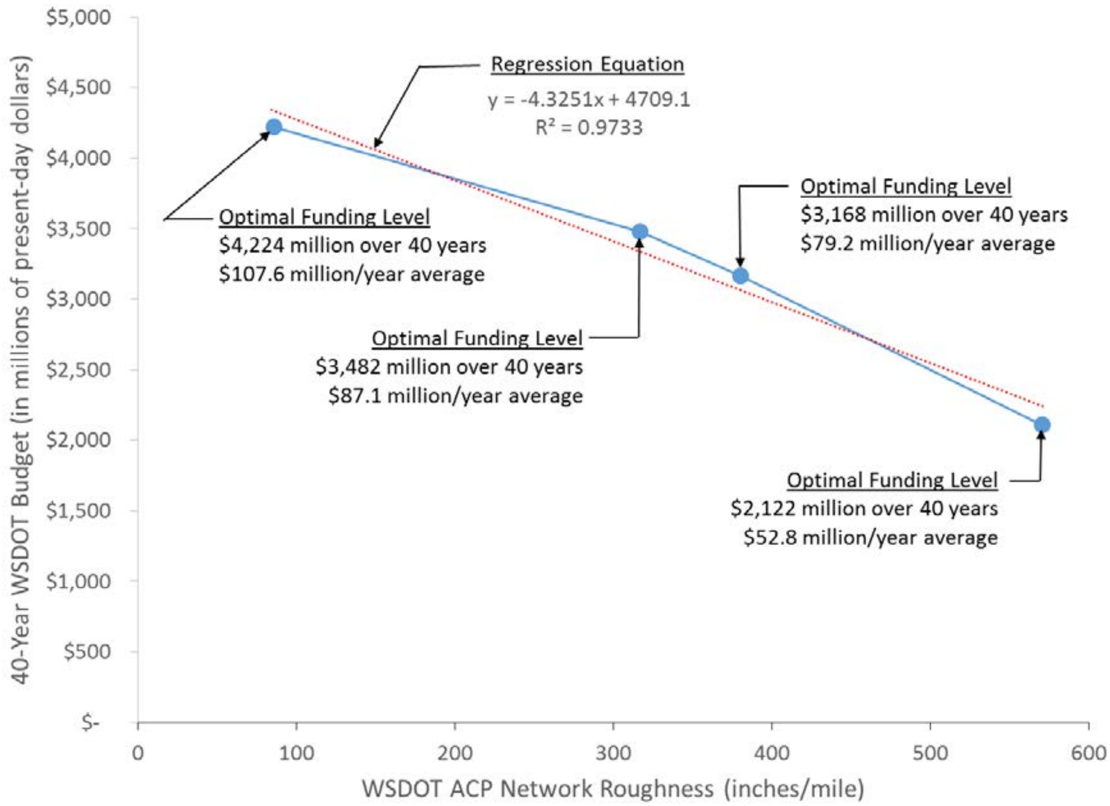

Figure 9. WSDOT budget scenarios and resulting ACP network roughness from Li et al. (2004). Regression model shown.

Regression equation:

$$y = -4.3251x + 4709.1 \qquad \text{(Equation 1)}$$

Where,

y = 40-year WSDOT budget for ACP network.

x = Equilibrium roughness for WSDOT ACP network.

This means that for every inch/mile of ACP network roughness improvement, a corresponding increase of $ 4.33 million in WSDOT funding is needed over 40 years.

Step 2: Determine the change in GHG associated with a change in ACP network roughness.

Use the models in Section 4.3 to determine the change in GHG associated with a unit change in roughness. This calculates to be 34,336 $MgCO_2e$ per inch/mile improvement over 40 years.

Step 3: Determine the associated cost per metric ton (MT) of GHG emissions reduction

Divide the increase in cost ($ 4.33 million over 40 years per inch/mile improvement) by the associated reduction in GHG emissions.

$$\frac{34{,}336}{\$\ 4{,}325{,}100} = \$\ 125.96\ per\ Mg\ of\ GHG\ emissions\ reduced$$

4.6.3 Results

This rough method indicates that reducing GHG emissions from vehicles traveling on WSDOT ACP pavements by improving pavement smoothness can cost about $125 per Mg CO2e. If the benefit of fuel use reduction is considered, the cost is quite dependent on the cost of fuel. For a fuel cost of $3.00/gallon, the cost is about $44 per Mg$CO_2$e. Note that given the rough nature of these calculations, the use of data from another report (Li et al., 2004) that was not intended for this purpose, and ever-changing fuel costs this value should only be taken as a rough, first order approximation. It will be hereafter reported as $10-$80/ MgCO_2e.

4.6.4 Findings

This section compares the results with (1) typical prices of carbon, and (2) the costs of other strategies for GHG reduction.

4.6.4.1 Comparison to the Price of Carbon

Duong (2009) points out five frequently used definitions for the price of carbon:

1. **The expected mitigation of climate change damage**. Assigns a value to the avoided impacts of carbon that is not released to the atmosphere. This is controversial since it involves placing economic values on non-economic items such as ecosystems and human life. Such issues make a value assigned in this way forever debatable therefore:, Duong (2000) does not give a value.
2. **The cost of reducing CO_2 emissions**. Abatement costs can be identified, are reported most often as marginal costs, and can vary greatly based on the marginal reduction sought. Duong (2000) report these cost $25 - $90/ Mg$CO_2$e.
3. **The social cost of CO_2 emissions**. An estimate of the economic damages resulting from CO2 emissions aggregated over time. This is controversial based on uncertainty, controversy, and value selection (Duong 2009). Duong (2009) states the value is most likely somewhere between 5 and 200 Euros/ MgCO_2e ($6 - $240/ Mg$CO_2$e). This wide range "…renders the SCC (social cost of carbon) almost useless as a guide to policy." (Duong 2009). A US government interagency working group (2010) estimated the social cost of carbon to be between $4.70 and $64.90 (based on different carbon discount rates and uncertainties), which is somewhat consistent with Duong's (2009) findings.
4. **The politically negotiated value of carbon**. Because other methods are controversial or at least debatable, setting a value for CO_2 emissions is essentially a political decision. Such decisions can take the form of fines or taxes. Duong (2009) gives a French example in the 27 to 100 Euro range ($33 - $121).
5. **CO_2 market prices**. Prices of CO_2 emissions associated with various trading markets. These can vary widely with European Union values in the 5 to 30 Euro range ($6 - $36), and U.S. prices being lower (Duong 2009). The Regional Greenhouse Gas Initiative (RGGI) – 10 northeastern states regulating emissions from electrical power plants producing 25 MW or more – had a closing price

equal to the reserve price (the lowest price allowed) of \$1.86/MgCO_2e in December 2010 (Potomac Economics 2011) but the most recent auction, on 3 December 2014, resulted in a clearing price of \$5.21/ MgCO_2e (Potomac Economics 2014).

This suggests the price of carbon is somewhere in the \$2 - \$240/MgCO_2e range, which is a wide range and rather useless for comparison.

4.6.4.2 Comparison to the Cost of Other GHG Mitigation Measures

Many authors discuss the relative costs of different GHG mitigation measures both domestically and internationally. Enkvist et al. (2007) offer a somewhat comprehensive look at global GHG mitigation (or "abatement" as they term it) costs (Figure 10).

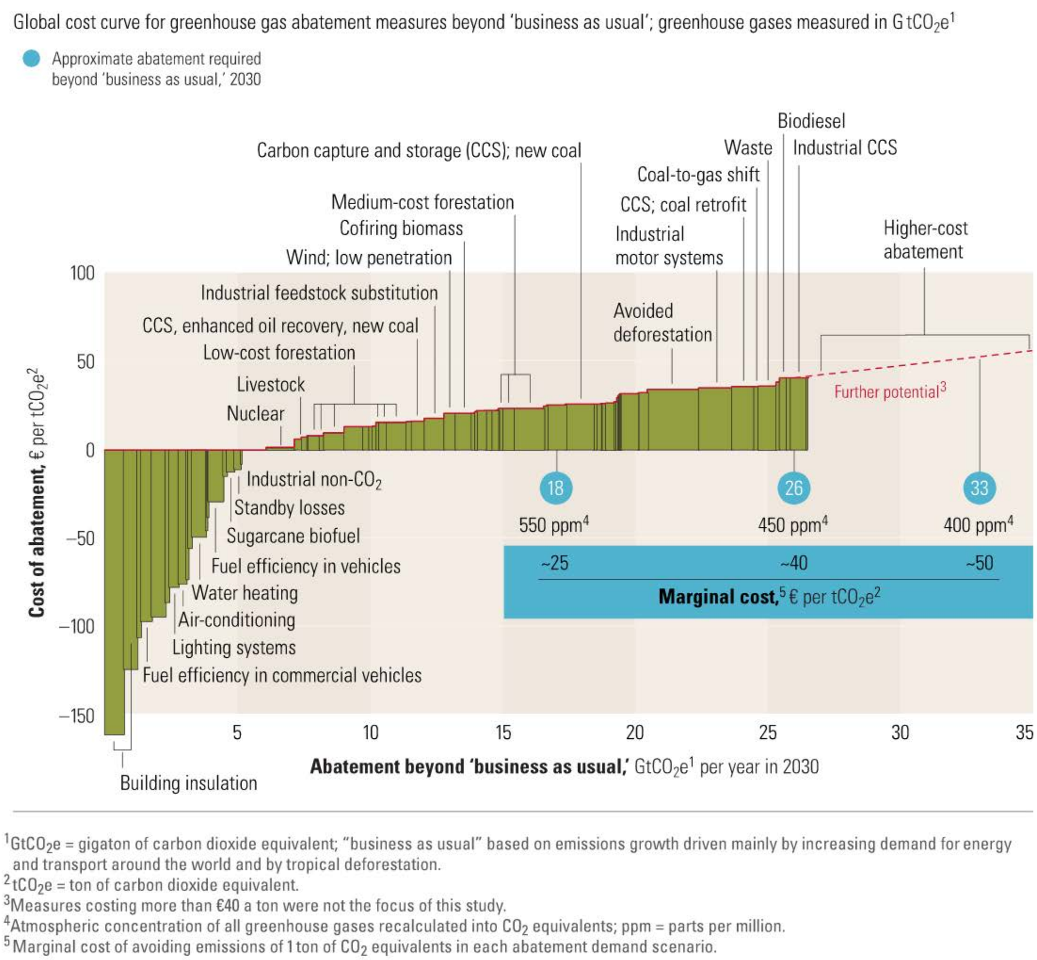

Figure 10. Global cost curve for GHG abatement measures beyond "business as usual"; greenhouse gas measured in GtCO_2e (from Enkvist et al. 2007). Note that the costs are in Euros and not U.S. Dollars.

With a cost of \$10-\$80/MgCO_2e (10-66 Euros), improving WSDOT ACP network smoothness ranks somewhere around avoided deforestation, industrial motor systems, and retrofitted carbon capture systems for coal power plants. It is certainly more expensive than the fuel efficiency options listed by Enkvist et al. (2007), which all involve negatives costs (i.e., savings).

5 LONG LIFE ASPHALT CONCRETE PAVEMENT (ACP)

Over the last 30 years or so WSDOT has generally followed a long-life pavement strategy in the area of maintenance and preservation. That is, WSDOT typically chooses to design pavements for long life, e.g., 50 year design period for new highways (WSDOT 2011). Such a design policy tends to result in long-lasting pavements that require only periodic surface renewal, typically in the form of ACP overlays or PCCP grinding. This section analyzes ACP for indicators of a long-life strategy. PCCP quantities are not analyzed since PCCP is paved full-depth at new construction only, and these depths have not changed appreciably from 1990 through 2010.

5.1 Hypothesis

The hypothesis for this section is that for ACP a gradual shift towards long-life pavements from 1990 to 2010 should result in fewer thick (> 2 inches) HMA structural overlays and more thinner (≤ 2 inches) surface renewal overlays (even though long-life pavements were being designed as early as 1990 and before, the effects of rehabilitating older pavements during this time would drive the thicker structural overlays). If this is true, this trend should be visible when comparing overlay thicknesses over time and annual tons of HMA per lane-mile paved for ACP. Using the generally accepted belief that long-life pavement strategies consume less materials (e.g., Muench et al. 2004, Ram et al., 2011), a savings of materials and GHG could be shown.

5.2 Method

This section describes the method used to obtain an estimate of ACP tons/lane-mile paved per WSDOT biennium from 1992/1993 through 2010/2011.

5.2.1 Data

Information from the WSDOT Construction Contract Information System (CCIS) and WSPMS (Washington State Pavement Management System) was used to estimate tonnage and lane-miles paved by WSDOT for each pavement type in preservation efforts only (new construction pavements were excluded to the extent possible). Specifics issues with the data follow:

- **There is likely a slight mismatch between reported tonnage/volume and lane-miles paved**. This is because tonnage/volume is based on contract award date, while lane-miles are based on the construction end date. This can result in some pavement tonnage/volume reported in one year (award date) but not given credit for lane-miles paved until a subsequent year (contract end date). We believe this mismatch to be minor and have assumed all lane-miles reported paved in a particular year were done so with tonnage/volume reported in that same year.

- **For ACP and BST the actual surface area paved is likely under-reported.** This is because ACP and BST used for non-mainline paving such as shoulders and ramps are not included in the lane-miles reported.
- **For PCCP the lane-miles paved includes the shoulder area**. For example, one lane of PCCP including the adjacent shoulder that is paved for one mile counts as two lane-miles of paving (one mile for the mainline, one mile for the shoulder).
- **Calendar years and WSDOT biennia do not match**. WSDOT paving is budgeted on a biannual basis (every other year) with fiscal years beginning in July. Thus, budgets, which control the amount of paving, are not aligned with the calendar year. Therefore, budget changes go into effect at the beginning of the fiscal year (July 1st) and their effects can be split between the current and subsequent years as reflected in this analysis.
- **Data for 1990 and 1991 are incomplete**. 1990 and 1991 ACP tonnage data is incomplete.

5.2.2 Calculations

Only ACP data is further analyzed. The following metrics were calculated on a biennium basis: lane-miles paved per pavement thickness group (see below), and tons of ACP per lane-mile paved.

5.2.2.1 ACP Overlay Thickness Groups

About 60 different ACP overlay thicknesses were observed in the data throughout the 20-year period. This was reduced to four basic ACP overlay thickness groups:

1. 0.03 – 0.12 ft. (most typical: 0.06, 0.08, 0.12 ft.)
2. 0.13 – 0.24 ft. (most typical: 0.13 and 0.24 ft.)
3. 0.25 – 0.34 ft. (most typical: 0.25 and 0.30 ft.)
4. > 0.35 ft. (30 different thicknesses, but all occurred infrequently)

5.3 Results

Figures 9, 10, 11 and Tables 19 and 20 show results.

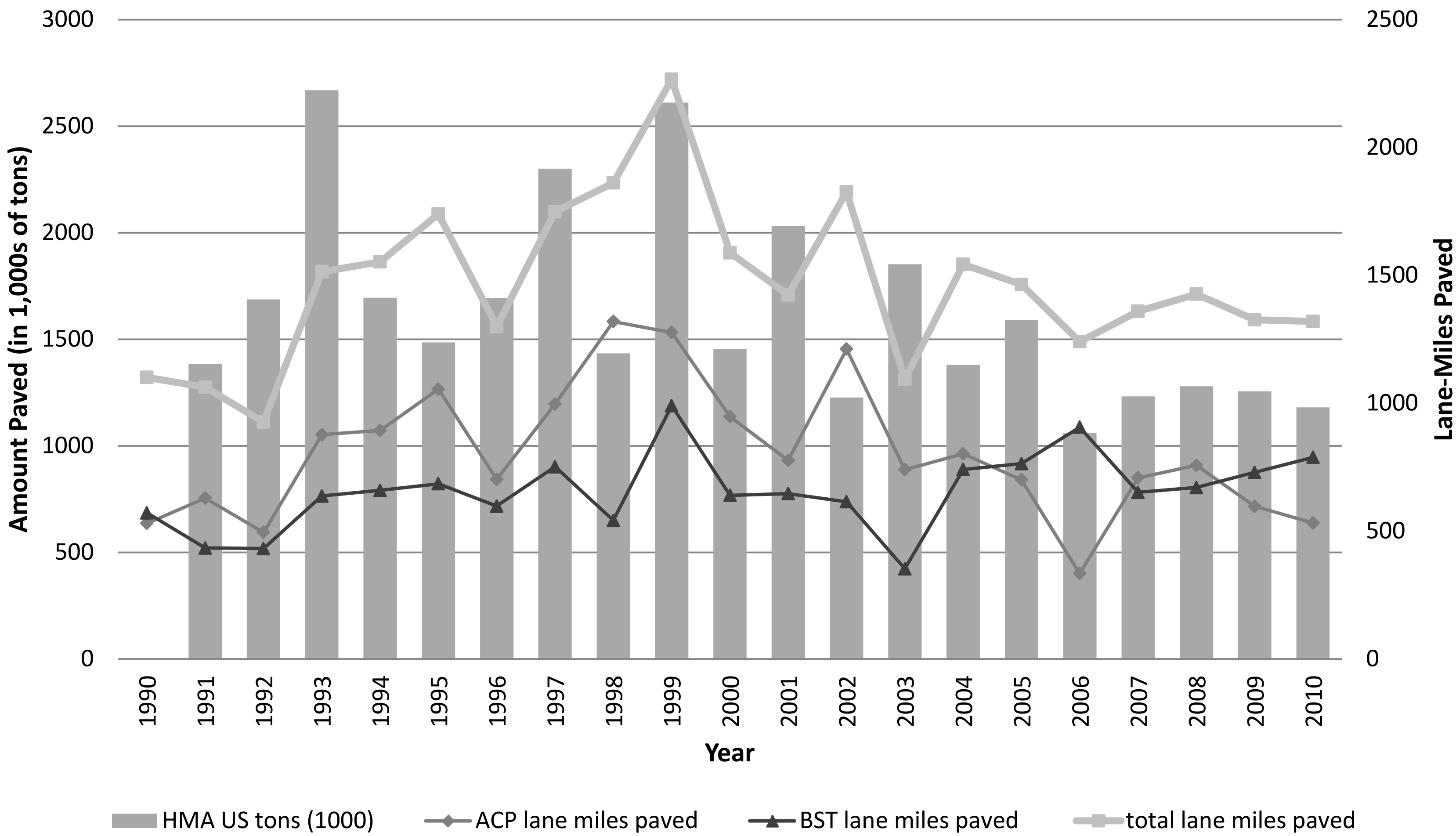

Figure 11. Tons per year and lane-miles paved for WSDOT flexible pavements (both ACP and BST). Note: ACP tonnage data for 1990 is incomplete and therefore not represented on this graph.

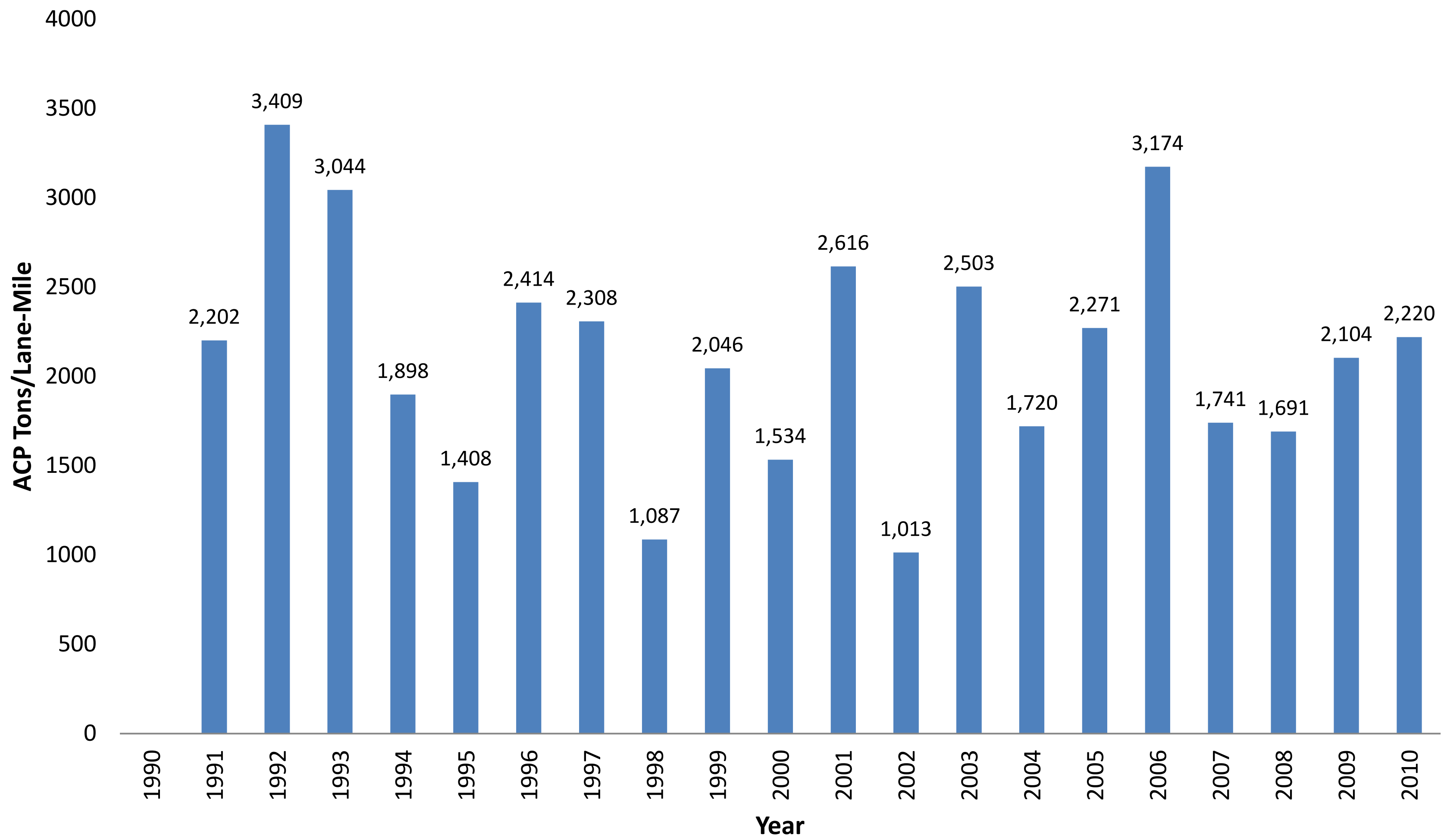

Figure 12. Annual tons of ACP per lane-mile paved for WSDOT pavements.

Table 21. Tons per year and lane-miles paved for WSDOT flexible pavements (both ACP and BST)

	1990[a]	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
ACP											
1,000s of tons	-	1,385	1,687	2,669	1,695	1,485	1,694	2,300	1,434	2,611	1,454
Lane -miles	530	629	495	877	893	1,055	702	997	1,319	1,276	948
Tons/lane-mile	-	2,202	3,409	3,044	1,898	1,408	2,414	2,308	1,087	2,046	1,534
BST											
lane -miles	571	434	431	637	659	685	597	751	541	990	640
TOTAL (ACP+BST)											
Lane -miles	1,101	1,063	926	1,514	1,552	1,740	1,299	1,748	1,861	2,266	1,587

		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
ACP											
1,000s of tons		2,031	1,227	1,852	1,379	1,591	1,061	1,232	1,280	1,256	1,181
Lane -miles		776	1,211	740	802	700	334	708	757	597	532
Tons/lane-mile		2,616	1,013	2,503	1,720	2,271	3,174	1,741	1,691	2,104	2,220
BST											
lane -miles		647	615	353	741	763	906	652	670	730	789
TOTAL (ACP+BST)											
Lane -miles		1,423	1,826	1,093	1,543	1,463	1,240	1,360	1,427	1,327	1,321

Note:

a. ACP tonnage data for this year is incomplete and therefore not reported here.

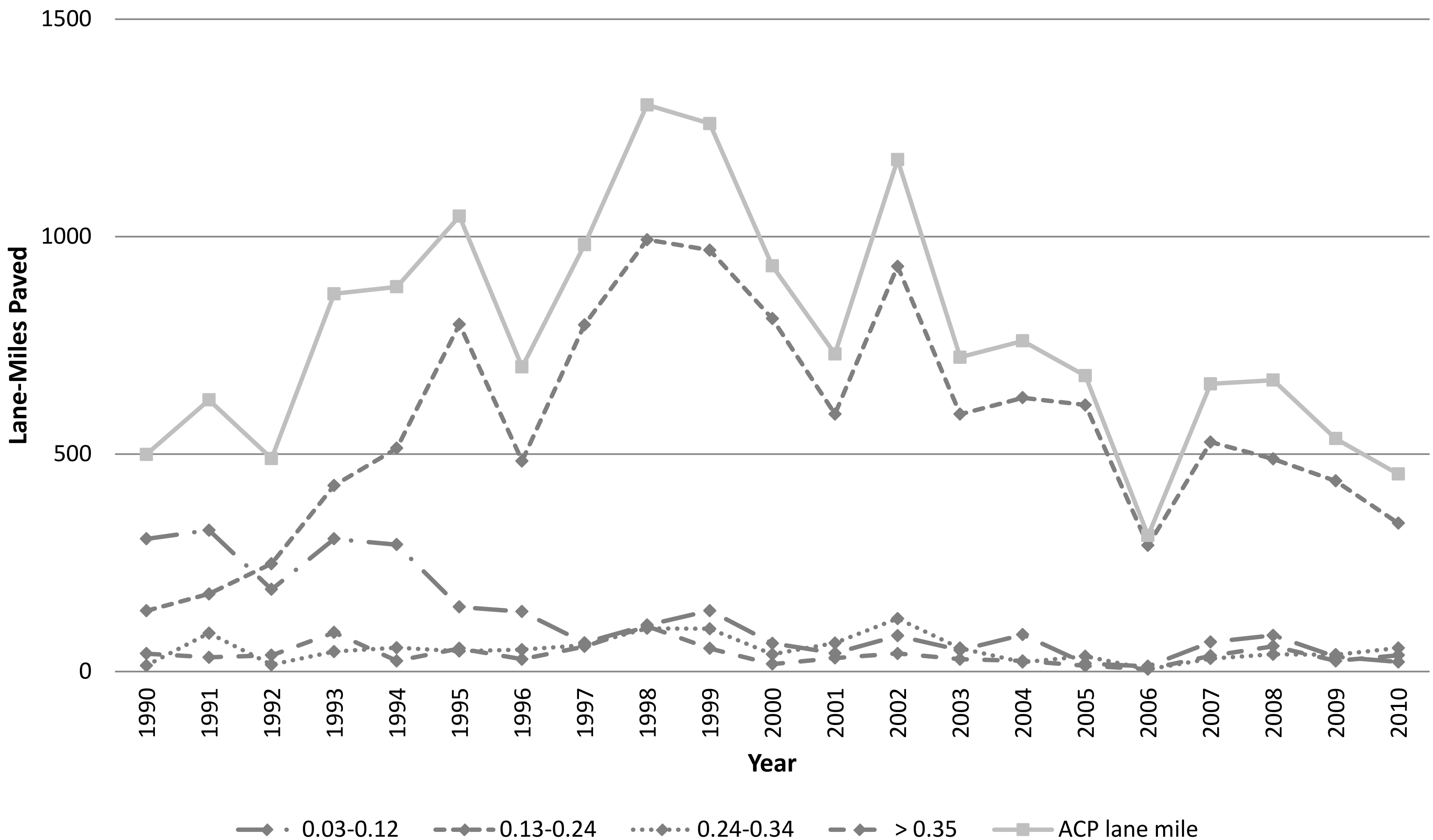

Figure 13. Annual lane-miles paved per thickness category for HMA pavements.

Table 22. Annual Lane-Miles Paved per Thickness Category for HMA Pavements.

Thickness types (ft.)	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
TYPE 1: 0.03-0.12 ft. lane-mile	305	325	189	305	292	148	138	66	107	140	65
TYPE 2: 0.13-0.24 ft. lane-mile	140	179	248	428	513	798	484	797	993	969	811
TYPE 3: 0.25-0.34 ft. lane-mile	14	88	16	46	55	47	50	60	99	98	40
TYPE 4: >0.35 ft. lane-mile	41	33	37	90	24	53	28	58	104	53	17
Total ACP lane-mile	499	624	490	868	884	1047	700	981	1303	1260	933
Total BST lane-mile	571	434	431	637	659	685	597	751	541	990	640

		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
TYPE 1: 0.03-0.12 ft. lane-mile		42	82	49	85	19	12	68	83	34	22
TYPE 2: 0.13-0.24 ft. lane-mile		592	932	591	629	613	290	528	489	438	341
TYPE 3: 0.25-0.34 ft. lane-mile		65	122	54	22	35	5	30	40	39	54
TYPE 4: >0.35 lane-mile		31	42	28	24	13	6	36	58	24	37
Total ACP lane-mile		730	1177	723	760	680	313	661	670	535	454
Total BST lane-mile		647	615	353	741	763	906	652	670	730	788

5.4 Findings

5.4.1 General Conclusion

Figure 11 through Figure 13 along with Table 21 and Table 22 show no discernable trend towards thinner overlays over time, therefore the hypothesis is rejected. This may be because there has been a long-standing unpublished strategy of long-life pavements that predates the data in this study or it may be because no such de facto strategy exists. The only evident trend is a marked reduction in the thinnest overlay category (0.03 – 0.12 inches) that occurred in the late 1990s.

5.4.2 Other Observations

Annual ACP tonnage and lane-miles paved has varied over the 1990-2010 time frame. In general, quantities peaked in the late 1990s around 2 million tons and 2,000 lane-miles annually and have been trending downward since.

6 CONCLUSIONS

This research quantifies the changes in GHG emissions and energy consumption from WSDOT between 1990 and 2010 due to the following pavement practices:

- Four paving materials practices: use of WMA, RAP, fly ash, and slag.
  - Savings for 2010 compared to 1990: 12,597 $MgCO_2e$ and 188 TJ
- Use of DBR as a PCCP rehabilitation practice.
  - Savings for 2010 compared to 1990: 3,854 $MgCO_2e$ and 29.69 TJ
- Improvements in WSDOT pavement network roughness.
  - Savings for 2010 compared to 1990: - 87,000 $MgCO_2e$ (pavement network got rougher so the increased in GHG results in a negative savings). Energy was not calculated for network roughness.
- Adoption of a long-life ACP strategy.
  - Savings for 2010 compared to 1990: none discernable.

Overall, this results in a 16,451 $MgCO_2e$ and 218 TJ savings in in GHG emissions and energy consumption respectively due to pavement technologies (i.e., WMA, RAP, fly ash) and DBR rehabilitation of PCCP. For GHG emissions this is offset by a theoretical increase of 87,000 $MgCO_2e$ due to a slightly rougher pavement network for a net increase in GHG emissions of about 70,000 $MgCO_2e$. Since energy consumption was not quantified for pavement roughness a number for energy consumption is not reported here but the answer would likely be of the same magnitude as that of GHG emissions.

Specific conclusions are listed for each pavement practice.

Use of WMA, RAP, fly ash, and slag (Figure 14 and Figure 15)

- All four practices can reduce GHG emissions and energy consumption.
- Materials production savings ranged from 4-44% for GHG emissions and from 5-32% for energy consumption depending upon the scenario.

- Considering just the materials production of HMA and PCC, actual savings for 2010 practices over 1990 practices are 12,597 $MgCO_2e$ (7,140 $MgCO_2e$ for HMA and 5,457 $MgCO_2e$ for PCC) and 188 TJ (160 TJ for HMA and 28 TJ for PCC) assuming 1,000,000 tons/year of HMA and 200,000 tons/year (98,500 yd^3/year) of PCC are produced.
- If the entire pavement structure (e.g., base course), materials transportation, and construction equipment emissions are considered, the absolute savings are identical but the fractional savings are less.
- There is room for improvement. None of the analyzed practices is currently at its technological limit, so more WMA, RAP, fly ash, and slag could be used in WSDOT mixes.

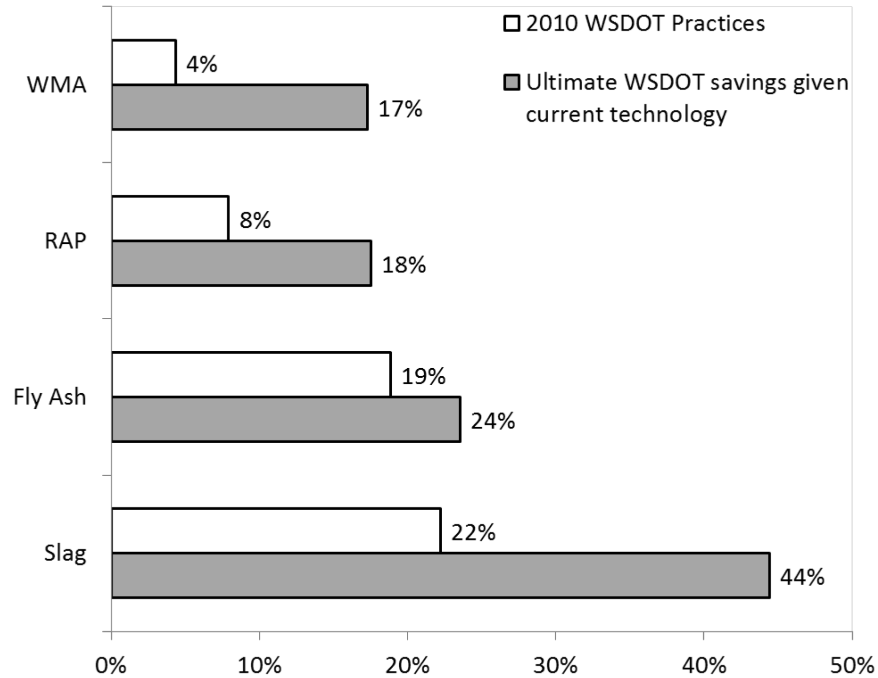

Figure 14. GHG emissions savings for HMA and PCC pavement materials production over 1990 baseline values (all practices were effectively not done in 1990).

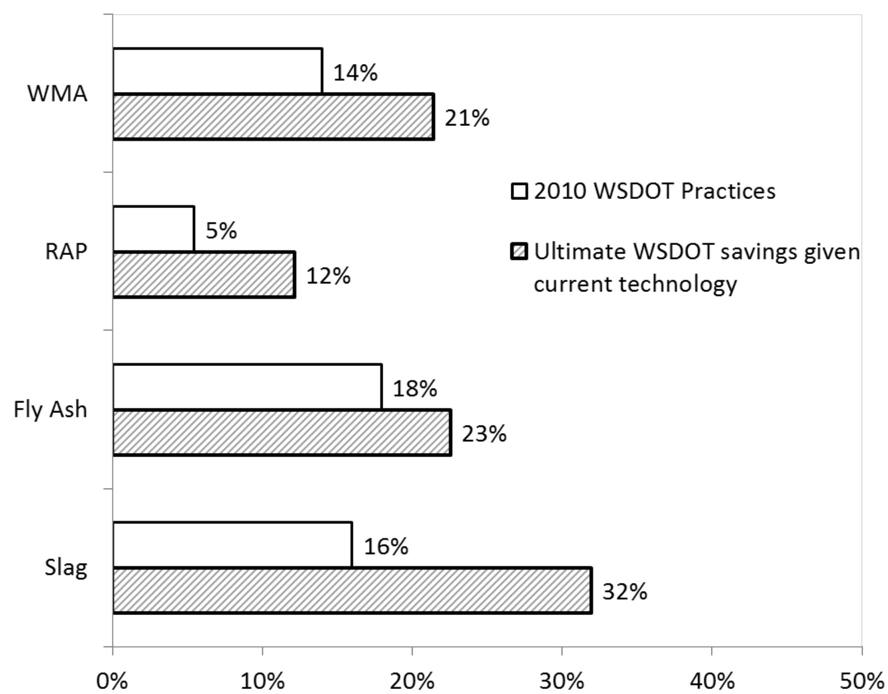

Figure 15. Energy consumption savings for HMA and PCC pavement materials production practices over 1990 baseline values (all practices were effectively not done in 1990).

Dowel bar retrofit (DBR)

- The added GWP and energy consumption associated with the DBR (33 $MgCO_2e$ and 0.47 TJ per lane-mile) are more than offset by the life extension (and associated GWP and energy consumption) offered by DBR (average savings are 135 $MgCO_2e$ and 1.04 TJ per lane-mile).
- For a life extension of 15 years, savings are on the order of 15% per lane-mile.
- Savings over the entire history of WSDOT DBR (1992 – present) average 3,854 $MgCO_2e$ in GHG emissions and 29.69 TJ of energy annually.

Improvements in network roughness

- Because the overall WSDOT pavement network has actually gotten rougher, and not smoother, no savings in GWP or energy consumption are realized.
- The overall WSDOT pavement network has become about 10% rougher.
- ACP surface roughness has remained about constant.
- PCCP surface roughness has become about 20% rougher.
- BST surface roughness has become about 30% rougher.
- The cost associated with mitigating GHG emissions by improving the WSDOT ACP network roughness is on the order of \$10-80/$MgCO_2e$. This is more than typical vehicle fuel efficiency improvements (which are typically computed as an overall savings rather than a cost).

Long life ACP

- There is no discernable trend towards thinner overlays over time therefore no savings in GWP or energy consumption can be attributed to a long-life pavement strategy.

6.1 Context

Given that WSDOT's vehicle fleet coupled with vehicles driving on WSDOT pavements in 2010 emitted 16 million $MgCO_2e$ and consumed 370,000 TJ of energy, savings in GHG emissions and energy consumption can be put into context:

- Savings associated with WMA, RAP, fly ash and slag use amounts to 0.2-0.3% of total WSDOT emissions and energy consumption.
- Savings associated with DBR projects are on the order of 0.02% of total WSDOT emissions and energy consumption.
- Savings due to improvements in WSDOT pavement network condition and an implementation of a long-life pavement strategy are negligible since there was no evidence either had occurred.
- Savings achieved by improving WSDOT ACP pavement network smoothness may cost on the order of \$10-\$80/ $MgCO_2e$, which by most standards is quite expensive either compared to the cost of carbon in general, or the cost of other GHG mitigation strategies involving demand reduction (e.g., more fuel efficient vehicles).

6.2 Closure

There are some limits and context to consider when interpreting results from this research.

6.2.1 Limits of LCAs

The pavement materials and DBR analysis used LCA as a tool to estimate some of the environmental impacts associated with these practices. Data availability and accuracy, differences in LCA scopes, assumptions, and model limitations make it difficult to duplicate these results without using the exact same input parameters and tool. Thus, comparison of these results with other LCA results using different data, scopes, assumptions, and models is not warranted. Despite these limitations, LCA standards are progressing, and performing LCAs such as these can provide valuable insight into some of the environmental impacts associated with pavements.

6.2.2 Accuracy of Results

Despite their perceived accuracy, results given for this research are general in nature and should be used carefully. All calculations are done in a deterministic manner, meaning that no input parameter variability is accounted for. However, in most all instances, variability is likely. In most instances this unaccounted for variability is acknowledged by providing a lower level of precision (e.g., 14% instead of 14.53%) or a plausible range (e.g., 10-80% instead of 44%) when reporting results.

6.2.3 Context

Since the savings achieved by even the most aggressive pavement practices are insignificant when compared to the total GHG emissions and energy for WSDOT each year, it might be inferred that such practices are inconsequential. However, such practices and their associated reduction in GHG emissions and energy consumption are significant and consequential for several reasons. First, they appear insignificant because vehicle operation is a much larger offender, but reductions on the order of 12,000 $MgCO_2e$ and 188 TJ annually (for WMA, RAP, fly ash and slag use) and 3,800 $MgCO_2e$ and 29 TJ annually (for DBR) are real and consequential. A significant shift to electric-powered vehicles would only accentuate this by greatly reducing traffic emissions, especially in Washington State where 88% of net electricity generation comes from hydroelectric and other renewables that have extremely small carbon footprints.

6.2.4 Caution

Results from this research should not be taken in isolation since they only report GHG emissions and energy use. It is not prudent to focus on just one or two metrics when judging the sustainability of roads in general since this can falsely prioritize those measures that can be quantified over those that cannot. In this case, a focus on GHG emissions and energy consumption may lead to conclusions that non-quantifiable practices such as scenic views, aesthetics, and community, are not worthy of consideration. In addition to LCA there is real value in more holistically considering the entire roadway system and its interaction with larger systems. Currently this is usually accomplished by using some sort of holistic rating system. Rating systems tend to sacrifice precise quantification for broader consideration. In such systems LCA should be a component and can play a prominent role in weighting various constituent credits. But other considerations, often difficult to quantify, are also given proper weighting.

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