A Comprehensive Life Cycle Costs Analysis of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices

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ABSTRACT

Recent studies based on Life Cycle Assessment (LCA) have highlighted the potential of in-place recycling techniques to enhance the sustainability of agency pavement management decisions for asphalt-surfaced pavements. However, a solution which is found to be environmentally advantageous by an LCA might not be preferred to another one which is technically equivalent if it is not economically competitive. In this context, it is necessary to evaluate the economic advantages taking into account the perspective of the main stakeholders who interact with a pavement system throughout its life cycle. This paper presents a comprehensive pavement life cycle costs (LCC) model that accounts for the different categories of costs incurred by highway agencies and road users over all the pavement life cycle phases. The results of the application of the pavement LCC model to a specific highway rehabilitation project in the state of Virginia showed that in-place recycling practices are beneficial for both highway agencies and road users.

Keywords: Life cycle costs analysis; Highway agency costs; Road user costs; In-place recycling; Pavement construction and management.

1. - INTRODUCTION

Transport infrastructure is one of the main backbones of all commodities and passenger flows in the US. Despite its undeniable contribution to the health of the national economy, the current road network requires significant investments in maintenance and rehabilitation (M&R) to keep its quality at an acceptable level *(1)*. In addition, as society becomes more aware of the effects of human activity on the environment, sustainability has started to play a more significant role in the decision-making and planning processes, including those regarding pavement management. To embrace the concept of sustainability pavement mangers need to change their practices in order to routinely deliver infrastructures that are also economically efficient.

An important part of this paradigm shift can be partially achieved by implementing in-place pavement recycling techniques to rehabilitate distressed pavements *(2,3)*. However, a solution which is found to be environmentally advantageous might not be preferred to another one which is technically equivalent if it is not economically competitive. Although this rehabilitation technique is commonly presented as advantageous from an economic point of view, there are still some questions about the extent to which such techniques are cost-effective throughout their life cycle. It also important to quantify which factors are the key drivers of economic performance, and which stakeholders are the ones that benefit the most with the application of in-place pavement recycling techniques.

Life-cycle costs analysis (LCCA) is an analytical methodology that uses economic principles to evaluate long-term alternative investment options in infrastructure management to select optimum strategies. Performing a LCCA requires a life cycle costs (LCC) model that comprehensively tracks the consumption of resources in their multiple categories (e.g., raw materials, energy sources, labor, equipment, etc.). Moreover, the chain of operations preceding the pavement life cycle phase in which a construction and M&R activity is delivered should not be merely summarized in its bid price, and viewed as a "black box." A detailed characterization of all the costs incurred by highway agencies when performing road construction and maintenance activities and imposed on other affected stakeholders over the entire life cycle of those activities is fundamental to gain in-depth insights into the extent to which new technical solutions, such as in-place recycling techniques, result potentially in costs reduction, and thereby to allow for making more transparent and informed decisions at an early stage of the project's development.

2. - OBJECTIVES

This paper presents the results from an extensive (cradle-to-grave) LCCA of an in-place pavement recycling rehabilitation project in the state of Virginia. It also illustrates the development of a comprehensive pavement LCC model intended to give decision-makers a systematic framework that will provide an in-depth perspective of the costs incurred by highway agencies and road users during pavement construction and maintenance activities. 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 features of the three M&R strategies are summarized in Table 1.

TABLE 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 13 cm (5 inches) of pavement. Right Lane: A combination of full depth reclamation and cold central plant recycling to treat 45 cm (18 inches) in depth. Both lanes received a AC riding surface.	Maintenance actions performed in years 12, 22, 32 and 44 (See Table 2 in *(3)* for further details)
Traditional reconstruction	Left Lane: Mill and replace the top 5 cm (2 inches) of pavement. Right Lane: Mill and replace full depth of existing pavement and apply a cement treatment to the base/subgrade. Apply an AC riding surface to both lanes.	Maintenance actions performed in years 12, 22, 32 and 44 (See Table 3 in *(3)* for further details)
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 (See Table 4 in *(3)* for further details)

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"; AC, asphalt concrete.

3. - METHODOLOGY

A comprehensive pavement LCC model was developed to calculate and compare several categories of costs borne by highway agencies and road users, not only during the application of M&R activities in a road pavement section, but also throughout its usage and end-of-life (EOL). This model builds on a previous life cycle assessment (LCA) model developed to calculate and compare the environmental impacts of in-place recycling and conventional pavement construction and M&R practices *(3)*.

The data required to carry out the case study were either provided by the Virginia Department of Transportation (VDOT) *(4)* or gathered from relevant literature and are available from the author upon request.

In order to automatically share the data between the multiple sub-models and compute the costs inherent to the successive pavement life cycle phases, the framework of the LCC model was implemented in a software written in Visual Basic .NET (VB.NET) and SQL programming languages. The latter was used for managing the data introduced and held in the system.

3.1. GOAL AND SCOPE DEFINITION

This paper presents the results from a comprehensive LCCA conducted for three M&R strategies applied to a pavement segment. The first step consisted of developing a comprehensive pavement LCC model to thoroughly estimate the costs incurred by the highway agency and road users throughout the entire life cycle of the pavement section. The LCC model used the life cycle inventory of resource flows, operating parameters and other exchanges reported in *(3)* as a starting basis for modeling the relationships between pavement life cycle phases and the costs supported by the different pavement stakeholders.

By applying the pavement LCC model to the case study presented in this paper we were able to:

(1) Estimate the potential economic advantages resulting from applying in-place pavement recycling techniques compared to two traditional M&R methods;

(2) Account for the interaction between technical aspects, production costs, and costs imposed on other affected stakeholders (i.e., road users);
(3) Identify the most important processes, and consequently pavement life cycle phases, in driving the economic performance of a road pavement section throughout its life cycle from the perspective of different stakeholders.

These results provide state and local agencies with quantitative evidence to support the adoption of cost effective pavement management processes.

3.1.1. Functional Unit

The specific project chosen for achieving the aforementioned objectives is a 5.89 km long, 2-lane asphalt section of Interstate 81 near Staunton, Virginia. The project analysis period (PAP) is 50 years, beginning in 2011 (date of completion of the in-place pavement recycling project that rehabilitated the existing pavement structure). The annual average daily traffic (AADT) value for the first year was obtained from the VDOT traffic website and consisted of 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%.

3.1.2. System Boundaries, System Processes and Life Cycle Inventory Data

The proposed pavement LCC model entails six pavement life cycle phases: (1) materials extraction and production, (2) construction and M&R, (3) transportation of materials, (4) Work Zone (WZ) traffic management, (5) usage, and (6) EOL. The various models used while computing the costs incurred during each pavement life cycle phase are introduced and discussed in the following sections.

3.1.2.1. Materials Extraction and Production Phase

This phase accounts for the costs incurred by the highway agency to produce the mixtures that are going to be applied during the construction and M&R phases. The typical total bid costs provided by DOTs comprises manufacturing and transportation of raw materials, manufacturing of mixtures, labor, overheads, profit margins and other costs in one number. This practice makes it difficult: (1) to differentiate the relative contribution of the fixed and variable costs, (2) to investigate the impact of variability in pricing, types of mixtures, mixtures compositions and mixtures process technologies on the total bid price, and (3) to identify the main cost drivers of the life cycle, and then point out improvements that can be advantageous for all or some of the stakeholders involved in the system. Therefore, due to the points listed above, the calculation procedure of the materials extraction and production phase costs cannot rely on bid prices.

To address this issue, the materials extraction and production phase costs were divided into three main categories: (1) raw materials costs, corresponding to the materials that make up the asphalt mixtures, as well as those that are directly applied at the work site (e.g., lime, hydraulic cement, etc.), (2) energy costs, specifically, the cost of the energy required to produce the asphalt mixtures, and (3) asphalt plant operating costs, representing the costs incurred in the operation of the asphalt plant. This last category was further divided into fixed and variable cost sub-categories. The fixed costs sub-category refers to those costs that remain fairly the same regardless of the volume of the mixtures produced, and were computed by allocating an annual cost. Typically, they include: (1) the asphalt plant depreciation cost, (2) the auxiliary equipment depreciation costs; (3) insurance; (4) taxes, licensing and permits; (5) utilities, and (6) labor costs (e.g., asphalt plant operator, auxiliary equipment operator, maintenance technician, etc.). Other fixed costs incurred prior to asphalt plant installation, such as engineering design/planning, real estate purchase, licenses and taxes were disregarded.

On the other hand, the variable costs sub-category refers to those costs dependent on the volume of production. Aside from the raw material costs and asphalt mixture production-related energy costs that were accounted for as individual categories, the variable asphalt plant operating costs includes the variable costs resulting from the operation of the asphalt plant (e.g. diesel consumed by the wheel loader, etc.).

3.1.2.2. Construction and M&R Phase

The construction and M&R phase costs include costs incurred by the highway agency during the actual performance of a construction or M&R activity at a particular work site on a specific day and at a specific time. They include the construction equipment ownership costs (i.e. depreciation, insurance, interest, taxes and licenses), construction equipment operation costs (i.e. fuel consumption, equipment routine maintenance, equipment repairs, tire wear, special wear items, mobilization and demobilization) and labor costs corresponding to the wages and benefits paid to the crew members. The materials costs, as well as the costs associated with the hauling movements required to deliver the materials from the production to the destination, are accounted for in individual phases.

3.1.2.3. Transportation of Materials Phase

The economic advantage of recycling-based construction and M&R practices is strongly affected by material transportation costs and how those costs compare to the cost of new virgin materials delivered to the construction site. Thus, unlike the majority of the LCC models existing in the literature, the proposed LCC model presents the costs incurred by the highway agencies due to the transportation of the materials separated out from the remaining categories that constitute the total delivery price.

Similar to construction and M&R phase costs, three main cost categories were considered: (1) hauling trucks ownership costs (i.e. depreciation, insurance, interest, taxes and licenses), (2) hauling trucks operation costs (fuel consumption, trucks routine maintenance, trucks repairs, tires wear), and (3) labor costs (i.e. drivers' wages and benefits).

3.1.2.4. WZ Traffic Management Phase

The WZ traffic management costs include the additional costs borne by the road users (RUC) when facing the disruption of the normal traffic flow as a consequence of the constraints imposed by a WZ traffic management plan. In this LCC model the following WZ traffic management costs categories were considered: (1) time delay costs (TDC) and (2) vehicle operating costs (VOC). The accidents costs, typically considered as another WZ RUC category, were disregarded due to the high level of uncertainty associated with the factors that might determine their occurrence (which are often related with driver errors and other factors not related to the WZ).

The TDC regard the difference between the cost of the time spent by a vehicle's occupants and goods while travelling at detour speed or WZ reduced speed, and that corresponding to go through the highway WZ section at the normal operating speed during a non-WZ period. The delays to personal travel, business travel, and freight inventory caused by the WZ and estimated according to the capacity and delay models proposed by the Highway

Capacity Manual 2000 *(5)* were multiplied by the unit costs ($/hr) of travel time, as suggested by the United States Department of Transportation Office of the Secretary of Transportation (OST)'s guidelines *(6)*.

The WZ-related VOC represent the costs incurred by the vehicle drivers due to the vehicle ownership, operating and maintenance, and are expressed as the difference between the costs incurred while travelling at detour speed or WZ reduced speed, and those corresponding to go through the highway WZ section at the normal operating speed during a non-WZ period. Five types of VOC subcategories were considered to contribute to the total VOC: (1) fuel consumption, (2) oil consumption, (3) tire wear, (4) vehicle maintenance and repair, and (5) vehicle depreciation.

The first VOC subcategory was determined using the United States Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) *(7)* as detailed by *(3)*, whereas the speed-constant and speed-change cycles HERST-ST sub-models *(8)* were adopted to calculate the remaining sub-categories.

3.1.2.5. Usage Phase

The usage phase costs, frequently named non-WZ RUC, account for the marginal VOC supported by the road users throughout the PAP as a consequence of the deterioration of the pavement condition. In the proposed LCC model, the pavement roughness, as measured by the international roughness index (IRI), was used to estimate the RUC associated with the overall pavement surface condition. The following costs categories were considered to contribute to the total usage phase costs: (1) fuel consumption, (2) tire wear, (3) vehicle maintenance and repair, and (4) mileage-related vehicle depreciation.

The first three costs categories were estimated by adopting the VOC model developed by *(9)* as result of the calibration of the HDM-4 VOC model to consider U.S. conditions. The effect of the pavement roughness on vehicle depreciation costs was determined according to the methodology presented by *(10)*.

3.1.2.6. End-of-Life Phase

When a road pavement reaches the end of its service life, it can be given two main destinations: (1) remain in place serving as support for a new pavement structure or, (2) be removed. Removed pavement materials are: (1) disposed of in a landfill (increasingly less frequently adopted in the U.S.), 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.

From the LCCA perspective, these two alternatives can be considered mutually exclusive and entail different costs (or benefits) for the highway agencies, each of which reflects the remaining worth of a pavement at the end of the PAP. In the present case study, the most likely EOL scenario for the analyzed pavement structure is that it will remain in place after reaching the end of the PAP, serving as foundation for the new pavement structure. Thus, the residual value of the pavement structure is given by the value of its remaining service life. The service life of the pavement was assumed to end when the IRI exceeds 3.16 m/km (200 in/mile), which according to the VDOT's Highway System Performance Dashboard *(11)* corresponds to the threshold ($IRI_{Terminal}$) beyond which a ride is classified as "very poor".

In order to compute the value of the remaining service life, and thus, the residual value of the pavement at end of the PAP, Equation (1) was adopted. It quantifies the residual value of the pavement as the proportion of the total highway agency costs incurred by the application of the last M&R activity compared to the proportion of the remaining life of that M&R activity *(12)*.

$$C_{EOL\ phase} = C_{Last\ M\&R\ activity} \times \frac{IRI_{Terminal} - IRI_{EOL}}{IRI_{Terminal} - IRI_{Initial}} \tag{1}$$

Where: $C_{Last\ M\&R\ activity}$ is the total highway agency costs resulting from the application of the last M&R activity. It is obtained by summing up the costs incurred by the highway agency during the materials, M&R and transportation of materials phases associated with the last M&R activity; $IRI_{Initial}$ is the IRI value of a new pavement (0.87 m/km); IRI_{EOL} is the IRI of the pavement at the end of the PAP, and $IRI_{Terminal}$ is the IRI value beyond which a ride is classified as “very poor” (3.16 m/km).

3.2. LIFE CYCLE COSTS COMPUTATION

Once we had identified and calculated all the cost categories associated with each M&R strategy under assessment, the net present value (NPV) was computed to compare the M&R strategies according to their life cycle economic performance. It allows expenses occurring at different points in time to be summed up on a yearly basis by using a discount rate in the calculations to reflect the “time value of money”. In this case study a real discount rate of 2.3% was used *(13)*.

3.3. RESULTS PRESENTATION AND DISCUSSION

Figure 1 depicts the NPV of the LCC of each M&R alternative and its distribution per pavement life cycle phase. Details on the costs incurred by the several pavement stakeholders in each pavement life cycle phase are available from the author upon request.

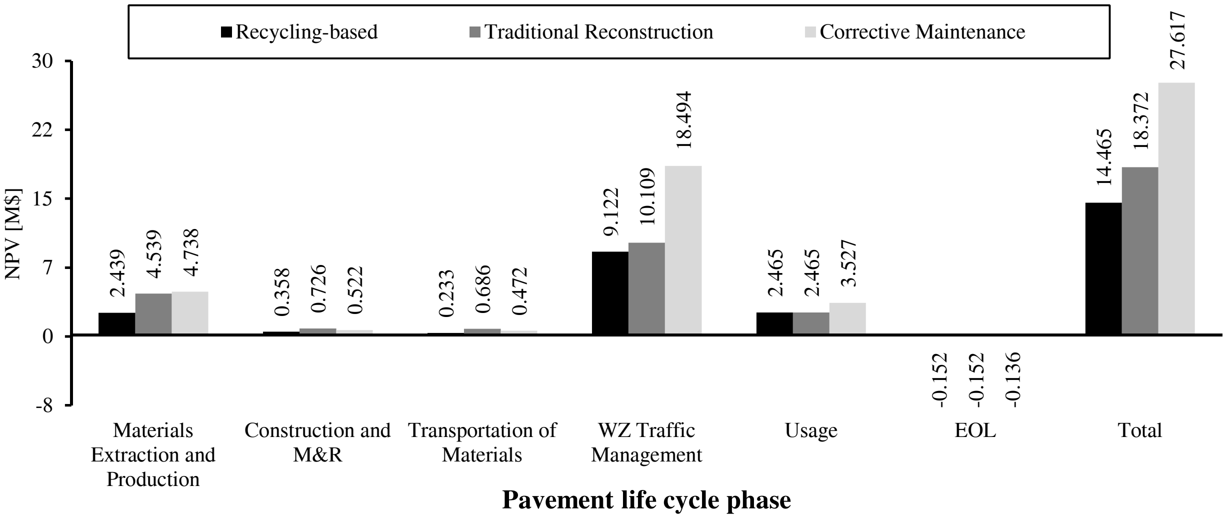
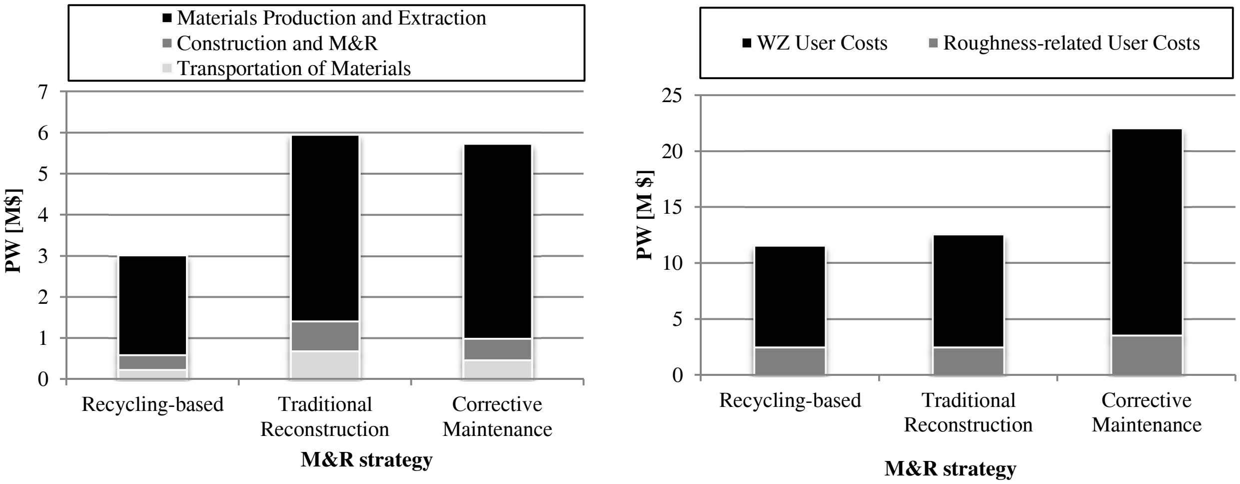


FIGURE 1 Breakdown of the NPV of LCC of each M&R alternative per pavement life cycle phase.

With a life cycle present worth (PW) of about $14.465 million, the recycling-based M&R strategy is the least costly M&R strategy, allowing life cycle net savings of $3.908 million (21%) and $13.152 million (48%) in relation to the expenses incurred with the adoption of the traditional reconstruction and corrective maintenance M&R activities, respectively. In absolute value, the majority of the recycling strategy advantage over the traditional reconstruction strategy is obtained during the materials phase (less $2.100 million), mostly as a consequence of a reduction in the consumption of bituminous-related materials. From a relative perspective, the largest cost saving happens during the transportation of materials phase (66%). With regard to the decrease of the expenditures that are expected to be achieved by implementing the recycling-based M&R strategy compared to a corrective maintenance M&R strategy, the reduction of the WZ traffic management phase costs is the main factor behind this outcome in absolute value (less 9.373 million), whereas from the relative viewpoint the transportation of materials and WZ traffic management phases are both responsible for the most meaningful LCC reduction (51%).

Figure 2 depicts the PW of the total LCC split into highway agency costs and RUC. Two interesting outcomes are: (1) that the traditional reconstruction M&R strategy is more costly to the highway agencies than the corrective maintenance M&R strategy, and (2) the lower preponderance of the usage phase (16-21%) in driving the total RUC in comparison to that of the WZ traffic management phase (79-84%).



(a) (b)

FIGURE 2 PW of the life cycle highway agency costs (a), and RUC (b).

Despite the greater number of M&R activities that need to be implemented throughout the PAP in the case of the corrective maintenance strategy, the first outcome can be explained by the fact that the reconstruction activity requires the removal and consequent transportation of all the materials applied in the existing subgrade/base. Therefore, the economic benefit resulting from the materials phase as a consequence of the reduction of the number of required M&R activities is offset by the greater consumption of human (i.e. labor) and mechanical (i.e. construction equipment and hauling trucks) resources associated with the materials removal.

To explain the second outcome, two main reasons can be pointed out. First, the WZ traffic management plan implemented during the M&R activities of any M&R strategy is exclusively designed to be efficient in dealing with the traffic demand existing in the year 0 of the PAP. In other words, it is unable to prevent road users and freight from experiencing substantial delays when facing the M&R events forecast for the forthcoming years. Second, either M&R strategy allows us to keep the pavement condition throughout the PAP with an IRI level lower than 3 m/km. According to *(9),* this IRI value is the threshold after which vehicle maintenance and repair costs will start to be incurred by the vehicles owners. This fact is particularly important given that *(14)* have shown that for IRI values greater than 3 m/km this cost category may amount to about 58% to 62% of the total usage phase costs. Consequently, its inexistence strongly contributes to the reduction of the total RUC incurred during the usage phase.

To further elaborate on the potential cost differences arising from implementing the recycling-based activity as opposed to the traditional reconstruction activity, the results were separated into extraction and production of materials, transportation of materials, construction and M&R, and WZ traffic management phases. In doing so, the costs incurred by highway agencies and road users due to the M&R activities that are expected to take place in the remaining years of the PAP were disregarded. Table 2 presents the costs of the two M&R activities broken down by pavement life cycle phase, as well as their differences, in absolute value and percentage. Negative numbers mean that the recycling-based M&R activity allows for cost savings in relation to the expenditures associated with the traditional reconstruction, while positive numbers represent additional costs.

TABLE 2 Difference Between the Costs Corresponding to Recycling-Based M&R Activity and Those of the Traditional Reconstruction M&R Activity (K $/lane-km)

M&R activity	Pavement life cycle phase				Total
	Materials extraction and production	Construction and M&R	Transportation of materials	WZ Traffic management	
Recycling-based	87.557	16.874	8.065	158.021	270.517
Traditional Reconstruction	265.719	48.316	46.416	241.680	602.131
Difference	-178.162 (-67%)	-31.442 (-65%)	-38.352 (-83%)	-83.658 (-35%)	-331.614 (-55%)

By looking at the results presented in Table 2 from the perspective of the highway agency, it can be seen that the responsibility for the most meaningful costs savings, in absolute value, resulting from applying the recycling activity is assigned to the materials phase. It shows a reduction of $178.162 thousands/lane-km, or 67% of the costs incurred during the homologous phase of the traditional reconstruction. However, if the analysis is carried out on a relative basis the transportation of materials phase leads highway agencies to the greatest costs savings, as the transportation of materials costs are expected to decrease by 83%, which in absolute value corresponds to a reduction from $46.416 thousands/lane-km to $8.065 thousands/lane-km.

As for the road users, Table 2 unsurprisingly reveals that the adoption of the recycling activity in lieu of the traditional reconstruction can also be beneficial. Road users are likely to take advantage of a costs reduction that amounts to $83.658 thousands/lane-km (35%).

4. -SUMMARY AND CONCLUSIONS

This paper presents the results of a comprehensive LCCA of three M&R strategies for a road pavement segment. A pavement LCC model was developed to assists decision-makers in determining, from a cradle-to-grave perspective, if the current request for the adoption of more environmentally friendly construction and M&R practices is also economically competitive. The results from this case study show that:

- The recycling-based M&R strategy significantly enhances the overall pavements over the life cycle cost by considerably lowering the costs incurred during the materials extraction and production phase;
- Regardless of the type of M&R strategy adopted, the majority of the LCC incurred by highway agencies and road users are due to the materials and WZ traffic management phases, respectively;
- The costs of the bituminous-related materials were found to be the main cost driver of the materials phase, whereas the TDC have revealed a decisive role in determining the WZ traffic management phase's economic performance;
- A reduction of 67% in the costs incurred by highway agencies during the extraction of materials and production phase can be achieved by undertaking the recycling strategy instead of the traditional reconstruction strategy.

To guide highway agencies towards an optimized allocation of resources while meeting environmental concerns, future work on this topic should focus on the development of a decision support system that integrates this LCC model with a LCA model systematically and in parallel.

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