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A Life Cycle Assessment of Recycling and Conventional Pavement Construction and Maintenance Practices

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1.1. Abstract

The application of in-place recycling techniques has emerged as a practical and effective way to enhance the sustainability of agency pavement management decisions for asphalt-surfaced pavements. However, the potential environmental benefits resulting from applying in-place recycling techniques have not been fully documented in the literature. This paper presents a comprehensive pavement life cycle assessment (LCA) model that extends the typical pavement LCA's system boundaries to include the environmental impacts resulting from the usage phase and the production of the energy sources. The results of the application of the pavement LCA model to a specific highway rehabilitation project in the state of Virginia showed that in-place recycling practices and an effective control of the pavement roughness can improve significantly the life cycle environmental performance of a pavement system.

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1.2. Introduction

The United States' National Highway System (NHS) includes over 264000 km of highways (Federal Highway Administration [FHWA], 2011). With the majority of highway construction complete since the 1980's, a large part of the national highway system is reaching the end of its design life. Recently, the American Society of Civil Engineers report card (American Society of Civil Engineering [ASCE], 2013) evaluated the United States' roads, and assigned it a grade of D, partly as a result of the fact that 32% of the major roads are in poor or mediocre conditions. The report card estimates that traveling on deficient pavements cost US motorists approximately $67 billion a year, or $324 per motorist.

In an effort to address poor pavements condition, agencies have adopted different maintenance and rehabilitation (M&R) approaches. However, M&R of such an extensive road network consumes a significant amount of natural resources, mainly aggregates and bitumen. For example, the United States Geological Survey (USGS) reported that 460 million tonnes of crushed aggregate were used in 2011, mostly in the construction, maintenance and rehabilitation of the US pavement network (United States Geologic Services [USGS], 2013). Furthermore, approximately 23.4 million tonnes of paving bitumen was produced in 2008, according to Freedonia Group (2009). This pattern of consumption of natural resources does not appear to be sustainable and there has been growing societal concern about the environmental effects of constructing, operating and maintaining the highway infrastructure network. In an attempt to mitigate the adverse environmental impacts, transportation authorities are seeking more sustainable pavement technologies and strategies.

Some common practices highlighted by the literature to increase the environmental performance of the road projects include the usage of asphalt mixes requiring lower manufacturing temperatures (Rubio et al., 2013), and the incorporation of recycled materials and byproducts (Jullien et al., 2006; Chiu et al., 2008; Huang et al., 2007; Huang et al., 2009; Sayagha et al., 2010). In particular, in-place pavement recycling reduces the need for virgin materials and reuses materials that would be otherwise hauled away and stockpiled or landfilled. While the true environmental benefit resulting from applying some of the aforementioned measures appears to be dependent on the system boundaries considered in the analysis (Tatari et al., 2012; Vidal et al., 2013), some recycling practices have been proven to enhance the life cycle environmental performance of pavements. One example is the application of in-place pavement recycling techniques to rehabilitate distressed pavements (Thenoux et al., 2007).

A life cycle assessment (LCA) is the tool that is generally used to account for a systems environmental performance. The results of an LCA can provide beneficial information to an agency that is in charge of managing infrastructure; for example, it can help determine which processes and maintenance techniques produce the highest and lowest environmental burdens. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life cycle of the materials, including all the processes involved with the system, as well as other processes impacted by the system. However, a lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement LCA. Thus, in the case of pavements, most LCA have excluded the use phase of the project (Park et al., 2003; Zapata and Gambatese, 2005; Huang et al., 2009).

Recently, research has produced more reliable models to quantify the impact of the pavement condition on vehicle fuel consumption and emissions (Karlsson et al., 2012; Chatti and Zaabar, 2012), which facilitates the inclusion of the use phase into a pavement LCA. By including the usage phase in the pavement LCA, the environmental footprint associated with the application of in-place pavement recycling techniques can be analyzed more thoroughly than in the previous LCA studies analyzing the environmental performance of this pavement M&R alternative (Thenoux et al., 2007; Miliutenko et al., 2013).

1.3. OBJECTIVE

This paper presents the results of a pavement LCA conducted for an in-place pavement recycling rehabilitation project in the state of Virginia. It also illustrates the development of a comprehensive pavement LCA model that includes the usage phase into the system boundaries and accounts for the upstream impacts in the production and transportation of the energy sources. The project under consideration incorporated several in-place pavement recycling techniques and a unique traffic management approach. The results for the recycling-based project are compared to two other pavement management alternatives: (1) a traditional pavement reconstruction, and (2) a corrective maintenance approach. The three alternatives are summarized in Table 0-1. The reason for including more future actions in the corrective maintenance strategy will be discussed more thoroughly in a later section of this paper.

Table 0-1 - Summary of the M&R Strategies

M&R Strategy	Initial M&R Activity	Future M&R Activities
Recycling-Based	Left Lane: Cold in place recycling method to mill, refine and replace the top 18 cm (7 inches) of pavement. Right Lane: A combination of full depth reclamation and cold central plant recycling to treat 55 cm (22 inches) in depth. Both lanes received a HMA riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (Detailed in Table 4-2)
Traditional Reconstruction	Left Lane: Mill and replace the top 18 cm (7 inches) of pavement. Right Lane: Mill and replace full depth of existing pavement and apply a cement treatment to the base/subgrade. Apply an HMA riding surface to both lanes.	Maintenance actions performed in years 12, 22, 32 and 44 (Detailed in Table 4-3)
Corrective Maintenance	Both Lanes: 5 percent full depth patching followed by a 10 cm (4 inch) mill and overlay.	Maintenance actions performed in years 4, 10, 14, 18, 24, 28, 34, 38, 44 and 48 (Detailed in Table 4-4)

Note: Throughout this document the pavement M&R strategies are named “M&R Strategies”, whereas the individual activities that integrate each M&R strategy are named “M&R Activities”

1.4. METHODOLOGY

A comprehensive pavement LCA model was developed to calculate and compare the life-cycle environmental impacts and energy consumption of multiple maintenance and rehabilitation (M&R) activities applied in a road pavement section. The LCA was performed taking into account the guidelines provided by International Standard Organization (ISO, 2006a, 2006b) and the University of California Pavement Research Center (UCPRC) Pavement LCA Guideline (Harvey et al., 2010). Field data for the case study were provided by the Virginia Department of Transportation (VDOT) (Diefenderfer et al., 2012). In the cases where no field data were available from VDOT, data were gathered from LCA inventories and relevant literature.

In order to automatically compute the environmental burdens assigned to the case study, the framework of the LCA model was implemented in a software written in Visual Basic .NET (VB.NET) and SQL programming languages (Santos et al., 2014a; 2014b), the latter being used for managing the data introduced and held in the system.

1.4.1. Goal and Scope Definition

The paper presents the results from an extensive LCA conducted for three M&R strategies applied on a pavement segment. The first step consisted of developing a comprehensive pavement LCA model to estimate the environmental burdens related to the entire life cycle of the pavement section. The application of the pavement LCA model to the case study presented in this paper allowed for the following actions:

(1) Estimation of the potential environmental advantages resulting from applying in-place pavement recycling techniques against two traditional M&R methods;
(2) Demonstration of a methodology that facilitates the inclusion of environmental loads assigned to the processes and pavement LCA phases typically excluded from the system boundaries of a pavement LCA; and
(3) Identification of the most important processes, and consequently pavement life cycle phases, in driving the environmental load of a road pavement section throughout its life cycle.

These results will provide state and local agencies with quantitative evidence to support the adoption of more environmentally sound pavement management processes.

1.4.2. Functional unit

The specific project chosen for achieving the aforementioned objectives is a 5.95 km long, 2 lane asphalt section of Interstate 81 near Staunton Virginia. The project analysis period (PAP) is 50 years, beginning in 2011 with the in-place pavement recycling project that rehabilitated the existing pavement structure. The annual average daily traffic (AADT) for the first year was obtained from the VDOT traffic website and consisted of approximately 25,000 directional vehicles with 28% trucks (85% of the truck traffic consisted of five- and six-axle tractor trailer combination vehicles). The traffic growth rate was assumed as 3%, and was calculated as compounding growth.

1.4.2.1. Pre-M&R conditions

Prior to the initial rehabilitation, the distresses along the pavement included cracking that extended through the full pavement depth in the right lane, and extensive rutting and patching throughout both lanes. The left lane was determined to be in better condition than the right lane, such that it was decided to design separate treatments for each lane. The overall structure of the pavement was evaluated, and deflection testing was used to determine that the structure of the pavement was in poor condition to the depth of the subgrade in the right lane. Thus, it was determined that a full reconstruction was needed for the right lane, and a heavy rehabilitation for the left lane. The project included two different construction methods, and further details about the project can be found in Diefenderfer et al. (2012). The left lane used a cold in place recycling (CIR) method to mill, refine, and replace the top layers of the pavement. The CIR was performed using one machine on the site. The reconstruction of the right lane consisted of a combination of cold central plant recycling (CCPR) and full depth reclamation (FDR) to extend to the subgrade.

1.4.2.2. M&R scenarios

This study compared the three maintenance alternatives presented in Table 4-1. Details on the actions performed in each M&R strategy, as well as the respective schedule for future M&R actions are presented in Tables 4-2, 4-3 and 4-4. For the recycling-based and traditional reconstruction M&R strategies, the expected M&R activities and respective M&R actions outlined by VDOT were followed (VDOT 2011). For the corrective M&R scenario, past performance and construction history indicates that a 5 cm mill and inlay would be required every four to six years, along with partial depth patching. This was verified by using deflection data obtained prior to the rehabilitation of the road to calculate the Modified Structural Index (MSI) of the pavement, and using it as a predictor of future performance as outlined in Bryce et al. (2013). The MSI of the pavement section was 0.78, which indicates a considerably weak structural condition and that the deterioration of the condition should occur much more rapidly than a pavement with adequate structure (i.e., a pavement with an MSI of 1) (Bryce et al., 2013). The predicted deterioration curve along with past condition data (in terms of the Critical Condition Index (CCI)), is shown in Figure 0-1a.

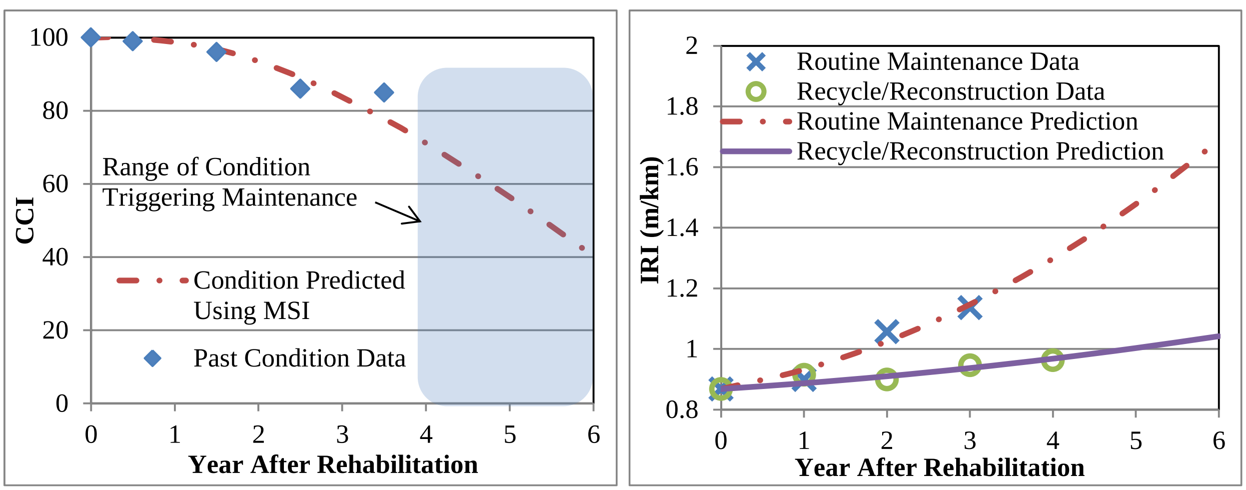

Figure 0-1 - (a) Predicted deterioration for the rehabilitation M&R strategy, and (b) predicted roughness for each M&R strategy

In order to determine the roughness of the pavement as a function of time for the corrective M&R strategy, past International Roughness Index (IRI) data for the pavement section was plotted and a function in the form of equation (4-1) was fitted to the data.

$$IRI(t) = at^2 + bt + c \tag{4-1}$$

Where *IRI(t)* is the IRI value in year *t*, *c* is the IRI value after M&R is performed and *a* and *b* are parameters that were found by minimizing the sum of square errors between the fitted function and the measured data.

The values of the aforementioned parameters are presented in Table 0-5. A similar procedure was conducted for the cases of the recycling-based and traditional reconstruction M&R strategies; however, in those M&R strategies data from an adjacent pavement section that was rehabilitated in 2005 was used. The reason for using data from the adjacent pavement section was the lack of long term IRI measurements for the pavement section under investigation. Furthermore, the adjacent pavement section had an MSI value of 1.3 (structurally adequate) and was expected to be subjected to similar environmental and traffic loading as the pavement section under investigation. The values of the parameters are presented in Table 0-5. The functions and measured data are shown in Figure 0-1b.

Table 0-2 - Features of the M&R actions included in the recycling-based M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Recycling-based reconstruction	Right lane: mill asphalt layers	25	0
	Right lane: FDR using calciment as the stabilizing agent	30	
	Right lane: CCPR using hydraulic cement and foamed asphalt as the stabilizing agents	15	
	Right lane: tack coat application	-	
	Right lane: overlay AC	10	
	Right lane: tack coat application	-	
	Right lane: overlay SMA	5	
	Left lane: mill	5	
	Left lane: CIR using hydraulic cement and foamed asphalt as the stabilizing agents	13	
	Left lane: tack coat application	-	
	Left lane: overlay AC	5	
	Left lane: tack coat application	-	
	Left lane: overlay SMA	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	12
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	22
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	41	32
	Right and left lanes: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	41	44
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	

Table 0-3 - Features of the M&R actions included in the traditional reconstruction M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Reconstruction	Right lane and outside shoulder: Mill	32	0
	Right lane and outside shoulder: undercut the existing base/subgrade	46	
	Right lane and outside shoulder: lay geotextile fabric	-	
	Right lane and outside shoulder: lay Open Graded Base (OGB)	30	
	Right lane and outside shoulder: lay 21B aggregate material	15	
	Right lane and outside shoulder: lay BM - 25.0D	25	
	Left lane and inside shoulder: mill	18	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lanes, and shoulders: lay IM-19.0D	5	
	Right and left lanes, and inside shoulder: tack coat application	-	
	Right and left lanes, and inside shoulder: resurface SMA- 12.5	5	
	Outside shoulder: tack coat application	-	
	Outside shoulder: overlay with SM-12.5A	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	12
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	36	22
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Major rehabilitation	Right and left lanes: pre-overlay full-depth patching 5%	41	32
	Right and left lanes: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC IM layer	5	
	Right and left lanes and shoulders: tack coat application	-	
	Right and left lanes and shoulders: overlay AC wearing course	5	
Functional mill and replace	Right and left lanes: pre-overlay full-depth patching 1%	41	44
	Right and left lanes: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lanes: replace AC wearing course	5	

Table 0-4 - Features of the M&R actions included in the corrective M&R strategy

M&R activity	M&R actions	Thickness (cm)	Schedule (year)
Major rehabilitation	Right and left lines: pre-overlay full-depth patching 5%	51	0
	Right and left lines: mill SM and IM layers	10	
	Right and left lines: replace AC IM	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	
Functional mill and replace	Right and left lines: pre-overlay full-depth patching 1%	36[a]	4, 18, 34, 38, 48
	Right and left lines: mill	5	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC wearing course	5	
Functional mill and replace	Right and left lines: pre-overlay full-depth patching 1%	36	10, 24
	Right and left lines: mill	10	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC IM course	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	
Major rehabilitation	Right and left lines: pre-overlay full-depth patching 5%	41[b]	14, 28, 44
	Right and left lines: mill SM and IM layers	10	
	Right and left lanes: tack coat application	-	
	Right and left lines: replace AC IM	5	
	Right and left lanes, and shoulders: tack coat application	-	
	Right and left lines, and shoulders - overlay AC wearing course	5	

[a] Whenever the "pre-overlay full-depth patching 1%" M&R action is applied, its thickness increases 5 cm relatively to the previous application. An exception to this rule occurs in the case of the first type of "Functional mill and replace" M&R activity. The "Right and left lines: pre-overlay full-depth patching 1%" M&R action scheduled at years 34 and 38 have the same thickness (46 cm).

[b] Whenever the "pre-overlay full-depth patching 5%" M&R action is applied, its thickness increases 5 cm relatively to the previous application

Table 0-5 - Parameter Values of Equation 4-1

M&R strategy	Parameters		
	a	b	c
Recycling-based	0.002	0.017	0.868
Traditional Reconstruction	0.002	0.017	0.868
Corrective Maintenance	0.015	0.05	0.868

1.4.3. System boundaries, system processes and life cycle inventory data

The life cycle of a road pavement is generally divided into five phases (Harvey et al., 2010): materials extraction and production; construction; M&R; usage and end-of-life (EOL). However, in the proposed model, the environmental impacts associated with the on-road vehicles when subject to a work-zone (WZ) traffic management plan (implemented during the reconstruction and M&R activities) are treated as an individual phase and designated as WZ traffic management phase. The WZ traffic management phase was separated out in order to highlight the influence of the WZ on the environmental performance when compared to normal traffic flow. Transportation of materials and asphalt mixtures between facilities and work site, and vice-versa, was also analyzed separately. Therefore, the proposed pavement LCA model entails six pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R;

(3) transportation of materials; (4) WZ traffic management; (5) usage and (6) EOL. The various models evoked while modeling each pavement LCA phase, as well as the data required to run those models, are introduced and discussed in the following sections.

1.4.3.1. Materials extraction and production phase

Pavement-related environmental burdens assigned to this phase are due to material acquisition and processing. This includes all materials manufacturing processes, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), and ending up with the mixture production at a mixing plant (materials production sub-phase). The manufacturing of the facilities, such as the construction of the mixture production plants, is excluded from the system boundaries. All environmental burdens stemming from transportation between facilities (e.g., transporting aggregates from the quarry to the mixture production plant) are assigned to the materials extraction and production phase. The life cycle inventory (LCI) of the materials and mixtures used in this case study was collected from several published LCI and LCA reports.

Inventory data for both fine and coarse natural aggregate was taken from Stripple (2001). The LCI's for the bitumen, which in this case study was used either as binder in asphalt mixtures or as stabilizing agent, were obtained from Eurobitumen (2011). The LCI for the hydraulic cement used as an active filler was obtained by adapting Marceau et al.'s (2006) LCI corresponding to the hydraulic cement production through the precalciner process. The LCI of calciment (the stabilizing agent used during the FDR portion), a combination of hydraulic cement (70%) and lime kiln dust (30%), was determined by multiplying by a factor of 0.7 the hydraulic cements LCI. No environmental load was assigned to the lime kiln dust given that it is an existing by-product of another manufacturing process.

To estimate the LCI associated with the asphalt mixtures production at a mixing plant, data on the average fuel consumption per tonne of asphalt mixture produced and the emissions factors published by the AP-42 study of HMA plants (United States Environmental Protection Agency [US EPA], 2004) for a drum mixing plant powered by natural gas were adopted. The environmental burdens from CCPR process are accounted by the construction and M&R phase, since they are produced by a mobile plant which is classified as construction equipment.

1.4.3.2. Transportation phase

The environmental impacts resulting from the materials and mixture transportation are due to the combustion process emissions released by the transportation vehicles. All materials and mixtures were assumed to be hauled by heavy-duty vehicles (HDVs), and the US EPA Motor Vehicle Emissions Simulator (MOVES) (US EPA 2010a) was used to determine the average fuel consumption and airborne emissions factors for operating diesel powered, single unit short-haul trucks and long haul combination trucks. These factors were computed for the typical climate conditions during the month of April for Augusta County in Virginia. The payload capacity of both HDV types was assumed to be equal to 20 tonnes. The transportation distances considered for each material and mixture used in this case study are shown in Table 0-6. Outside of the system boundaries of this model are the air emissions associated with the production and maintenance of the hauling HDVs, as well as the transportation of the construction equipment from the construction company's facilities to the work-site.

Table 0-6 - Features of the movements of transportation of materials

Material/ mixture	One-way trip distance (km)
Milled asphalt material (prior to FDR)	1.9
Milled asphalt material (prior to CIR)	25
Removed granular material (Subgrade)	25
CCRP material	1.9
Hydraulic Cement and Calciment	346
Tap Water	20
Crushed and Fine Aggregates	0.6
Binder and Bitumen Emulsion	125
OGB 25.0 Asphalt Pavement Mix	25
21B aggregate material	25
Asphalt Mixes (to site)	25

1.4.3.3. Construction and M&R phase

The construction and M&R related environmental burdens were obtained by applying the methodology adopted by the US EPA's NONROAD 2008 model (US EPA, 2010b). Pollutants covered by this methodology include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM), carbon dioxide (CO2) and sulfur dioxide (SO2). Fuel consumption is accounted for on the basis of the brake specific fuel consumption (BSFC) indicator. The calculation of N_2O and CH_4 emissions used the US EPA's guide on calculating GHG emissions from mobile sources (US EPA, 2008). Information regarding the type and features (brand, model, engine horsepower, etc.) of each equipment used to perform the several M&R activities, as well as their respective production rates were taken from Diefenderfer et al. (2012) and complemented with technical specifications from the equipment's manufacturers. Future M&R activities are assumed to take place during the month of April, as was the reconstruction and rehabilitation performed in the beginning of the PAP of each M&R scenario. The same production rates of construction equipment were assumed for the remaining M&R activities.

1.4.3.4. WZ traffic management phase

The WZ traffic management includes aspects for two routes: the single lane of I-81 to remain open during the work, and the detour road. As discussed in Diefenderfer et al. (2012), this project included an innovative traffic management technique that consisted of detouring cars from the road onto a parallel route, while trucks were allowed to remain on I-81 during construction. In this pavement LCA model, the fuel consumption and airborne emissions assigned to on-road vehicles during the WZ traffic management plan have been determined by adopting a two-step method. First, the US EPA's MOVES model was run multiple times to compute a set of fuel consumption and emissions factors representing the national scale vehicle fleet characteristics per type of vehicle, and Augusta county's average climatic conditions during the month of April in three distinct years of the PAP (2011, 2035 and 2050). For years between 2011 and 2050, the emissions factors were interpolated according to a Lagrangian interpolation function. The emission factors for the year 2050 were applied to analysis years beyond 2050. Each model run generated an output file displaying the emissions factors on an hourly basis as a function of sixteen speed ranges, called speed bins, and two types of road categorized as rural restricted access and rural unrestricted access. The former category is assumed to represent the operating conditions existing in I-81, whereas the latter fits the features of the detour road (Virginia Route 11).

Secondly, changes in driving patterns were modelled using the capacity and delay models proposed by the Highway Capacity Manual 2000 (Transportation Research Board [TRB], 2000) to determine several outputs, such as the number of vehicles that traversed the WZ, the average queue length, the average queue speed in each hour, etc. Each section where there is a change in driving pattern was considered to be a new road "link." The characteristics of each link (length, number of vehicles and average speed) was combined with the MOVES fuel consumption and emissions factors previously computed and stored in look up tables to derive the environmental load of a WZ day. Finally, the marginal fuel consumption and airborne emissions due to the WZ traffic management plan were calculated by subtracting fuel consumption and airborne emissions released during a WZ period from the results of an equivalent non-WZ period.

1.4.3.5. Usage phase

The usage phase addresses the pavement's environmental burden resulting from the interaction of the pavement with the vehicles and environment throughout its PAP. The following are factors that have been identified in past research as pertinent to consider during the use phase of the pavement (Santero et al., 2011; Sandberg et al., 2011; Chatti and Zaabar, 2012); Tire – Pavement Interaction, Traffic Flow, Albedo, Leachate and Runoff, Carbonation and Lighting. However, many of these factors (e.g., Albedo, Carbonation and Lighting) do not directly apply to the project currently under evaluation. Thus, the main contribution that was considered from the usage phase in this analysis is the tire-pavement interaction. Tire-pavement interaction influences vehicle rolling resistance, and is impacted by several variables such as macro-texture, pavement stiffness, roughness and the transversal slope of the pavement. Given that this study compared several maintenance plans using the same surface materials, the only factor that was considered in the usage phase is the impact of the pavement roughness on the pavements overall environmental burden.

In order to determine the impact of the pavement roughness on vehicle fuel consumption and emissions, the Vehicle Operating Cost (VOC) developed by Chatti and Zaabar (2012) was combined with data from the EPA's MOVES model. The approach proposed in this paper differs from other proposed approaches (e.g., Wang et al., 2012) in that the impact of increasing rolling resistance can be combined with the MOVES emissions rates models without the need to modify the vehicle specific power model within the MOVES program (which calculates emissions rates from vehicles travelling along a smooth surface). The first step in the proposed approach is to use the model given in Chatti and Zaabar (2012) to calculate the additional fuel consumption due to the vehicles travelling over the rough pavement surface when compared to the fuel consumption of the vehicles travelling over a smooth surface. Then, instead of using the actual AADT in the MOVES emissions rate model, an effective AADT was used to relate the increase in roughness to the increase in fuel consumption and emissions. The effective AADT ($AADT_E$) for a given roughness at time t, in terms of the International Roughness Index (IRI), was calculated using equation 4-2.

$$AADT_E(t) = AADT(t) * \frac{FC_{IRI(t)}}{FC_{Smooth}} \tag{4-2}$$

Where $FC_{IRI(t)}$ is the fuel consumption for the vehicle fleet travelling on a pavement with a specified

IRI at time t, and FC_{Smooth} is the fuel consumption of the same vehicle fleet travelling along a typical smooth pavement.

1.4.3.6. End-of-life phase

When a road pavement reaches its service life, it can be given two main fates: (1) remain in place serving as support for a new pavement structure; and (2) be removed. Removed pavements materials are: (1) disposed in a landfill (generally a very small percentage in the US); or (2) recycled and re-used either as a replacement for virgin aggregate base or as a replacement for virgin asphalt and aggregate in new HMA. It is expected that the most likely EOL scenario for the pavements in this analysis is that they remain in place after reaching the end of the PAP, serving as foundation for the new pavement structure. Thus, no environmental impacts were assigned to the EOL phase of all M&R scenarios in comparison.

1.4.4. Energy source production

Energy source production refers to the impact of producing the energy that is used to power the various equipment and processes that are required for the project (e.g., the production of the fuel to power the transportation of the materials). Although it is not considered a pavement life cycle phase, as those previously introduced, the energy sources production and transportation is an unavoidable process that is common to all pavement life cycle phases. For this reason their life cycle impacts should be considered and displayed separately from the impacts due to the process energy consumption. Presenting the impacts from the energy sources production facilitates the understanding of where in the pavement life cycle the use of less environmentally burdensome energy sources may help reduce the environmental load of a road pavement. Therefore, before inclusion in the database, the LCI of each material and mixture was disaggregated to the processes level in order to distinguish the LCI due to the pre-combustion energy, from that due to the process energy combustion in the final destination. In this case study, the GREET model (Argonne National Laboratory, 2013) was used as the source of the LCI for the production and transportation of energy sources. For all energy sources except electricity, the GREET model default data was used. In the case of the electricity, a default electricity mix was modified to reflect the electricity production in the state of Virginia (United States Energy Information Administration [US EIA], 2012).

1.5. LIFE CYCLE INVENTORY

The LCI corresponding to the case study was performed for each life cycle phase of each pavement M&R strategy using the models and data sources presented in the previous sections. The inventory analysis was used to determine, both qualitatively and quantitatively, the materials, the energy flows and the atmospheric emissions associated with each individual process within the system under analysis. The outputs from those unit processes were posteriorly combined in order to derive the total environmental burden of the system. Table 0-7 provides the overall LCI per pavement life cycle phase of each pavement M&R strategy, expressed in terms of atmospheric emissions.

Table 0-7 - LCI per pavement life cycle phase of each M&R strategy

M&R Strategy	Life cycle phase	Sub component	CO_2 (Kg)	CH_4 (Kg)	N_2O (Kg)	SO_2 (Kg)	NO_x (Kg)	NH_3 (Kg)	CO (Kg)	VOC (Kg)	NMVOC (Kg)	$PM_{2.5}$ (Kg)	Pb (Kg)
Recycling-based	Materials	P.E:	1.33E+06	4.09E+02	4.35E+00	5.92E+02	2.13E+03	2.94E-01	1.23E+04	5.50E+02	6.16E+01	3.41E+02	2.70E-02
		P.C.E.	5.92E+05	1.18E+04	7.80E+02	1.53E+03	1.28E+03	0.00E+00	3.04E+02	1.48E+02	0.00E+00	2.01E+02	0.00E+00
	Construction and M&R	P.E:	1.38E+05	7.80E+00	3.47E+00	1.05E+02	8.16E+02	0.00E+00	5.55E+02	0.00E+00	0.00E+00	4.87E+01	0.00E+00
		P.C.E.	2.87E+04	2.50E+02	3.87E-01	4.48E+01	8.11E+01	0.00E+00	2.07E+01	1.43E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	1.81E+05	6.36E+00	3.27E-01	1.23E+00	4.92E+02	3.41E+00	1.52E+02	3.19E+01	2.69E+01	1.83E+01	0.00E+00
		P.C.E.	3.82E+04	3.33E+02	5.16E-01	5.98E+01	1.08E+02	0.00E+00	2.77E+01	1.90E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	3.48E+06	2.29E+02	3.60E+01	4.69E+01	3.15E+03	2.11E+02	1.51E+04	7.69E+02	5.40E+02	1.82E+02	0.00E+00
		P.C.E.	7.45E+05	6.50E+03	1.01E+01	1.17E+03	2.12E+03	0.00E+00	5.38E+02	9.81E+02	0.00E+00	1.27E+02	0.00E+00
	Usage	P.E:	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		**1.48E+08**	**2.83E+05**	**1.48E+03**	**5.22E+04**	**2.34E+05**	**2.93E+04**	**1.60E+05**	**3.36E+04**	**7.02E+03**	**7.16E+05**	**2.70E-02**
Traditional Reconstruction	Materials	P.E:	2.14E+06	7.91E+02	1.55E+01	1.47E+03	5.31E+03	4.03E-01	6.24E+03	1.89E+03	4.85E+01	2.68E+02	2.76E-02
		P.C.E.	1.12E+06	1.97E+04	1.40E+03	2.86E+03	2.34E+03	0.00E+00	5.50E+02	2.67E+02	0.00E+00	2.91E+02	0.00E+00
	Construction and M&R	P.E:	2.23E+05	1.26E+01	5.60E+00	2.76E+02	1.29E+03	0.00E+00	9.00E+02	0.00E+00	0.00E+00	4.91E+01	0.00E+00
		P.C.E.	4.62E+04	4.03E+02	6.24E-01	7.23E+01	1.31E+02	0.00E+00	3.35E+01	2.30E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	5.57E+05	1.79E+01	1.07E+00	3.78E+00	2.11E+03	1.11E+01	6.91E+02	1.75E+02	1.60E+02	8.13E+01	0.00E+00
		P.C.E.	1.17E+05	1.02E+03	1.58E+00	1.84E+02	3.32E+02	0.00E+00	8.49E+01	5.84E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	3.76E+06	2.41E+02	4.08E+01	5.31E+01	3.43E+03	2.45E+02	1.85E+04	9.84E+02	7.43E+02	2.21E+02	0.00E+00
		P.C.E.	8.04E+05	7.02E+03	1.09E+01	1.27E+03	2.28E+03	0.00E+00	5.81E+02	1.10E+03	0.00E+00	1.44E+02	0.00E+00
	Usage	P.E:	1.12E+08	2.33E+03	2.46E+02	1.54E+03	1.39E+05	2.91E+04	1.09E+05	0.00E+00	6.39E+03	7.12E+05	0.00E+00
		P.C.E.	3.00E+07	2.61E+05	4.04E+02	4.71E+04	8.50E+04	0.00E+00	2.17E+04	3.11E+04	0.00E+00	3.36E+03	0.00E+00
	Total		**1.51E+08**	**2.93E+05**	**2.12E+03**	**5.48E+04**	**2.42E+05**	**2.94E+04**	**1.58E+05**	**3.56E+04**	**7.34E+03**	**7.16E+05**	**2.76E-02**
Corrective Maintenance	Materials	P.E:	2.00E+06	9.06E+02	5.81E+00	7.51E+02	3.41E+03	4.99E-01	7.08E+03	2.17E+03	4.79E+01	3.10E+02	3.21E-02
		P.C.E.	1.03E+06	2.13E+04	1.37E+03	2.69E+03	2.21E+03	0.00E+00	5.29E+02	2.64E+02	0.00E+00	2.79E+02	0.00E+00
	Construction and M&R	P.E:	2.06E+05	1.16E+01	5.16E+00	5.65E+01	1.23E+03	0.00E+00	9.08E+02	0.00E+00	0.00E+00	1.01E+02	0.00E+00
		P.C.E.	4.27E+04	3.72E+02	5.76E-01	6.68E+01	1.21E+02	0.00E+00	3.09E+01	2.12E+01	0.00E+00	0.00E+00	0.00E+00
	Transportation	P.E:	4.46E+05	1.78E+01	8.54E-01	3.02E+00	8.76E+02	8.84E+00	2.93E+02	6.26E+01	4.78E+01	2.86E+01	0.00E+00
		P.C.E.	9.39E+04	8.19E+02	1.27E+00	1.47E+02	2.66E+02	0.00E+00	6.80E+01	4.67E+01	0.00E+00	0.00E+00	0.00E+00
	WZ Traffic Management	P.E:	7.26E+06	4.83E+02	7.18E+01	9.10E+01	7.48E+03	3.91E+02	2.59E+04	1.36E+03	8.74E+02	3.67E+02	0.00E+00
		P.C.E.	1.55E+06	1.35E+04	2.09E+01	2.44E+03	4.40E+03	0.00E+00	1.12E+03	1.93E+03	0.00E+00	2.41E+02	0.00E+00
	Usage	P.E:	1.54E+08	3.29E+03	3.42E+02	2.16E+03	1.89E+05	4.04E+04	1.47E+05	0.00E+00	9.01E+03	1.00E+06	0.00E+00
		P.C.E.	4.22E+07	3.68E+05	5.69E+02	6.63E+04	1.20E+05	0.00E+00	3.05E+04	4.40E+04	0.00E+00	4.77E+03	0.00E+00
	Total		**2.09E+08**	**4.09E+05**	**2.38E+03**	**7.47E+04**	**3.28E+05**	**4.08E+04**	**2.13E+05**	**4.98E+04**	**9.98E+03**	**1.01E+06**	**3.21E-02**

Acronyms: P.E. - Process Energy; P.C.E. - Pre-Combustion Energy.

1.6. LIFE CYCLE IMPACT ASSESSMENT

The purpose of the life cycle impact assessment (LCIA) is to assign the LCI results to different impact categories based on the potential effects that the several pollutants have on the environment. According to the type of pollutants inventoried and the impact categories commonly recognized as the most representative of the three protection areas (human health, natural environment and natural resources), the following categories were selected: climate change (CC); acidification (AC); eutrophication (EU); human health criteria air pollutants (HH); photochemical smog (PS) and abiotic resource depletion (ARD). The US-based impact assessment tool, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts 2.0 (TRACI 2.0), was chosen as the main methodology to conduct the impact assessment step of the LCA. The reader is referred to Bare (2011) for a more detailed discussion of TRACI 2.0. The characterization models and associated characterization factors from TRACI 2.0 were applied to quantify the contribution of each LCI element to the acidification, eutrophication, human health criteria air pollutants and photochemical smog impact category. The time-adjusted characterization model for the CC impact category that was proposed by Kendall (2012) was used in this approach as opposed to the traditional time-steady International Panel on Climate Change (IPCC) model. The April 2013 updated version of the CML-IA's characterisation factors (Guinée, 2002) was used to determine the impact assessment for ARD of mineral resources and fossil fuels. Furthermore, an energy analysis was carried out based on the cumulative energy demand (CED) indicators, expressed as fossil (CED F), nuclear (CED Nuc.) and renewable resources (CED R). This indicator was computed according to Hischier et al. (2010) but adopting the upper heating values (UHVs) defined in the GREET model.

Lastly, according to ISO 14044, normalization, grouping, and weighting steps in LCA are optional. While they might be useful in translating the impact scores of different impact categories into a more understandable and somehow digestible form (Dahlbo et al., 2013), they also entail a risk of oversimplifying the results. Therefore, in the pavement LCA model application reported in this paper the normalization, grouping and weighting steps were not included.

1.7. LIFE CYCLE IMPACT ASSESSMENT RESULTS AND DISCUSSION

The potential life cycle impacts for each pavement M&R strategy are shown in Table 0-8. Figure 0-2 shows the relative contribution of each life cycle phase for each impact category. As can be seen from Figure 0-2, the usage phase is by far the phase of the life cycle with the greatest impact in almost all the impact categories. Its contribution ranges between 90% (CC in corrective M&R strategy) and 96% (EU in recycling-based M&R strategy) depending on the impact category and the M&R strategy under analysis. Those results agree well with the literature that have accounted for the effects of this phase on the environmental performance of a pavement structure (Wang et al., 2012; Yu and Lu, 2012; Loijos et al., 2013). However, it should be noted that the impact from the usage phase could potentially be greater if the traffic carried by the section of interstate throughout the PAP was not constrained by the road capacity, since the possibility of increasing the road capacity by adding new lanes to existing ones was not considered. The exception to the dominance of the usage phase when evaluating the ARD MR, because this indicator is dominated by the use of raw materials. This outcome can be explained by the fact the mineral resources consumed during the pre-combustion energy-related processes are not tracked by the GREET model. Consequently, all the mineral resources accounted for the ARD MR are exclusively those existing in the aggregates and cement-based materials consumed during the M&R activities.

Table 0-8 - Total life cycle environmental impacts per pavement life cycle phase of each M&R strategy

M&R Strategy	Life cycle phase	CC (tonnes CO_2-eq.)	AC (H^+ moles eq.)	EU (Kg N eq.)	HH (Kg $PM_{2.5}$ eq.)	PS (g NO_x eq.)	ARD MR (Kg Sb- eq.)	ARD FF (MJ- eq.)
Recycling-based	Materials	(-52%) 1 436	(-55%) 144 914	(-53%) 99	(-46%) 604	(-53%) 3 336	(-40%) 0. 0022727	(-49%) 31 631 566
	Construction and M&R	(61%) 729	(71%) 196 680	(40%) 155	(31%) 513	(39%) 3 593	0	(41%) 9 870 565
	Transportation	(-37%) 197	(-25%) 26 789	(-23%) 26	(24%) 57	(-23%) 630	0	(-42%) 2 796 061
	WZ Traffic Management	(-54%) 6 111	(-57%) 605 749	(-58%) 557	(-55%) 1 700	(-55%) 9 605	0	(-53%) 100 834 016
	Usage	(-28%) 112 926	(-27%) 19 912 635	(-27%) 19 467	(-28%) 44 745	(-27%) 267 081	0	(-29%) 2 321 530 245
	Total	**(-22%) 121 398**	**(-19%) 20 886 765**	**(-28%) 20 305**	**(-29%) 47 618**	**(-29%) 284 244**	**(-40%) 0. 0022727**	**(-31%) 2 466 662 453**
Traditional Reconstruction	Materials	(8%) 3 209	(-9%) 293 477	(-0.46%) 208	(-1%) 1 102	(-3%) 6 869	(8%) 0.0041290	(-10%) 56 252 998
	Construction and M&R	(-7%) 420	(-3%) 112 002	(-16%) 93	(-20%) 313	(-16%) 2 164	0	(-15%) 5 910 886
	Transportation	(99%) 620	(174%) 98 591	(193%) 100	(180%) 208	(195%) 2 417	0	(61%) 7 757 770
	WZ Traffic Management	(-51%) 6 551	(-72%) 396 568	(-54%) 602	(-51%) 1 847	(-51%) 10 461	0	(-49%) 106 993 480
	Usage	(-28%) 112 926	(-27%) 19 912 635	(-27%) 19 467	(-28%) 44 745	(-27%) 267 081	0	(-29%) 2 321 530 245
	Total	**(-21%) 123 727**	**(-19%) 20 813 273**	**(-28%) 20 471**	**(-28%) 48 213**	**(-28%) 288 991**	**(8%) 0.0041290**	**(-30%) 2 498 445 378**
Corrective Maintenance	Materials	2 982	323 871	209	1 118	7 094	0.0038097	62 375 100
	Construction and M&R	452	115 338	111	391	2 580	0	6 989 318
	Transportation	312	35 942	34	74	819	0	4 823 867
	WZ Traffic Management	13 292	1 409 130	1 310	3 766	21 529	0	221 728 627
	Usage	156 859	27 292 378	26 580	62 018	368 370	0	3 268 590 284
	Total	**173 898**	**29 176 659**	**28 245**	**67 368**	**400 392**	**0.0038097**	**3 564 507 198**

Acronyms: CC- climate change; AC- acidification; EU- eutrophication; HH- human health criteria air pollutants; PS- photochemical smog; ARD MR- abiotic resources depletion of mineral resources; ARD FF- abiotic resources depletion of fossil fuels; Sb- antimony.

Note 1: The potential environmental impacts in terms of CC were estimated for a 100-year time horizon.

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category indicator values with respect to the homologous phase of the corrective M&R strategy.

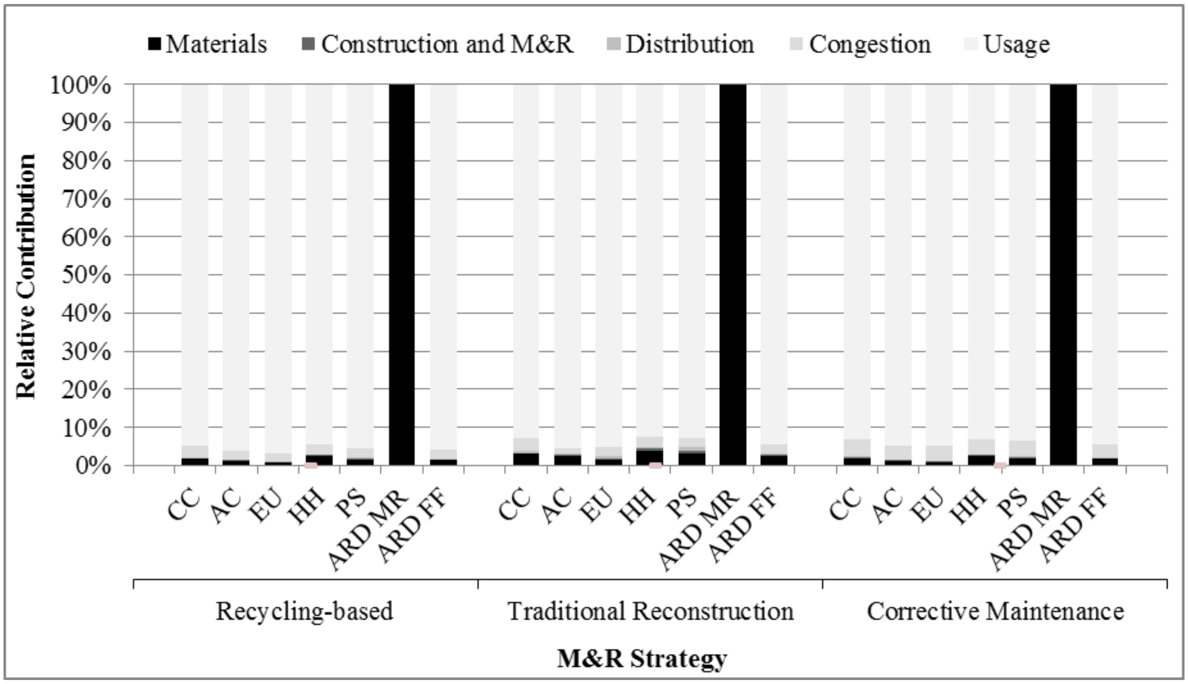

Figure 0-2 - Relative contributions to each impact category (percentage) per pavement life cycle phase of each M&R strategy. Impact category acronyms: CC- climate change; AC- acidification; EU- eutrophication; HH- human health criteria air pollutants; PS- photochemical smog; ARD MR- abiotic resources depletion of mineral resources; ARD FF- abiotic resources depletion of fossil fuels

Due to the relatively high influence of the usage phase on the overall environmental performance of the M&R strategies in comparison, it can be inferred that the M&R strategy with the worst environmental performance during the usage phase is simultaneously the least environmentally friendly overall. Therefore, it seems plausible to expect that the adoption of an M&R strategy that slows the deterioration rate of the pavement roughness would lead to valuable improvements in the life cycle environmental performance of a pavement system.

In response to the issues raised in the previous paragraph, this study demonstrated that by implementing a recycled-based M&R strategy, a reduction of approximately 30% in the overall life cycle impacts can be achieved relatively to those of a corrective M&R strategy. Moreover, in the case that only the materials and construction and M&R phases are considered in the LCA system boundaries, the recycling-based M&R strategy was still found to outperform the remaining M&R strategies in comparison.

Table 0-9 presents the feedstock, process and primary energy along with the CED Total corresponding to each M&R strategy, split up in fossil, nuclear and renewable resources. By definition, CED should account for the usage of any sort of energy, including direct and indirect energy, throughout the life cycle. That means that the feedstock energy of bitumen should also be included when accounting for CED. However, since the feedstock energy inherent to bitumen remains unexploited while used as a binder in a pavement, it was presented separately from the process and pre-combustion energy as recommended by the UCPRC Pavement LCA Guideline (Harvey et al., 2010).

Table 0-9 - Feedstock, process and primary energy and CED indicator values per pavement life cycle phase of each M&R strategy

M&R strategy	Life cycle Phase	Feedstock energy (MJ)	Process energy (MJ)	Primary energy (MJ)	CED F (MJ)	CED Nuc (MJ)	CED R (MJ)	CED Total (MJ)
Recycling-based	Materials	(-42%) 150 020 350	(-41%) 31 653 145	(-41%) 37 588 448	(-42%) 39 582 252	(-44%) 478 450	(-43%) 235 798	(-42%) 40 296 499
	Construction and M&R	0	(-33%) 1 854 509	(-33%) 2 226 086	(-33%) 2 374 473	(-33%) 3 974	(-33%) 2 487	(-33%) 2 380 933
	Transportation	0	(-59%) 2 473 366	(-59%) 2 968 939	(-59%) 3 166 843	(-59%) 5 300	(-59%) 3 316	(-59%) 3 175 460
	WZ Traffic Management	0	(-52%) 48 210 242	(-52%) 57 897 901	(-50%) 61 818 525	(-50%) 198 809	(-54%) 99 796	(-50%) 62 117 129
	Usage	0	(-29%) 1 938 650 938	(-29%) 2 327 831 483	(-29%) 2 484 626 344	(-29%) 4 157 553	(-29%) 2 601 593	(-29%) 2 491 385 490
	Total	**(-42%) 150 020 350**	**(-30%) 2 022 842 201**	**(-30%) 2 428 512 857**	**(-30%) 2 591 568 437**	**(-32%) 4 844 086**	**(-32%) 2 942 989**	**(-30%) 2 599 355 512**
Traditional Reconstruction	Materials	(-19%) 208 041 104	(-1%) 53 285 763	(-1%) 64 375 381	(-0.2%) 67 635 921	(6%) 901 930	(7%) 444 755	(-0.04%) 68 982 606
	Construction and M&R	0	(8%) 2 992 992	(8%) 3 592 680	(8%) 3 832 161	(8%) 6 414	(8%) 4 013	(8%) 3 842 588
	Transportation	0	(25%) 7 594 020	(25%) 9 115 587	(25%) 9 723 216	(25%) 16 273	(25%) 10 182	(25%) 9 749 672
	WZ Traffic Management	0	(-48%) 52 045 077	(-48%) 62 505 020	(-46%) 66 741 303	(-45%) 217 508	(-52%) 104 541	(-46%) 67 063 351
	Usage	0	(-29%) 1 938 650 938	(-29%) 2 327 831 483	(-29%) 2 484 626 344	(-29%) 4 157 553	(-29%) 2 601 593	(-29%) 2 491 385 490
	Total	**(-19%) 208 041 104**	**(-29%) 2 054 568 791**	**(-29%) 2 467 420 151**	**(-29%) 2 632 558 946**	**(-26%) 5 299 677**	**(-27%) 3 165 084**	**(-29%) 2 641 023 707**
Corrective Maintenance	Materials	257 799 624	53 857 196	63 930 785	67 741 997	847 904	417 166	69 007 067
	Construction and M&R	0	2 762 386	3 315 868	3 536 898	5 919	3 704	3 546 522
	Transportation	0	6 075 245	7 292 504	7 778 610	13 018	8 146	7 799 774
	WZ Traffic Management	0	100 376 784	120 542 044	123 082 069	397 567	217 687	123 697 322
	Usage	0	2 729 510 520	3 277 462 866	3 498 239 621	5 853 635	3 662 918	3 507 756 174
	Total	**257 799 624**	**2 892 582 130**	**3 472 544 067**	**3 700 379 196**	**7 118 043**	**4 309 621**	**3 711 806 860**

Acronyms: CED F- cumulative fossil energy demand; CED Nuc.- cumulative nuclear energy demand; CED R- cumulative renewable energy demand; CED Total- cumulative total energy demand.

Note 1: The feedstock energy, process energy and primary energy were computed through the GREET model's low heating values (LHV). The CED indicators values were computed through the GREET model's upper heating values (UHV).

Note 2: The numbers in brackets represent the reduction (negative values) or the increase (positive values) of the impact category indicator values with respect to the homologous phase of the corrective M&R strategy

Following the trend noticed for the remaining impact categories, the results presented in Table 0-9 show that the recycling-based M&R strategy is also the least harmful to the environment from the point of view of energy consumption. Overall, a reduction of about 32% in all the types of energy can be achieved as a result of implementing the recycling-based M&R strategy over the corrective maintenance one. Similar overall reductions might be obtained through the reconstruction M&R strategy, even though it denotes the most energy demanding transportation phase among the various strategies under assessment. This is because the reconstruction M&R activity requires the removal, and consequent transportation, of all the materials applied in the existing subgrade/base. The poor performance of the corrective M&R activity with respect to the CED indicator can be explained by the higher rate of change of IRI and pavement condition over the PAP, which requires vehicles to spend additional amounts of fuel to overcome the rolling resistance. Although less energy demanding than the usage phase, the WZ traffic management phase exhibit the second worst behavior, as a considerable amount of fuel is burned by the light vehicles while detouring the WZ.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, it can be seen that the nuclear and renewable energy sources are only consumed to power the pre-combustion energy-related processes. This fact explains the residual contributions of approximately 0.18% and 0.11% given by the CED Nuc. and CED R to the CED Total. The negligible role played by the nuclear and renewable energy sources can be seen as a mirror of a road transport mode, and particularly a road pavement construction and management sector, still excessively depending on the consumption of fossil fuels for energy sources. It is expected that the results would differ slightly if the introduction of alternative automotive fuels was taken into account in modeling the usage phase. However, there are both considerable uncertainties on how the rolling resistance effect would change the fuel consumption pattern of the vehicles propelled by alternative fuels, and the assumptions on the proliferation of alternative fuels in the long-term market.

Another notable result from Table 0-9 is that, excluding the case of the materials phase, approximately 17% of the primary energy attributable to each pavement life cycle phase is due to the pre-combustion energy for all M&R strategies. However, in the case of the remaining impact categories, the environmental impacts due to the upstream processes might be of such dimension that they turn out to be the main contributor to the global value of a determined impact category result. Thus, it is clear that the pre-combustion energy has a significant indirect impact on the environmental burdens of the several competing M&R strategies. Therefore, adopting narrowly defined system boundaries by neglecting supply-chain related impacts can result in underestimates of life cycle environmental footprint of pavement systems.

When comparing feedstock energy and CED F, Table 0-9 shows the feedstock energy of the bitumen to be almost three to five times the energy spent during the materials phase corresponding to the traditional reconstruction, recycling-based and corrective M&R strategies. This result is roughly 6%-9% of the CED Total for each of the strategies. If the energy spent during the usage phase were excluded from the CED indicator, the values would rise to be 96%-109% of the CED Total for the recycling-based, traditional reconstruction and corrective M&R strategies.

To further elaborate on the potential environmental differences arising from implementing the recycling-based activity as opposed to the traditional reconstruction activity, the results were separated into the materials, construction and M&R, transportation and WZ traffic management phases. In doing so, the environmental impacts assigned to the M&R activities that are expected to take place in the remaining years of the PAP were disregarded. The difference between the environmental impacts stemmed from the recycling-based activity and those arisen from the traditional reconstruction activity can be interpreted as "potential environmental impact savings", since the pavement is assumed to behave similarly after the initial recycling-based/traditional reconstruction. Figure 0-3 presents the impact of the two M&R activities on CC, with regard to materials, construction and M&R, transportation and WZ traffic management phases, respectively. Table 0-10 shows the changes in environmental impacts of each phase of the recycling-based activity relative to the traditional reconstruction M&R activity, presented in absolute value and percentage. Those results are to be understood as follows: negative relative numbers mean that the recycling-based M&R activity improves the LCIA results in relation to those associated with the traditional reconstruction M&R activity, while positive numbers represent a deterioration of the environmental profile. The CC impact category has been chosen to be analysed in more detail due to three main reasons: (1) it is the impact category with which most of the stakeholders tend to be more familiar with; (2) the majority of the measures aiming at reducing the environmental footprint of a process or an activity focus on attenuating the GHG emissions; (3) for both intervention strategies the relative contribution of each phase to the remaining impact categories is analogous to that observed in the case of the CC. Furthermore, the results were discretized in terms of the contributions given by the process energy and pre-combustion energy related processes.

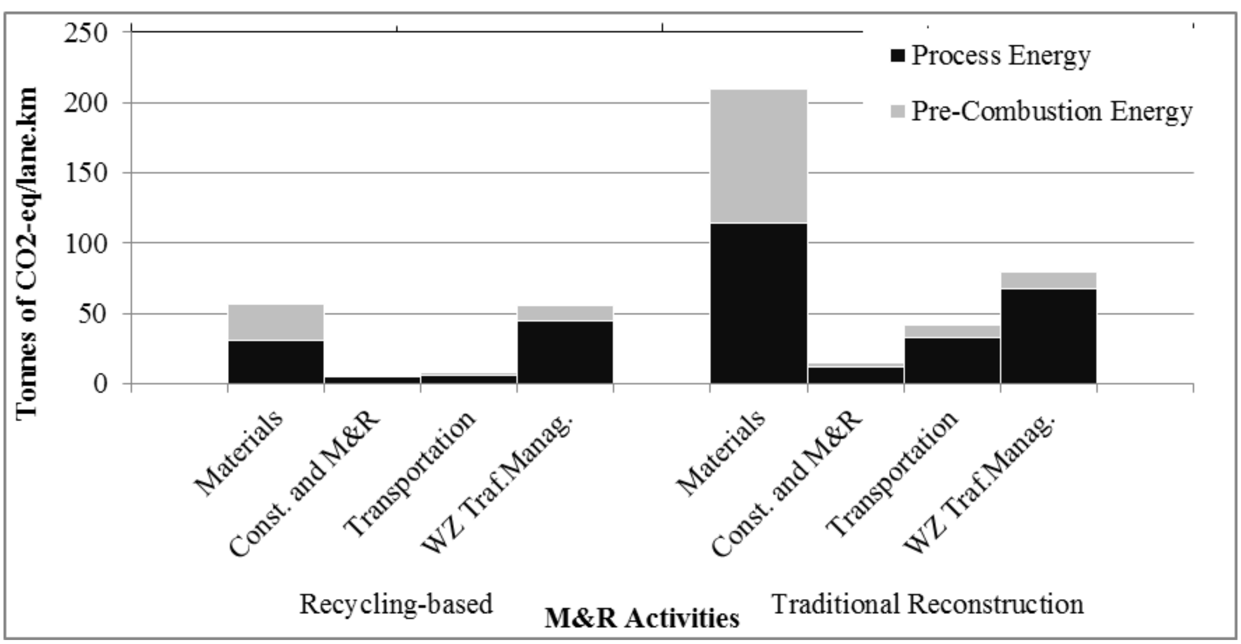

Figure 0-3 - Comparison of the global warming scoring associated with the application of the recycling-based and traditional reconstruction M&R activities

Table 0-10 - Changes in CC impact category indicator results of the recycling-based M&R activity relative to the traditional reconstruction M&R activity (absolute values in tonnes CO_2-eq/km.lane)

Pavement life cycle phase				Total
Materials	Construction and M&R	Transportation	WZ traffic management	
-150	26	-32	-30	-186
-80%	115%	-81%	-35%	-55%

As can be seen from Figure 0-3, the most meaningful environmental advantage obtained when applying the recycling-based M&R activity comes from the materials phase. A reduction of 150 tonnes of CO_2-eq/lane.km, meaning 80% of the emissions occurred during homologous phase of the traditional reconstruction M&R activity, is expected to be achieved if the recycling-based M&R activity is undertaken. However, this outcome must be interpreted having in mind that the reduction in CO_2-eq is not exclusively the reflection of the reduction of the virgin materials consumption. It also results from the fact that the production of the recycling-based mixtures (FDR, CCPR and CIR) taking place on the site are included in the construction and M&R phase, whereas the production of the asphalt mixtures applied in the traditional reconstruction activity are accounted for the materials extraction and production phase, namely the materials production sub-phase.

The WZ traffic management phase was found to have the second highest contribution for environmental impacts, behind the usage phase. Both the M&R strategies were modelled assuming the implementation of the same traffic management plan [as described in Diefenderfer at al. (2012)]. Therefore, the reduction of 30 tonnes of CO_2-eq/lane.km emissions obtained through the implementation of *in-place* recycling activity over the traditional reconstruction activity is due to the fact that the former M&R activity requires less time to be undertaken than the latter.

Finally, the recycling-based activity was found to have a much lower contribution from the transportation phase, bringing down the CO_2-eq/lane.km emissions from 40 tonnes to 7 tonnes. The cut in the CO_2-eq emissions was the result of a reduction in the total hauling movements from 50.490 giga tkm to 1.288 giga tkm. However, it should be noted that the transportation phase-related environmental benefits associated with the recycling-based activity would be greater if the quarry that supplied the aggregates consumed during the project was not inside the boundary of the asphalt drum plant facility.

Despite the recycling strategy's better overall environmental performance, not all the life cycle phases contribute positively to this achievement. The construction equipment required to implement the pavement recycling techniques were found to release 26 more tonnes of CO_2-eq/lane.km than what would be potentially released by the construction equipment used to carry out the traditional reconstruction activity. It is expected that this increase is due to the fact that the equipment producing the recycled materials (e.g., milling machine, reclaimer, cold-recycling mixing plant, cold recycler, etc.), along with the usage of construction equipment, possess engines with a greater power than those equipped by typical asphalt paving equipment (e.g., paver, rollers, etc.). However, the magnitude of this increase is not enough to offset the recycling strategy's better overall environmental performance obtained due to the improvements accounted for the remaining phases.

1.8. KEY FINDINGS

From the results presented and discussed in the previous section, the following findings are worth highlighting:

- the usage phase accounts for up to 96% of the overall life cycle environmental impacts of a pavement system;
- a significant decrease in environmental pollutants is realized by increasing the strength of the pavement, and thus decreasing the frequency of needed maintenance;
- the recycling-based M&R strategy significantly enhance the environmental performance of the pavements over the life cycle by improving the environmental impacts of the initial activity;
- the recycling-based M&R strategy reduce the overall life cycle environmental impacts and energy consumption by as much as 30 and 32 percent, respectively, when compared to the corrective M&R strategy;
- the pre-combustion energy represents approximately 17% of the primary energy consumed over the life cycle of a pavement system. However, regarding the remaining impact categories, this value might be of such dimension that they turn out to be the main contributor to the global value of a determined impact category result;
- a reduction of 80% in the environmental impacts occurring during the raw materials extraction and mixtures production can be achieved by undertaking the recycling-based M&R activity as an alternative to traditional reconstruction M&R activity;
- the recycling-based M&R activity allow savings of about 97% in the hauling movements, as measured by tonnes-kilometer, which represents a reduction of approximately 80% in the GHG emissions; and
- Even though it is not enough to offset its overall better environmental performance, in-place recycling activities are expected to lead to higher construction equipment-related emissions and fuel consumption when compared to those of traditional pavement M&R activities.

1.9. SUMMARY AND CONCLUSIONS

This paper presents the results of a comprehensive LCA of three M&R strategies for a pavement segment, and compares the relative environmental impacts of each strategy. A comprehensive pavement LCA model was developed that allows accounting for the environmental impacts resulting from the entire life cycle of a pavement system, including the upstream processes to the production and transportation of the energy sources. The pavement LCA model comprises six pavement life cycle phases: (1) materials extraction and production; (2) construction and M&R; (3) transportation of materials; (4) WZ traffic management; (5) usage and (6) EOL. In addition, an original methodology is implemented that easily combines the vehicle emissions model MOVES with the HDM-4 rolling resistance model calibrated to North American conditions, to estimate the additional fuel consumption, and consequently the environmental impacts, resulting from the deterioration of the pavement over the life cycle.

The results from this case study show that the usage phase is the phase of the life cycle with the greatest contribution across the majority of the impact categories. This outcome was found to be common to all M&R strategies, but with a greater impact, in absolute value, for the corrective M&R strategy. Consequently, this M&R strategy was also found to have an additional total energy consumption, as measured by the CED Total, of 44% and 42% relatively to the total energy consumed in the case that the recycling-based and traditional reconstruction M&R strategies are alternatively adopted.

When analyzing the relevance of each type of energy (fossil energy, nuclear energy and renewable energy) in the energy consumption, the nuclear and renewable energy sources were found to have residual contributions of 0.18% and 0.11% to the CED Total. Concerning the contribution given by the upstream processes in the production and transportation of the energy sources, it was shown that approximately 17% of the primary energy consumed during each pavement life cycle phase is due to energy source production. The magnitude of this value clearly suggests that the consumption of more sustainable energy sources may play an important role in lowering the life cycle environmental burdens of a road pavement.

By comparing the *in-place* recycling-based activity against the traditional reconstruction activity, a reduction of 150 tonnes of CO_2-eq/lane.km is expected to be achieved exclusively due to the materials phase if the recycling-based activity is undertaken. This value represents a reduction of 80% relatively to the CO_{2a}-eq emissions accounted for equal phase of the rehabilitation activity. Despite the lower impact when compared to the materials phase, the environmental benefits arisen from the WZ traffic management and transportation phases should also not be disregarded. However, it is important to note that the results may be strongly dependent on the traffic management and material location decisions made within this particular project. Consequently, generalizations of those results must be made carefully.

In spite of the exclusivity of each project, by implementing in-place recycling strategies the highway agencies are moving in the right direction towards reducing the overall life cycle environmental impacts related to the pavement construction and management practices. However, while the LCA is useful to increase the environmental consciousness of highway agencies, the environmental aspect is only one of the three elements that compose the triple bottom line that schematically represent the concept of sustainability.

To guide highway agencies towards complete life cycle thinking, future work on this topic should compare the various M&R strategies according to their performance in terms of the criteria addressed by the remaining branches of the sustainability concept.

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