A LIFE CYCLE ASSESSMENT OF IN-PLACE RECYCLING AND CONVENTIONAL PAVEMENT CONSTRUCTION AND MAINTENANCE PRACTICES

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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.

INTRODUCTION

With the majority of highway construction complete since the 1980's, a large part of the national highway system is showing evidence of aging and, in some cases, severe deterioration. According to the American Society of Civil Engineers report card (*1*) driving on a pavement in poor conditions would cost U.S. 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, if the traditional M&R strategies are adopted. 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 and the incorporation of recycled materials and byproducts. 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, some recycling practices have been proven to enhance the life cycle environmental performance of pavements *(2)*.

A Life cycle assessment (LCA) is used to account for a systems' environmental performance according to a cradle to grave analysis principle. 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. In the case of pavements, most LCA have excluded the use phase of the project *(3).* However, recent research has produced more reliable models to quantify the impact of the pavement condition on vehicle fuel consumption and emissions *(4)*, 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 these pavement M&R alternatives.

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 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 1: Summary of the Maintenance Strategies

M&R Strategy	Initial M&R Activity	Future M&R Activities[a]
Recycling-Based	Left Lane: Cold in place recycling (CIR) method to mill, refine and replace the top 18 cm [7 in.] of pavement. Right Lane: A combination of full depth reclamation (FDR) and cold central plant recycling (CCPR) to treat 55 cm [22 in.] in depth. Both lanes received a HMA riding surface.	Maintenance actions performed in years 12[b], 22[b], 32[c] and 44[b]
Traditional Reconstruction	Left Lane: Mill and replace the top 18 cm [7 in.] 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[b], 22[b], 32[c] and 44[b]
Corrective Maintenance	Both Lanes: 5% full depth patching followed by a 10 cm [4 in.] mill and overlay.	Maintenance actions performed in years 4[b], 10[b], 14[c], 18[b], 24[b], 28[c], 34[b], 38[b], 44[c] and 48[b]

a. The M&R activities are defined according to the Virginia Department of Transportation (VDOT) guidelines *(5).*
b. Functional mill and replace.
c. Major rehabilitation.

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 the University of California Pavement Research Center (UCPRC) Pavement LCA Guideline *(6).* Field data for the case study were provided by the VDOT *(7).* 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.

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 to: 1) estimate the potential environmental advantages resulting from applying in-place pavement recycling techniques against two traditional M&R methods, 2) demonstrate 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) identify 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 sustainable pavement management processes.

<u>Functional Unit</u>
The specific project chosen for achieving the aforementioned objectives is a 5.89 km [3.66 mi.] 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 approximately 25,000 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%.

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 *(7)*.

M&R Scenarios
This study compared a corrective maintenance strategy (base M&R strategy) against two alternative strategies: the innovative strategy (which is the recycling-based M&R strategy that was conducted on the pavement segment), and the traditional reconstruction M&R strategy, where reconstruction is

performed using traditional methods without any in-place recycling methods. The three alternatives are briefly summarized in Table 1. For the recycling-based and traditional reconstruction strategies, the expected maintenance actions outlined by VDOT were followed *(5).* For the corrective maintenance scenario, past performance and construction history indicates that a 5 cm [2 in.] 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 *(8).* 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). In order to determine the roughness of the pavement as a function of time for routine M&R (corresponding to rehabilitation M&R strategy), past International Roughness Index (IRI) data for the pavement section was plotted and a function in the form of the Equation (1) was fitted to the data. The values of the parameters are presented in Table 2.

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

Where:

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

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 2.

Table 2: Parameters Values of the Equation *(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

System Boundaries, System Processes and Life Cycle Inventory Data

The life cycle of a road pavement is generally divided into five phases *(6)*. They are the following: 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 potential 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.

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 life cycle inventories (LCIs) referring to the production of the materials used in this case study were collected from several published LCI and LCA reports *(9-11).* The LCI associated with the asphalt mixtures production at a mixing plant were obtained by combining the emissions factors published by the AP-42 study of HMA plants *(12)* for a drum mixing plant, with the energy consumption presented by Sathaye et al. *(13)* for the same type of plant. The electricity consumption referring to the operation of the conveyor system was obtained from *(9)*. Emissions and energy consumption due to the operation of the wheel loader were estimated based on the rate at which the wheel loader can move aggregates and the methodology adopted by the US EPA's NONROAD 2008 model *(14)*. The environmental burdens from the 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.

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) that run at their maximum payload capacity (ranges between 15 and 27 tonnes depending on the type of material) when loaded and empty on return journeys. The United States Environmental Protection Agency (US EPA) Motor Vehicle Emissions Simulator (*MOVES*) *(15)* 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.

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 NONROAD2008 model *(14).* Information regarding the type and features (e.g., 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 *(7)* and complemented with technical specifications from the equipment's manufacturers.

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. The 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. The fuel consumption and airborne emissions released by vehicles either traversing or detouring a WZ 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. Secondly, changes in driving patterns were modelled using the capacity and delay models proposed by the Highway Capacity Manual 2000 *(16)* 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 derivate 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.

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. Given that this study compared several maintenance plans using the same surface materials, only the impact of the pavement roughness on the pavements overall environmental burden was considered. In order to determine the impact of the pavement roughness on vehicle fuel consumption and emissions, the Chatti and Zaabar's Vehicle Operating Cost (VOC) model *(4)* was combined with data from the EPA's *MOVES* model *(15)*. The approach proposed in this paper is innovative in the sense 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 *(4)* 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 (2). For each year of the PAP, the $AADT_E(t)$ value is computed and compared with the $AADT_E$ value corresponding to the condition of a new pavement, taken as baseline scenario. Fuel consumption and greenhouse gas (GHG) emissions are posteriorly calculated based on the deviation from that baseline scenario.

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

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.

End-of-Life Phase

When a road pavement reaches its service life, it can remain in place serving as support for a new pavement structure or be removed. Taken into account that the pavement section under assessment belongs to an interstate, it is expected that it would remain in place after reaching the end of the PAP, serving as foundation for the new pavement structure. By adopting a "cut-off" allocation method no environmental impacts were assigned to the EOL phase of all M&R scenarios in comparison in the current pavement system.

Energy Source Production

Although it is not considered a pavement life cycle phase, as those previously introduced, the energy sources production is an unavoidable process that is common to all pavement life cycle phases. Energy source production refers to the impact of producing and delivering 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, etc. 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. The *GREET* model *(17)* was used as the source of the LCI for the production and delivery 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.

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. The time-adjusted characterization model for the Climate Change (CC) impact category proposed by Kendall *(18)* was used in this approach as opposed to the traditional time-steady International Panel on Climate Change (IPCC) model. 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. *(19)* but adopting the upper heating values (UHVs) defined in the *GREET* model.

RESULTS AND DISCUSSION

The potential life cycle impacts for each pavement M&R strategy are displayed in Table 3. This table also 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. 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 *(6).*

As can be seen from Table 3, the usage phase is by far the phase of the life cycle with the greatest contribution to the CC. 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 best environmental performance during the usage phase is simultaneously the most environmentally friendly overall. Indeed, by implementing a recycled-based M&R strategy, a reduction of approximately 30% in the global warming score can be achieved relatively to that 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 found to outperform the remaining M&R strategies in comparison. Therefore, it is expectable that the adoption of an M&R strategy able to slow down the deterioration rate of the pavement roughness would lead to valuables improvements in the life cycle environmental performance of a pavement system. Following the trend noticed for the CC impact category, the results presented in Table 3 show that the recycling-based M&R strategy is also the least harmful to the environment from the standpoint of energy consumption.

Table 3: Comparison of the Environmental Performance of the three M&R Strategies in terms of Climate Change and Energy-Related Impact Categories

M&R Strategy	Life cycle Phase	CC[a] (tonnes CO_2-eq.)	Feedstock Energy[b] (MJ)	Process Energy[b] (MJ)	Primary Energy[b] (MJ)	CED F[c] (MJ)	CED Nuc[c] (MJ)	CED R[c] (MJ)	CED Total[c] (MJ)
Recycling-based	Materials	(-51%) 1,937	(-51%) 150,020,350	(-49%) 32,407,121	(-49%) 38,416,682	(-50%) 40,498,823	(-52%) 478,720	(-52%) 235,497	(-50%) 41,213,490
	Construction and M&R	(-37%) 152	0	(-40%) 1,854,509	(-40%) 2,226,086	(-40%) 2,374,473	(-40%) 3,974	(-40%) 2,487	(-40%) 2,380,933
	Transportation	(-50%) 260	0	(-52%) 2,250,145	(-52%) 3,901,356	(-52%) 4,161,414	(-52%) 6,965	(-52%) 4,358	(-52%) 4,172,736
	WZ Traffic Management	(-51%) 3,593	0	(-52%) 48,210,242	(-52%) 57,897,901	(-50%) 61,818,525	(-50%) 198,809	(-54%) 99,796	(-50%) 62,117,129
	Usage	(-28%) 112,926	0	(-29%) 1,938,650,938	(-29%) 2,327,831,483	(-29%) 2,484,626,525	(-29%) 4,157,553	(-29%) 2,601,593	(-29%) 2,491,385,490
	Total	**(-30%) 118,868**	**(-51%) 150,020,350**	**(-30%) 2,024,372,955**	**(-30%) 2,430,273,508**	**(-30%) 2,593,479,578**	**(-33%) 4,846,020**	**(-33%) 2,944,180**	**(-30%) 2,601,269,779**
Traditional Reconstruction	Materials	(-5%) 3,788	(-32%) 208,041,104	(-16%) 53,285,763	(-15%) 64,375,381	(-16 %) 67,635,921	(-10%) 901,930	(-10%) 444,755	(-16%) 68,982,606
	Construction and M&R	(6%) 258	0	(-4%) 2,976,271	(-4%) 3,572,608	(-4%) 3,810,752	(-4%) 6,378	(-4%) 3,991	(-4%) 3,821,121
	Transportation	(33%) 694	0	(9%) 7,335,245	(9%) 8,804,963	(9%) 9,391,886	(9%) 15,718	(9%) 9,835	(9%) 9,417,440
	WZ Traffic Management	(-46%) 3,942	0	(-48%) 52,045,077	(-48%) 62,505,020	(-46%) 66,741,303	(-45%) 217,508	(-52%) 104,541	(-46%) 67,063,351
	Usage	(-28%) 112,926	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	**(-28%) 121,607**	**(-32%) 208,041,104**	**(-29%) 2,054,293,295**	**(-29%) 2,467,089,456**	**(-29%) 2,632,206,207**	**(-27%) 5,299,087**	**(-28%) 3,165,714**	**(-29%) 2,640,670,008**
Corrective Maintenance	Materials	3,980	306,134,253	63,788,792	75,765,936	80,231,939	1,004,434	494,185	81,730,559
	Construction and M&R	242	0	3,088,334	3,707,125	3,954,235	6,618	4,141	3,964,994
	Transportation	524	0	6,746,643	8,098,426	8,638,253	14,457	9,046	8,661,756
	WZ Traffic Management	7,335	0	100,376,784	120,542,044	123,082,069	397,567	217,687	123,697,322
	Usage	156,859	0	2,729,510,520	3,277,462,866	3,498,239,621	5,853,635	3,662,918	3,507,756,174
	Total	**168,940**	**306,134,253**	**2,903,511,072**	**3,485,576,396**	**3,714,146,117**	**7,276,711**	**4,387,978**	**3,725,810,805**

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

a. The potential environmental impacts in terms of CC were estimated for a 100-year time horizon.
b. The feedstock energy, process energy and primary energy were computed through the *GREET* model's low heating values (LHVs).
c. The CED indicators were computed through the *GREET* model's UHVs.

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

Overall, a reduction of about 30%-33% in all the types of energy can be achieved as result of implementing a recycling-based M&R strategy over a corrective 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. Regarding the poor performance of the corrective M&R activity with respect to the CED indicator, this outcome 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 that the usage phase, the WZ traffic management phase exhibit the second worst behavior, as 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 CED Nuc and CED R indicators exhibit residual contributions of approximately 0.20% and 0.12% 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. When comparing feedstock energy and CED F, Table 3 shows the feedstock energy of the bitumen to be almost three to four 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%-8% of the CED Total for each one of the strategies. If the energy spent during the usage phase were excluded from the CED indicator, the values would rise to be 137%-140% of the CED Total in all the strategies in comparison.

Figure 1 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 4 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.

As illustrated by Figure 1, the most meaningful environmental advantage, in absolute value, resulting from applying the recycling-based M&R activity comes from the materials phase. A reduction of about 157 tonnes of CO_2-eq/lane.km, meaning 75% 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. Although the reduction of the virgin materials consumption is the main responsible for this achievement, it also benefits from the fact that the in-place production of the recycling-based mixtures (FDR, CCPR and CIR) 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. However, if the analysis is carried out on a relative basis, then the transportation phase would be the greatest benefited from the application of the recycling-based M&R activity.

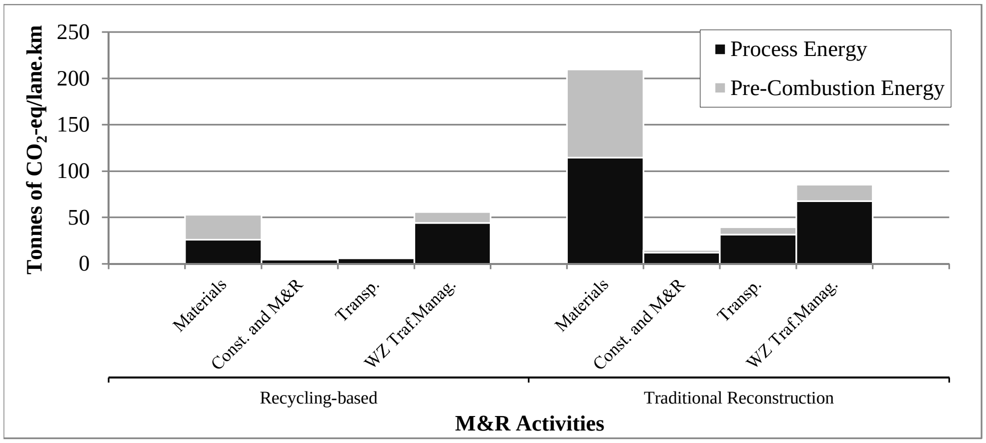

Figure 1: Comparison of the global warming score associated with the application of the recycling-based and traditional reconstruction M&R activities.

Table 4: Changes in the Global Warming Score of the Recycling-Based M&R Activity Relative to the Traditional Reconstruction M&R Activity (absolute values in tonnes of CO_2-eq)

Pavement Life Cycle Phase				Total
Materials	Construction and M&R	Transportation	WZ traffic management	
-157 (-75%)	-9 (-62%)	-32 (-81%)	-30 (-35%)	-228 (-65%)

The resulting reduction in the CO_2-eq/lane-km emissions from 39 tonnes to 7 tonnes translates to an improvement in the environmental performance as measured by the CC impact category of 81%. Such an outcome is a consequence of a reduction in the total hauling movements from 10.875 mega tonne-km to 1.771 mega tonne-km. However, it should be noted that the transportation phase-related environmental benefits associated with the recycling-based M&R 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. Another result worth noting from Figure 1 is that in both M&R activities, approximately 20% of the GHG emissions are due to the processes required to produce and deliver the energy sources to theirs point of use. In the case of the materials phase corresponding to the recycling-based M&R activity, this value was found to be even more meaningful (45%). Therefore, adopting narrowly defined system boundaries by neglecting supply-chain related impacts can result in underestimates of life cycle environmental footprint of the pavement systems.

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 pavement LCA model was developed that allows accounting for the environmental impacts resulting from the entire life cycle of a pavement system, including the usage phase and the upstream processes underlying to the production and delivery of the energy sources. The results from this case study show that: 1) the usage phase accounts for up to 95% of the overall life cycle environmental impacts of a pavement system, as measured by global warming score, 2) a significant decrease in the environmental burdens is realized by increasing the strength of the pavement, and thus decreasing the frequency of needed maintenance, 3) the recycling-based M&R strategy significantly enhance the environmental performance of the pavements over the life cycle by lowering the environmental impacts of the initial M&R activity, 4) the recycling-based M&R strategy reduce the overall life cycle environmental impacts and energy consumption by as much as 30%-33 %, respectively, when compared to the corrective M&R strategy, 5) a reduction of 75% in the environmental impacts occurred during the raw materials extraction and mixtures production can be achieved by undertaking the recycling-based M&R activity in alternative to traditional reconstruction M&R activity, and 6) the recycling-based M&R activity allows savings of about 82% in the GHG emissions associated with the hauling movements.

In the future, since the pavement performance model developed to simulate the behavior of the pavement section treated with the in-place recycling techniques was developed taking as basis performance data from an adjacent section, it would be desirable to further assess the possibility of the in-place recycling techniques perform insufficiently. If so, the environmental benefits of using such treatments might be totally or partially off-set by the need for more frequent M&R activities, and mostly by the impacts resulting from the additional fuel consumption required to overcome the increasing rolling resistance associated with a rougher pavement surface. Consequently, the generalization of the results presented in this paper should be made carefully.

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