NATIONAL SUSTAINABLE PAVEMENT CONSORTIUM

TPF 5 (268)

Pre-Print

Santos, J., Bryce, J., Flintsch, G. and Ferreira, A. (2017) "A Comprehensive Life Cycle Costs Analysis of In-Place Recycling and Conventional Pavement Construction and Maintenance Practices." *International Journal of Pavement Engineering*, 2017, vol. 18, 2017. pp 727-743.

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

Joao Santos (Corresponding Author)
Ph.D. Student, Road Pavements Laboratory, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, Email: jmos@student.dec.uc.pt

James Bryce
Graduate Research Assistant, Virginia Tech Transportation Institute, Department of Civil and Environmental Engineering, Virginia Tech, 3500 Transportation Research Plaza, Blacksburg, VA 24061, Phone: (573) 289-9236, Fax: (540) 231-1555, Email: jmbp54@vt.edu

Gerardo Flintsch, Ph.D., P.E.
Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute. Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, 3500 Transportation Research Plaza, Virginia Tech, Blacksburg, VA 24061-0105, Phone: (540) 231-9748, Fax: (540) 231-1555, Email: flintsch@vt.edu

Adelino Ferreira, Ph.D.
Director, Road Pavements Laboratory, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788, Coimbra, Portugal, Email: adelino@dec.uc.pt

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

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 environmentally advantageous by an LCA might not be preferred to another one technically equivalent if it is not economically competitive. In this context, it is necessary to evaluate its economic 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 cost (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, and the availability of transport is an essential condition for trade and economic growth. 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. For example, the most recent American Society of Civil Engineers' report card (American Society of Civil Engineering [ASCE], 2013) estimates that maintaining all of the nation's highways at their current condition would cost $101 billion in annual capital investment between 2008 and 2028. Thus, the use of long term scope-based decision support methodologies able to help decision makers in determining the costs of providing road infrastructures service beyond the construction phase, as well as in efficiently allocating road investment funds to competing projects is of capital importance.

Life-cycle costs analysis (LCCA) is an analytical methodology that uses economic principles to evaluate long-term alternative investment options in infrastructure management possess and to select optimum strategies. By comparing the resulting life cycle costs between two or more alternatives an optimal investment alternative can be found that should minimize the total, long-term, cost by finding a suitable trade-off between spending today and future savings (Walls & Smith, 1998). Thus, life-cycle costs (LCCs) involves evaluation of all future costs related to design, construction and/or production, distribution, operation, maintenance and support, retirement, and material disposal; that means all of the phases in the system life cycle (Fabrycky & Blanchard, 1991).

During the last decade, many state department of transportation (DOTs) and researchers have dedicated their efforts on: (1) improving LCCA concepts and methodologies (Salem, Abourizk & Ariaratnam, 2003; Li & Madanu, 2009; Swei, Gregory & Kirchain, 2013; Mirzadeh et al., 2013; Salem et al., 2013) and computer tools (Santos & Ferreira, 2012; Santos & Ferreira, 2013); (2) providing guidance on how to apply and handle the LCCA methodology and their key issues (Walls & Smith, 1998; Federal Highway Administration [FHWA], 2002 and 2003; Hall et al., 2003; Ozbay et al., 2003); (3) documenting how LCCA has been applied by DOTs (Rangaraju, Amirkhanian & Guven, 2008; Chan, Keoleian & Gabler, 2008), and (4) applying the LCCA concept for making comparative assessments of the cost effectiveness of pavement design, materials and maintenance and rehabilitation (M&R) alternatives (Tighe, Haas, & Ponniah, 2007; Amini et al., 2012; Sakhaeifar et al., 2013).

Recently, as the society has becoming more aware of the human activities' effects on the environment, sustainability has started to play a more significant role in the decision-making and planning processes, including those regarding the pavement management. To embrace the concept of sustainability pavement managers 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 both by constructing new pavement structures with the incorporation of recycling materials in the sub-base and base layers and by implementing in-place pavement recycling techniques to rehabilitate distressed pavements (Lee et al., 2010; Thenoux, González & Dowling, 2007; Miliutenko, Björklund & Carlsson, 2013; Santos et al., 2014). However, a solution which is found environmentally advantageous might not be preferred to another one technically equivalent if it is not economically competitive. Although the rehabilitation technique aforementioned 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 is also important to quantify which factors are the key drivers of their economic performance, and what stakeholders are the ones that benefit the most with the application of in-place pavement recycling techniques.

Answering to those questions require a change in a way LCCA has been conducted in the pavement management field. Instead of just a cash flow analysis focused on *ad hoc* information, it would be given a better purpose if used as an accounting method from a process-oriented perspective, allowing to understand the interaction of the contributing costs elements that cumulate among the relevant stakeholders during the different phases of the asset (Lindholm & Suomala, 2005).

To implement the LCC methodology from the aforementioned perspective it is necessary to comprehensively track the consumption of resources in their multiple categories (e.g., raw materials, energy sources, labor, equipment, etc.). Moreover, the operations chain 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 on 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 development.

In summary, there is a growing and significant need for a general LCCA framework that includes a long term scope-based and explicit cost-tracking mechanism, bringing together information from diverse proveniences, and from which would result the basis for the delivery cost computation of the pavement construction and M&R practices. Such a framework is essential to account for the connection between technical changes, production costs and follow up costs, and thus, to provide the decision maker with a complete understanding of construction and M&R activities costs by asset over time, and in a form that can be used either to update or clarify the understanding of assumptions in the pavement management decision-making process.

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 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.

3. Methodology

A comprehensive pavement LCCs model was developed to calculate and compare several categories of costs borne by highway agencies and road users, not only during the application of maintenance and rehabilitation (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 (Santos et al., 2014). Therefore, besides the main references on how to conduct LCCA of pavements (Walls & Smith, 1998; Federal Highway Administration [FHWA], 2002; Federal Highway Administration [FHWA], 2003; Hall et al., 2003), the methodology adopted to develop this model took into account, as far as possible and suitable, the *University of California Pavement Research Center's (UCPRC's) Pavement LCA Guideline* (Harvey et al., 2010).

The pavement LCC model described in this paper is intended to give highway agencies a systematic framework that allow them to get an in-depth perspective of the costs incurred by those stakeholders when performing highway construction and maintenance activities and by other affected stakeholders. This fact led often to the choice of data- and time-intensive sub-models in detriment of other ones, which although being not seldom less data intensive and of easier application to general case studies, do not allow for performing analysis with the same level of detail and customization when applied to specific projects.

The data required to carry out the case study were provided by the Virginia Department of Transportation (VDOT) (Diefenderfer et al., 2012) and gathered from relevant literature.

In order to automatically cross 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) (Loureiro, 2010) and SQL (Damas, 2005) programming languages, the latter used for managing the data introduced and held in the system.

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 Santos et al (2014) for further details)
Traditional Reconstructio n	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 Santos et al (2014) 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 Santos et al (2014) 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.

3.1. *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. However, it should be kept in mind that this study was not intended to be strictly the counterpart of the LCA performed according to the life cycle sustainability assessment (LCSA) scheme defined in Klöpffer (2008), since it imposes several methodological requirements (e.g., the share of the same system boundaries, etc.) that have not been intentionally adopted. Rather, it used the life cycle inventory of resources flows, operating parameters and other exchanges reported in Santos et al. (2014) as a starting basis for modelling the relationships between pavement life cycle phases and the costs supported by highway agencies and road users.

However, the concern of gathering cost information from different entities to implement the LCC methodology is constrained to some extent by supply chain relationships. Then, it may be impossible to gain insight into the costs structure of other supply chain actors with different and competing interests, and with whom the highway agencies interact (e.g., raw materials, energy sources and construction equipment suppliers, etc.). Unless an unlikely joint effort to achieve cost savings beyond the influence of a highway agency is undertaken, there is no way of truly managing the drivers that controls the cost propagation through the supply chain upstream the highway agency. Therefore, this part of the whole pavement's supply chain is left out of the scope of this model. The total value of the costs within the boundaries of those organizations or actors is viewed by the highway agency as a cradle-to-factory gate cost that reflects the complete upstream process. In this case, the market price for a given process input is used as a measure for the aggregated upstream costs, thus not requiring any differentiation and knowledge on the detailed costs and added values of those upstream processes. The same assumption is made with regard to the expenses incurred by the road users due to pavement deterioration and work zone (WZ) traffic management plans (e.g. fuel consumption, oil consumption tires wear, vehicles maintenance and repair, etc.).

Additionally, planning, engineering, design, administrative overhead costs (e.g. office and management, etc.) and profit were not accounted and added to the total highway agency costs because they do not depend on the scope and nature of the work being performed, or in other words, they are not a direct consequence of the pavement management decision-making process. Rather, they are determined by the overall agency and/or contractor structure, scope, size and geographic location, and are allocated according to the organization-specific cost allocation.

Another important clarification which matters to be made regards whether or not, the asphalt mixtures production and delivery should be seen as a product acquired by the highway agency in which only the final cost is important (it falls into the case above mentioned), or as a product produced in-house, and thus requiring a detail process costs analysis that includes accounting for raw materials costs, energy sources costs, transportation of materials costs, etc. Given the core importance of this activity for the pavement management decision-making process, the proposed model handles it from the perspective of a product manufacturer, meaning that the process costs inherent to it are thoroughly analyzed.

The application of the pavement LCC model to the case study presented in this paper aims to:

(1) Estimate the potential economic advantages resulting from applying in-place pavement recycling techniques against two traditional M&R methods;
(2) Demonstrate a methodology that explicitly track the costs resulting from the use of diverse materials, energy sources, equipment and technological processes, allowing to account for the connection between technical aspects, production costs, and costs imposed on other affected stakeholders (i.e., road users);
(3) Identify on 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 for 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[4] 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 life cycle of a road pavement is generally divided into five phases (Harvey et al., 2010). They are the following: materials extraction and production, construction, M&R, usage, and end-of-life (EOL). However, in the proposed model, the costs incurred by road users when facing a work-zone (WZ) traffic management plan (implemented during the reconstruction and M&R activities) are accounted in an individual phase designated as WZ traffic management phase. The WZ traffic management phase was separated out from the construction and M&R phase in order to facilitate the identification, computation and report of the costs borne by different actors (highway agency and road users) who may have conflicting goals. The costs associated with the transportation of materials and asphalt mixtures between facilities and work site, and vice-versa, were also analyzed separately. Therefore, 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) WZ traffic management; (5) usage, and (6) EOL. The various models evoked while computing the costs incurred during each pavement life cycle phase, as well as the data required to run those models, 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 cost provided by DOTs comprises manufacturing and transportation of raw materials, manufacturing of mixtures, labor, overhead, profit margins and other costs into 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 to 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 compose the asphalt mixtures, as well as those that are directly applied at the work site (e.g., lime, hydraulic cement, etc.); (2) energy sources costs, referring specifically to the cost of the energy required to produce the asphalt mixtures, and (3) asphalt plant operating costs, representing the costs incurred due to the operation of the asphalt plant. This last category was further divided into fixed and variable costs sub-categories. The fixed costs sub-category refer 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; (4) insurance; (5) taxes, licensing and permits; (6) utilities, and (7) the 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 and real estate purchase were disregarded.

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

The unit costs adopted to calculate the several category and sub-categories of costs incurred during this pavement life cycle phase are presented in Tables 2, 3 and 4.

Table 2. Unit costs of the raw materials items (in 2011 US dollars).

Raw material item	Unit cost		Data Source
	Units	Value[a]	
Bitumen	$/tonne	653.94	VDOT (http://www.virginiadot.org/business/const/indices-previous.asp)
Calciment	$/tonne	76.98 [b]	United States Army Corps of Engineers (2011a)
Hydraulic cement	$/tonne	76.81	United States Geologic Services (2013a)
Bitumen emulsion	$/tonne	792.52	Virginia Paving Company (www.virginiapaving.com)
Crushed aggregates	$/tonne	10.73 [c]	United States Geologic Services (2013b)
Fine aggregates	$/tonne	10.96[c]	United States Geologic Services (2013b)

[a]Free On Board costs.

[b]Value bid adopted by the material supplier: Mintek.

[c]Data referring to aggregates sold or used by producers and use in 2011, in the state of Virginia.

Table 3. Unit costs of the energy sources items (in 2011 US dollars).

Energy source item	Unit cost		Unit cost
	Units	Value	
Diesel	$/liter	1.00	Unites States Energy Information Administration [US EIA](2014a)
Electricity	$/kWh	0.065[a]	Unites States Energy Information Administration [US EIA](2014b)
Natural gas	$/m^3	227.43[a]	Unites States Energy Information Administration [US EIA](2014c)
Gasoline	$/liter	0.93	Unites States Energy Information Administration [US EIA](2014a)

[a]Industrial sector price.

Table 4. Unit values of the asphalt plant operating costs items (in 2011 US dollars).

Sub-category	Item	Unit cost [$/ tonne of asphalt mixture] [a]	Data Source
Fixed	Asphalt plant depreciation costs	0.75[b]	Morgan (2005)[c]
	Auxiliary equipment depreciation costs	0.32[d]	Morgan (2005)[c]
	Utilities (water and electricity)	0.66[e]	Morgan (2005)[c]
	Licensing, taxes and general operation permits	0.09[f]	Estimated
	Insurance	0.18[g]	Estimated
	Labor: asphalt plant operator	0.63[h]	Unites States Department of Labor (2011a)
	Labor: wheel loader operator	0.46[i]	Unites States Department of Labor (2011a)
	Labor: maintenance technician	0.48[j]	Unites States Department of Labor (2011a)
Variable	Asphalt plant maintenance and repair	1.00	Morgan (2005)[c]
	Diesel consumed by the wheel loader	0.24[k]	Unites States Energy Information Administration [US EIA](2014a)
	Anti-strip additive	0.50[l]	Epps, Berger & Anagnos (2003)

[a]The calculation procedure relies on the average annual asphalt mixtures production per plant (114,000 tonnes) during the year of 2011 in Virginia (Hansen & Copeland, 2013).

[b]Value obtained by considering an acquisition cost of $1,500,000.00 depreciated throughout 15 years and a residual value equal to 15% of the acquisition cost ($225,000.00).

[c]Since these unit costs depend on a huge quantity of factors, the values reported by this source were used as reference in setting representative values.

[d]Includes the acquisition costs of the following auxiliary equipment: quality control laboratory ($100,000.00; 15 years; 15%), anti-strip system ($20 000.00; 8 years; 15%), platform scales ($45,000.00; 15 years; 15%) and wheel loader ($246,000.00; 8 years; 15%). Where ($; years; %) stands for (acquisition cost; depreciation period; residual value as percentage of the acquisition cost).

[e]Although the utilities cost comprises a fixed and a variable component, the total cost was assigned to the fixed sub-category due to the absence of more detailed information that would allow for a further division of this item.

[f]Based on an annual value of $10,000.00.

[g]Based on 1% of the value of all assets existing in the facility.

[h]Value obtained by considering the annual 90th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (Unites States Department of Labor, 2011b).

[i]Value obtained by considering the annual 50th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (Unites States Department of Labor, 2011b).

[j]Value obtained by considering the annual 50th percentile total compensation for the "Maintenance and Repair Workers, General" occupational group in Virginia. It results from considering the wages and salaries equal to 68% of the total compensation (Unites States Department of Labor, 2011b).

[k]Energy consumption corresponding to the operation of a wheel loader Caterpillar 950K estimated according to the rate at which the wheel loader can move aggregates and the methodology adopted by the US EPA's NONROAD 2008 model (United States Environmental Protection Agency [US EPA], 2010a). See Santos et al. (2014) for further details.

[l]Based on an additive usage rate of 0.5% by weight of the binder (Diefenderfer & Hearon, 2010). The 2003 price was escalated to 2010 dollars by using the Producer price index (PPI) for "material and supply inputs to highway and street construction sector". The 2010 year is the last year to which the annual index is known.

3.1.2.2. *Construction and M&R phase*

The construction and M&R phase costs include the 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 time. They comprise: (1) the construction equipment owning costs (i.e. depreciation, insurance, interests, taxes and licenses); (2) construction equipment operation costs (i.e. fuel consumption, equipment routine maintenance, equipment repairs, tire wear, special wear items, mobilization and demobilization), and (3) 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 places are accounted for in individual phases. A detailed description of the LCC model formulation referring to this pavement life cycle phase can be found in Supplemental material 1.1.

Data required for computing the various subcategories of construction equipment owning and operating costs were collected for each piece of equipment according to the information made available by equipment manufacturers, suppliers and dealers, or existing in the literature (United States Army Corps of Engineers, 2011b; Caterpillar Inc., 2012). Table 1.1 in Supplemental material 1.1 displays the values of the variables corresponding to each piece of equipment required to perform the M&R actions that constitute the M&R activities considered in the case study analyzed in this paper.

Finally, the labor costs were calculated according to the data displayed in Table 1.2 presented in Supplemental material 1.1. The number of workers needed for carrying out the several M&R actions that comprise a given M&R activity was estimated according to data gathered in the field during visits to similar recycling projects, or existing in the literature (European Asphalt Pavement Association [EAPA] & National Asphalt Pavement Association [NAPA], 2011).

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 owning costs; (2) hauling trucks operation costs, and (3) labor costs. The two first categories were further divided into several subcategories as shown in Supplemental material 1.2. The meaning of each costs category and subcategory, its respective formulation and the values of the variables required to calculate them are presented in Supplemental material 1.2.

3.1.2.4. *WZ traffic management phase*

Whenever an M&R activity takes place on a highway segment, it is likely that the drivers who make trips on those highways segments will experience changes in their normal travelling patterns, such as slowdowns, which force vehicles to be operated at less than-optimal speeds, and detours (either externally or driver's self-impose) that requires drivers to increase the distance travelled.

Operating a vehicle in those WZ conditions result commonly in additional costs to the road users. Therefore, the WZ traffic management costs comprise the additional costs borne by the road users (RUC) when facing a 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 (TDCs), and (2) vehicle operating costs (VOCs). 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 with the WZ). The methodologies adopted to calculate these costs are presented in the following sections.

3.1.2.4.1 Time delay costs (TDCs)

The TDCs regard the difference between the cost of the time spent by the vehicle's occupants and goods while travelling at detour speed or WZ reduced speed, and that corresponding to transverse the highway WZ section at the normal operating speed during a non-WZ period. Four types of WZ delays were considered to contribute to the total TDCs: (1) the time necessary to decelerate from the upstream approaching speed to the WZ speed and then to accelerate back to the initial approaching speed after traversing the work zone under unrestricted traffic flow; (2) the time required to go through the WZ section at the WZ speed; (3) the idling time corresponding to stop-and-go driving conditions in the upstream queue, and (4) time required to travel the additional distance resulting from detouring around the WZ section.

The capacity and delay models proposed by the Highway Capacity Manual 2000 (Transportation Research Board [TRB], 2000) were used to determine, in each hour of a WZ period, the number of vehicles that undergo a variation in their normal operation speed and the distance during which it is experienced. Finally, to calculate the TDCs, the estimated delays to personal travel, business travel, and freight inventory caused by the WZ is multiplied by the unit cost ($/hr) of travel time. The monetary value of the time loss for users and goods while traveling through the WZ or detouring was estimated according to the United States Department of Transportation (US DOT) Office of the Secretary of Transportation (OST)'s guidelines and procedures for calculating the value of travel time saved or lost by road users (United States Department of Transportation [US DOT], 2003). It relies on the concept that time spent traveling otherwise would have been spent productively, whether for remunerative work or recreation (Mallela & Sadasivam, 2011). The unit cost of travel time for the several categories of vehicles is presented in Table 5. The values of the main parameters used in the computation of the unit costs of travel time are presented in Supplemental material 1.3.

Table 5. Unit cost of travel time for the several categories of vehicles (in 2011 US dollars).

Vehicle category	Unit cost of travel time [$/hr]
Hourly time value of passenger cars (PCs)	28.70
Hourly time value of single-unit trucks	22.42
Hourly time value of combination-unit trucks	29.27
Hourly freight inventory costs for single-unit trucks	0.21
Hourly freight inventory costs for combination-unit trucks	0.31

3.1.2.4.2 Vehicle operation costs (VOCs)

The WZ-related VOCs represent the costs incurred by the vehicle drivers due to the vehicle owning, 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 transverse the highway WZ section at the normal operating speed during a non-WZ period. Five types of VOCs subcategories were considered to contribute to the total VOCs: (1) fuel consumption; (2) oil consumption; (3) tire wear; (4) vehicle maintenance and repair, and (5) vehicle depreciation. The costs of operating a vehicle on a given road section are obtained by multiplying the "consumption" of the aforementioned subcategories with the corresponding unit cost.

The methodology adopted for quantifying the additional VOCs resulting from changes in traffic flow conditions consisted of initially modelling each cost subcategory separately, and posteriorly summing them to obtain the total VOCs value. This modelling procedure was adopted in order to ensure the coherence with the work performed by Santos et al. (2014) and to allow for a better integration with the subsequent research work. The fuel consumption was determined using the United States Environmental Protection Agency (US EPA) Motor Vehicle Emissions Simulator (MOVES) (United States Environmental Protection Agency [US EPA], 2010b) as detailed by Santos et al. (2014). The speed-constant and speed-change cycles HERST-ST sub-models (Federal Highway Administration [FHWA], 2005) were considered in calculating the rates of oil consumption, tire wear and maintenance and repair. Finally, the vehicle depreciation costs were equally estimated according to the methodology outlined in the HERS-ST Technical Report (Federal Highway Administration [FHWA], 2005). It relies on the assumption that vehicles depreciate both as a result of their usage and their aging, which is independent of the vehicle use. Thus, the time lost by the occupants of the different vehicle categories while traversing or detouring a WZ was considered to contribute to the time-related depreciation costs, whereas the additional distance travelled to detour the WZ was assumed to contribute to the mileage-related depreciation costs.

The unit costs expressed in 2011 US dollars, and respective data sources, required to compute the additional VOCs incurred during the WZ period are display in Table 6. To estimate the costs referring to the beginning of the PAP (year 2011), the unit costs were accordingly multiplied by standard prices indices, such as Consumer Prices Index (CPI) and Producer Prices Index (PPI).

Table 6. Unit costs of the WZ-related VOC subcategories (in 2011 US dollars).

WZ-related VOC subcategory	Cost units	Unit costs per vehicle category			Data source
		PC	Single-unit truck	Combination-unit truck	
Fuel: gasoline	$/liter	0.93	-	-	Unites States Energy Information Administration [US EIA](2014a)

Fuel: diesel	$/liter	-	1.00	1.00	Unites States Energy Information Administration [US EIA](2014a)
Oil	$/ liter	9.58	3.83	3.83	Federal Highway Administration [FHWA] (2005)
Tires	$/tire	93.11	613.32	613.32	Federal Highway Administration [FHWA] (2005)
Maintenance and repair	$/1000 miles	158.79	553.23	553.23	Federal Highway Administration [FHWA] (2005)
Time-related depreciation	$/hr	1.23	3.16	9.57	Federal Highway Administration [FHWA] (2005)
Mileage-related depreciation	$/hr	0.58	0.49	2.20	Federal Highway Administration [FHWA] (2005)

3.1.2.5. *Usage phase*

The usage phase costs, frequently named non-WZ RUC, account for the marginal VOCs supported by the vehicle drivers 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 VOCs model developed by Chatti & Zaabar (2012) as result of the calibration of the HDM-4 VOCs model to consider U.S. conditions.

In order to allow for an automatic computation of the usage phase costs categories and an easy integration with the remaining LCC sub-models, the Chatti & Zaabar’s model was run multiple times to compute a set of unit cost factors representing the usage phase costs originated by the full range of IRI values that are likely to be measured over the PAP in the three M&R strategies in comparison. The model runs were conducted in a step wise way, keeping constant the surface texture, pavement grade and unit traffic composition, but changing the temperature according to the Stauton’s monthly average air temperature in the months of February, April and June. The generated unit cost factors referring to each usage phase costs category were plotted and trend lines following a linear equation were fitted to the data. The unit cost factors obtained by using those equations were then combined accordingly to derive, for each cost category, the unit cost factors representing both the Stauton’s annual average climatic conditions and the road segments’ pavement condition.

With regard to the mileage-related depreciable value, the study carried out by Barnes & Langworthy (2003) was used to estimate the effect of the pavement roughness on vehicle depreciation costs. It relies on the assumption that a vehicle driven almost exclusively on smooth highways will be able to travel more kilometers than one that is driven mostly on rough pavement. Therefore, since mileage-related depreciation is reflecting the loss in “life expectancy” of the vehicle as it is driven more, factors that reduce the ultimate number of kilometers that the car can be driven must be taken into account by increasing the rate at which the car depreciates.

The Equation (1) was incorporated into the LCC model to estimate the marginal effects of pavement roughness on the mileage-related depreciable value. It was developed by fitting a function in the form of the Equation (1) to the adjustment factors reported by Barnes & Langworthy (2003) to estimate VOCs as a function of pavement condition taking as baseline an IRI value of 1.2 m/km.

$$AF_{Mileage\text{-}related\,depreciation} = a \times IRI^2 + b \times IRI + c \,, \qquad (1)$$

where $AF_{Mileage\text{-}related depreciation}$ is adjustment factor that represent the effect of pavement roughness on VOC, and IRI is the International Roughness Index [m/km]. The values of the parameters *a*, *b* and *c* were found to be 0.0125, 0.0225 and 0.9625, respectively. The value for R^2 in Equation (1) is 0.9966.

3.1.2.6. *End-of-life phase*

When a road pavement reaches its service life, it can be given two main destinations: (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 (increasingly less 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 that reflect the remaining worth of a pavement at the end of the PAP. In the case that the pavement is considered to remain in place after reaching the end of the PAP, the residual value is designated as remaining service life value and refers to the value (positive cash flow) of the structural and functional life remaining in the pavement at the end of the PAP. On the other hand, if the pavement is expected to be demolished once reached the end of the PAP, then the residual value is designated as salvage value and refers to either: (1) the net value of the recycled materials (the monetary value of the recycled materials minus the costs of removal, transportation and recycling) if the pavement debris are supposed to be recycled, or (2) the sum of the costs resulting from the removal, transportation and landfilling of the pavement debris in the case that the pavement it is supposed to be landfilled.

In the case study the most likely EOL scenario for the analyzed pavement structure is that it remains 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 exceed 3.16 m/km (200 in/mile), which according to the VDOT's Highway System Performance Dashboard (Virginia Department of Transportation [VDOT], 2012) 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 the Equation (2) was adopted. It quantifies the residual value of the pavement as the proportion of the total highway agency costs incurred due to the application of the last M&R activity equal to the proportion of the remaining life of that M&R activity (Walls & Smith, 1998).

$$C_{EOL\,phase} = C_{Last\,M\&R\,activity} \times \frac{IRI_{Terminal} - IRI_{EOL}}{IRI_{Terminal} - IRI_{Initial}}, \tag{2}$$

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 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 (Equation 3). 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. It follows the Office of Management and Budget (OMB)'s guidelines for conducting benefit-cost of federal programs with durations longer than 30 years for the calendar year of 2011 (Office of Management and Budget [OMB], 2013).

$$NPV = \sum_{i=0}^{all\,life\,cycle\,phases} \sum_{t=0}^{T+1} \left[\begin{array}{l} X_i \times X_t \times \sum_{j=0}^{NCostCateg_i} \sum_{k=0}^{NCostSubCateg_{ij}} \frac{C_{ijk}(t)}{(1+d)^t} + \\ (1-X_i)\times(1-X_t)\times \sum_{j=0}^{NCostCateg_{EOL}} \sum_{k=0}^{NCostSubCateg_{EOLj}} \frac{C_{EOLjk}(t)}{(1+d)^t} \end{array} \right], \quad (3)$$

where NPV is the net present value of the total LCCs of a given M&R strategy; i is the pavement life cycle phase; T is the number of years of the PAP; X_i is a factor equal to one if i is not equal to EOL phase, otherwise it is equal to zero; X_t is a factor equal to one if t is lower or equal to T, otherwise it is equal to zero; $C_{ijk}(t)$ is the value in the year t of the costs subcategory k belonging to the costs category j accounted for during the pavement life cycle phase i; $NCostCateg_i$ is the number of cost categories considered in the pavement life cycle phase i; $NCostSubCateg_{ij}$ is the number of costs subcategories belonging to the cost category j accounted for during the pavement life cycle phase i, and; $C_{EOLjk}(t)$ is the value in the year $T+1$ of the costs subcategory k belonging to the costs category j accounted for during the EOL phase; $NCostCateg_{EOL}$ is the number of cost categories considered in the EOL phase; $NCostSubCateg_{EOLj}$ is the number of costs subcategories belonging to the cost category j accounted for during the EOL phase, and d is the discount rate.

4. Results and discussion

The following sections provide an overview and discussion of the outcomes obtained by applying the pavement LCC model to the case study. Firstly, the costs incurred by the several pavement stakeholders in each pavement life cycle phase are introduced. Secondly, the total LCCs corresponding to each M&R strategy are presented and compared. Thirdly, a sensitivity analysis is performed to enhance the understanding of the sensitivity of the results to variation of the input parameters.

4.1. *Costs per pavement life cycle phase*

4.1.1. *Materials extraction and production phase*

Table 7 shows the present worth (PW) of the LCCs incurred by the highway agency during the materials extraction and production phase corresponding to each M&R strategy. They are estimated at approximately $2,438,588 for the recycling-based M&R strategy, $4,538,675 for the traditional reconstruction M&R strategy, and $4,737,806 for the corrective maintenance M&R strategy. According to these values, the recycled-based M&R strategy would allow highway agency savings throughout the pavement life cycle of about $2,299,217 (49%) and $2,100,086 (46%) relatively to the expenses incurred during the homologous phase of the corrective maintenance and traditional reconstruction strategies, respectively.

Regarding the contributions of the several categories to the total cost, the raw materials costs were found to be by far the main costs driver of this pavement life cycle phase. Its contribution ranges between 87% (traditional reconstruction and corrective maintenance strategies) and 88% (recycling-based strategy), whereas the costs incurred with the remaining categories do not exceed 6% of the total share in all M&R strategies.

To give insights on which elements are behind of such an expressive contribution and to what extent they dominate de costs incurred by highway agencies during this life cycle phase, Figure 1 shows the breakdown of the PW of the total life cycle raw materials costs. As can be seen from the aforementioned Figure, the majority of the costs assigned to this category are due to the consumption of the asphalt binder. It represents 76%, 65% and 76% of the PW of the total life cycle raw materials costs corresponding to the recycling-based, traditional reconstruction and corrective maintenance M&R strategies, respectively. On the other hand, the consumption of aggregates although being 16, 28 and 17 times (in mass) greater than the consumption of asphalt binder represents nothing but 19%, 33% and 21% of the PW of the total life cycle raw materials costs. Therefore, the adoption of construction and M&R solutions that do not rely exclusively on the application of virgin bituminous-related materials, such as in-situ recycling techniques, are demonstrated to be an effective way of lowering the highway agency expenditures.

Table 7. Materials extraction and production phase costs per cost category for each M&R strategy.

M&R strategy	Asphalt plant operation costs: fixed [$]	Asphalt plant operation costs: variable [$]	Raw materials [$]	Energy [$]	Total [$]
Recycling-based	140,995 (6%)	68,837 (3%)	2,143,750 (88%)	85,006 (3%)	2,438,588
Traditional reconstruction	274,610 (6%)	134,072 (3%)	3,964,745 (87%)	165,247 (4%)	4,538,675
Corrective maintenance	305,642 (6%)	149,222 (3%)	4,098,819 (87%)	184,122 (4%)	4,737,801

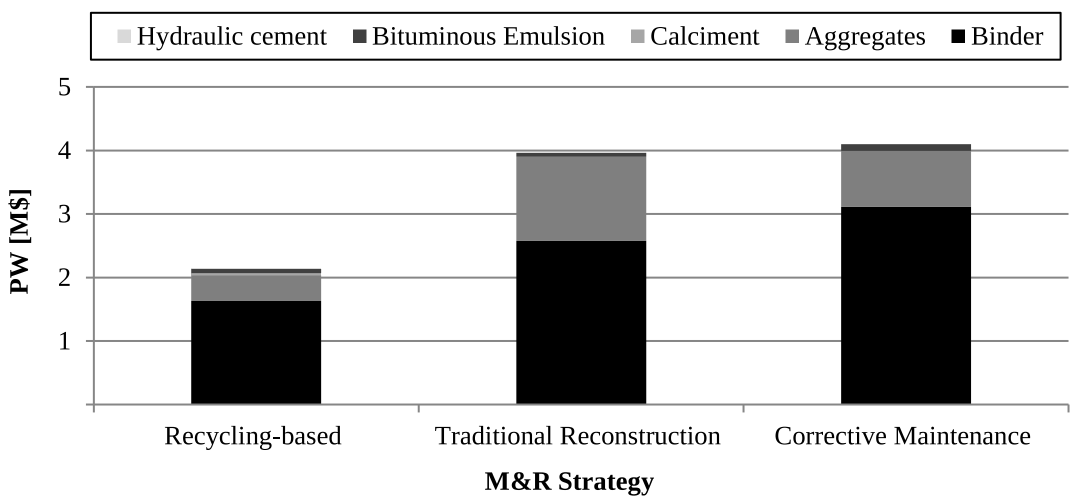


Figure 1. Breakdown of the raw material cost category for each M&R strategy.

4.1.2. *Construction and M&R phase*

Table 8 displays the PW of the LCCs incurred by highway agency during the construction and M&R phase corresponding to each M&R strategy. The total costs associated with the ownership and operation of the construction equipment over the pavement life cycle ranges from $358,230, for the recycling-based strategy, to $726,126 for the traditional reconstruction strategy. The majority of the costs supported by the highway agency during this phase are due to the labor costs (38%-42%), followed by the cost of the fuel consumed (17%-18%), the costs of the construction equipment repair (15%) and the construction equipment capital costs (12%-13%), respectively. The costs associated with the allocation of the construction equipment to the work site represent a small share of the total costs (6%-7%), whereas the contribution of the remaining subcategories is almost negligible (less than 2%).

Looking at the life cycle construction and M&R costs associated with the application of the various competing M&R strategies, the recycling-based strategy denotes a remarkable economic advantage relatively to the traditional reconstruction and corrective maintenance strategies. It would allow life cycle highway agency savings of about 51% and 31%, respectively.

4.1.3. *Transportation of materials phase*

Table 9 reveals the PW of the LCCs incurred by highway agency during the transportation of materials phase corresponding to each M&R strategy. The results presented in Table 9 shows that the vast majority of the materials transportation costs comes from the labor costs category, which was found to be responsible for 53%-55% of the total life cycle transportation of materials costs. The two remaining costs categories (i.e. owning and operating costs) represent nearly 9 % and 37% of the total LCCs incurred during this phase. The main contributors to these outcomes are hauling trucks capital costs (5%-6%) and the cost of the fuel consumed (25%-26%), respectively. The plausibility of such results is sustained by the American Transportation Research Institute (ATRI) that reports, on an annual basis, the operational costs of trucking. According to the 2013 updated version of this report (Fender & Pierce, 2013), driver wages and fuel costs were also found to constitute the majority of costs supported by motor carriers in 2011.

When comparing the various M&R strategies according to their economic performance during this pavement life cycle phase, the recycling-based strategy evidence an outstanding performance relatively to that of the competing alternatives. For the conditions considered in this study a reduction of approximately 66% and 51% in the total life cycle materials transportation costs can be achieved relatively to those of a traditional reconstruction and corrective strategies, respectively.

4.1.4. *WZ traffic management phase*

Table 10 illustrates the PW of the additional life cycle WZ traffic management costs associated with the application of M&R activities. As can be seen in this Table, the TDCs are the main contributors to the life cycle WZ traffic management costs. This result is strongly attributable to the cost of the additional time required to creep through the queues under forced flow conditions and to transverse both the WZ and the detour at the lower posted speed. They represent 62%-68% and 11%-17%, respectively, of the total life cycle RUC incurred during this pavement life cycle phase. Less expressive than the previous subcategories but equally worthy of mention is the relative importance of the cost of the fuel consumed within the set of costs that constitute the WZ traffic management phase costs. With a LCC ranging between $855,968 (recycling-based M&R strategy) and $1,678,343 (traditional reconstruction M&R strategy), it was found to be responsible for 9%-10% of the life cycle RUC accounted for this phase. In contrast, several cost subcategories, such as vehicle maintenance and repair costs and mileage-related vehicle depreciation costs denoted a negligible share of the total costs (slightly greater than 0%).

Regarding the economic performance of the competing M&R strategies, the recycling-based strategy was found to outperform the remaining ones, allowing road user savings of $987,168 (10%) and $9,372,764 (51%) relatively to the expenses incurred during the homologous phase of the traditional reconstruction and corrective maintenance strategies, respectively. When compared with the traditional reconstruction strategy, its advantage results from the lower time required to complete the recycling-based M&R activity relatively to that of the traditional reconstruction. In the opposite side, the corrective maintenance strategy exhibited the poorest economic performance. From the broader point of view of the life cycle, this M&R strategy is particularly penalizing for the road users due to the greater number of M&R activities that need to be performed during this M&R strategy comparatively to that for the remaining M&R strategies.

Table 8. PW of the LCCs incurred by the highway agency during the construction and M&R phase per cost subcategory for each M&R strategy.

M&R strategy	Owning costs [$]				Operating costs [$]						Labor [$]	Total [$]
	Capital	Interest	Insurance	Taxes	Fuel consumption	PM and FOG	Repair	Tire wear	Special wear items	Mobilization		
Recycling-based	44,100 (12%)	1,744 (0%)	8,158 (2%)	5,439 (6%)	65,422 (18%)	7,742 (2%)	54,175 (15%)	4,724 (1%)	1,943 (1%)	21,428 (6%)	143,355 (40%)	358,230 (100%)
Traditional Reconstruction	92,741 (13%)	3,755 (1%)	17,857 (2%)	11,904 (2%)	131,415 (18%)	16,129 (2%)	109,764 (15%)	9,024 (1%)	13,313 (2%)	42,373 (6%)	277,852 (38%)	726,126 (100%)
Corrective Maintenance	60,641 (12%)	2,387 (0%)	10,990 (2%)	7,327 (1%)	87,596 (17%)	10,423 (2%)	75,996 (15%)	9,273 (2%)	859 (0%)	34,727 (7%)	221,890 (42%)	522,108 (100%)

Notes: PM and FOG, planned maintenance and filters, oil and greases.

Table 9. PW of the LCCs incurred by the highway agency during the transportation of materials phase per cost subcategory for each M&R strategy.

M&R strategy	Owning costs [$]				Operating costs [$]				Labor [$]	Total [$]
	Capital	Interest	Insurance	Taxes	Fuel consumption	PM and FOG	Repair	Tire wear		
Recycling-based	13,353 (6%)	854 (0%)	4,415 (2%)	2,944 (1%)	61,786 (26%)	7,353 (3%)	14,581 (6%)	3,234 (1%)	124,704 (53%)	233,224 (100%)
Traditional Reconstruction	35,061 (5%)	2,442 (0%)	13,046 (2%)	8,697 (1%)	176,404 (26%)	20,992 (3%)	40,182 (6%)	9,262 (1%)	379,527 (55%)	685,612 (100%)
Corrective Maintenance	25,902 (5%)	1,727 (0%)	9,070 (2%)	6,047 (1%)	119,971 (25%)	14,277 (3%)	29,357 (6%)	6,627 (1%)	258,988 (55%)	471,965 (100%)

Notes: PM and FOG, planned maintenance and filters, oil and greases.

Table 10. PW of the marginal life cycle RUC incurred during the WZ traffic management phase per cost subcategory for each M&R strategy.

M&R strategy	Vehicle Operation Costs (VOCs) [$]						Time delay costs (TDCs) [$]	Total [$]
	Fuel consumption	Oil consumption	Tire wear	Vehicles maintenance & repair	Vehicles time-related depreciation	Vehicles mileage-related depreciation		
Recycling-based	855,968 (9%)	86,414 (1%)	43,084 (0%)	152 (0%)	851,363 (9%)	19,460 (0%)	7,265,082 (80%)	9,121,523 (100%)
Traditional Reconstruction	967,485 (10%)	96,855 (1%)	50,777 (1%)	182 (0%)	935,501 (9%)	24,388 (0%)	8,033,503 (79%)	10,108,692 (100%)
Corrective Maintenance	1,678,343 (9%)	268,001 (1%)	117,693 (1%)	392 (0%)	1,736,790 (9%)	30,020 (0%)	14,663,049 (79%)	18,494,287 (100%)

4.1.5. *Usage phase*

Table 11 illustrates the PW of the marginal life cycle usage phase costs per cost category for each M&R strategy. From the results in Table 11, the corrective maintenance M&R strategy was found to be the least suitable for the road user's interests, as it requires vehicle owners to spend more $1,061,820 (43%) throughout the pavement life cycle comparatively to what it is predicted to be spent in the same time period in the case that either a recycling-based or a traditional reconstruction M&R strategy is adopted. The fact that the recycling-based and traditional reconstruction M&R strategies entail the same life cycle roughness-related RUC is related to the schedule and features of the M&R actions included in the M&R strategies, and respective consequences on pavement performance. As thoroughly discussed in Santos et al. (2014) both M&R strategies are expected to originate the same pavement deterioration pattern.

An interesting result that can be seen in Table 11 regards the fact that no additional vehicle maintenance and repair costs are expected to be incurred throughout the 50-year PAP. Although seeming unlikely, two main explanations can be listed to support this outcome: (1) Chatti & Zaabar (2012) showed that there is no effect of roughness on vehicle maintenance and repair costs up to an IRI of 3 m/km and (2) according to the roughness prediction models developed by Santos et al. (2014) and applied in this case study, the pavement roughness, as measured by IRI, is never expected to reach that threshold value throughout the life cycle of any M&R strategy.

Contrasting with the vehicle maintenance and repair costs category, the greatest share of the life cycle usage phase costs is attributable to the fuel consumption, from which it is expectable a relative contribution that amounts up to 59%. On the other hand, the tire wear costs category denotes a reduced relative contribution (4%), whereas the vehicle mileage-related depreciation costs category exhibits an intermediate relevance by accounting for 37% of the PW of the total life cycle costs.

Table 11. PW of the marginal life cycle RUC due to pavement roughness per cost category for each M&R strategy.

M&R strategy	Fuel consumption [$]	Tire wear [$]	Vehicles maintenance & repair [$]	Vehicles mileage-related depreciation [$]	Total [$]
Recycling-based	1,465,882 (30%)	96,674 (2%)	0 (0%)	902,588 (18%)	2,465,145 (100%)
Traditional Reconstruction	1,465,882 (59%)	96,674 (4%)	0 (0%)	902,588 (37%)	2,465,145 (100%)
Corrective Maintenance	2,067,987 (59%)	136,383 (4%)	0 (0%)	1,322,595 (37%)	3,526,964 (100%)

4.1.6. *End-of-life phase*

Table 12 presents the PW of the EOL phase costs for each M&R strategy. In this case study the EOL phase costs represent the residual value of the pavement structures and are given by the value of the remaining service life. Thus, they are better designated as a credit given to the highway agency rather than a cost incurred by this authority. This fact explains the negative values of the cost displayed in Table 12. As can be seen in this table, regardless the M&R strategy adopted the IRI value at the end of the PAP is approximately the same. However, as the discounted total cost incurred by the highway agency with the application of the last M&R activity is lower for the corrective maintenance strategy than for the remaining competing strategies, the former M&R strategy entails a credit to the highway agency that is approximately 11% lower than that associated with the recycled-based and traditional reconstruction strategies.

Table 12. PW of the EOL cost incurred by the highway agency for each M&R strategy.

M&R strategy	Total highway agency costs corresponding to the last M&R Activity [$]	IRI at EOL [m/km]	EOL cost (Residual value) [$]
Recycling-based	163,363	1.03	- 151,932
Traditional reconstruction	163,363	1.03	- 151,932
Corrective maintenance	145,394	1.02	- 135,856

4.2. *Total life cycle costs*

Figure 2 depicts the NPV of the LCCs of each M&R strategy and its distribution per pavement life cycle phase. Table 13 shows the difference in the PW of the LCCs associated with each phase of the recycled-based strategy relatively to those of the traditional reconstruction and corrective maintenance strategies. Those results are to be understood as follows: negative relative numbers mean that the recycling-based M&R strategy allows for cost savings in relation to the expenditures associated with the traditional reconstruction and corrective maintenance strategies, while positive numbers represent additional costs.

With a life cycle PW of about $14.465 million, the recycling-based strategy is the least costly M&R strategy, allowing life cycle net savings of $3.908 million (21%) and $13.152 million (48%) relatively to the expenses incurred with the adoption of the traditional reconstruction and corrective maintenance strategies, respectively. In absolute value, the majority of the recycling-based strategy's life cycle economic 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 savings happens during the transportation of materials phase (66%). With respect to the decrease of the expenditures that are expected to be achieved by implementing the recycling-based strategy in detriment of a corrective maintenance M&R strategy, the reduction of the WZ traffic management phase costs (less $9.373 million) is the main factor behind this result in absolute value, whereas from the relative standpoint the transportation of materials and WZ traffic management phases are both responsible for the most meaningful LCCs reduction (51%).

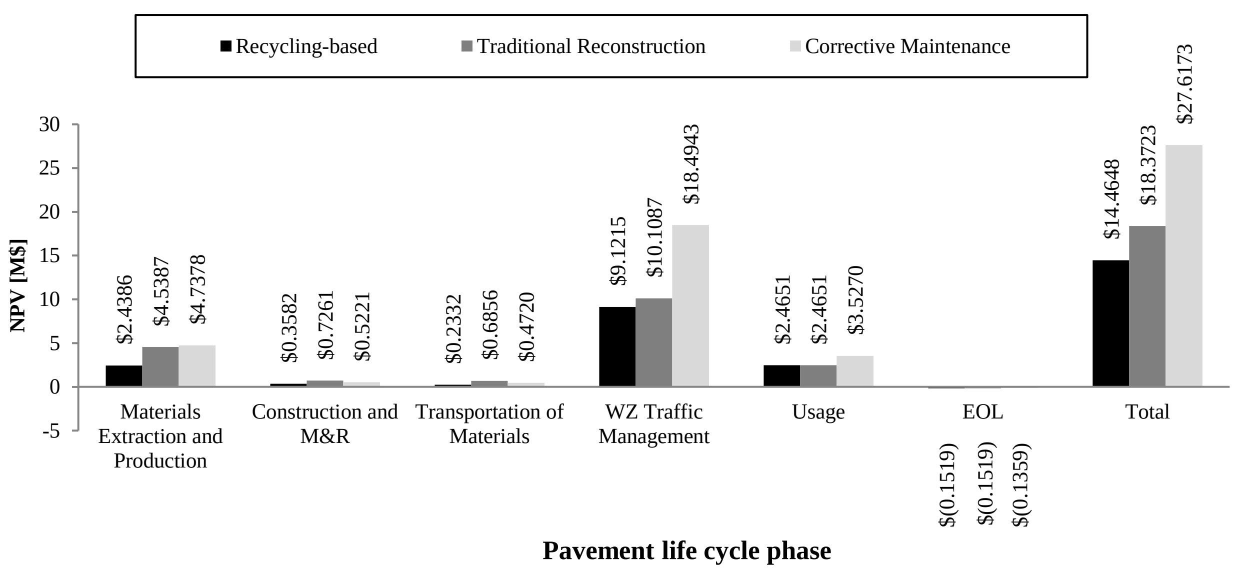


Figure 2. Breakdown of the NPV of LCCs of each M&R alternative per pavement life cycle phase.

Table 13. Difference between the PW of the LCCs associated with each phase of the recycled-based strategy and those of the traditional reconstruction and corrective maintenance strategies.

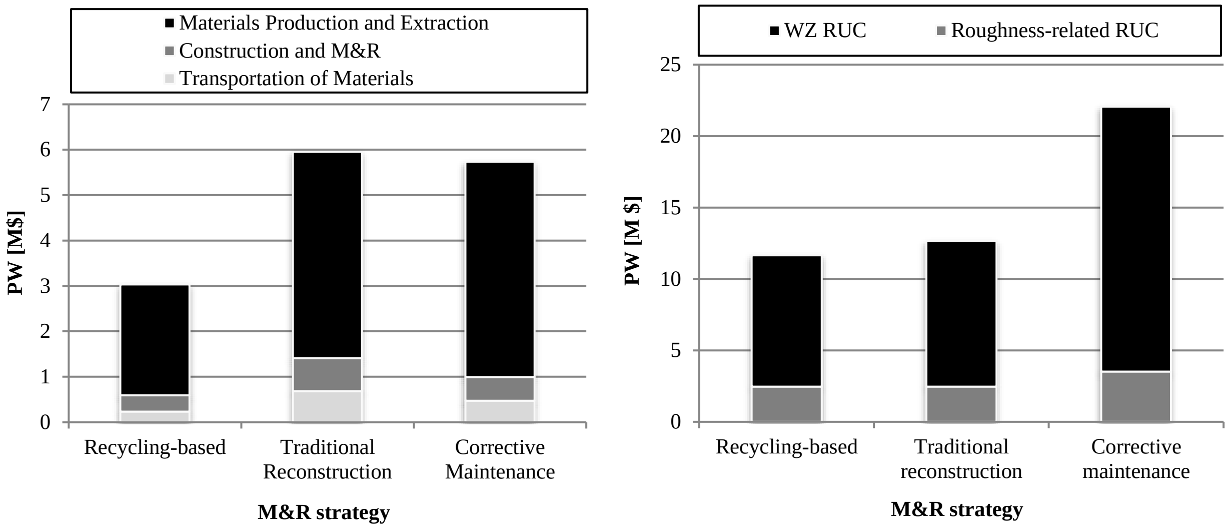
M&R strategy	Pavement life cycle phase						Total
	Materials extraction and production	Constructio n and M&R	Transportation of materials	WZ Traffic management	Usage	EOL	
Traditional reconstructio n	-2.100 (-46%)	-0.368 (-51%)	-0.452 (-66%)	-0.987 (-10%)	0 (0%)	0 (0%)	-3.908 (-21%)
Corrective maintenance	-2.299 (-49%)	0.164 (31%)	-0.239 (-51%)	-9.331 (-51%)	-1.062 (-30%)	-0.016 (-12%)	-13.152 (-48%)

To give pavement stakeholders a better perception of the costs borne by highway agencies and road users when one M&R strategy is preferred over another, Figures 3 depicts the PW of the total LCCs split into highway agency costs and RUC. Two interesting facts are: (1) that the traditional reconstruction strategy is more costly to the highway agencies than the corrective maintenance 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%).

With respect to the former, despite the greater number of M&R activities that need to be implemented throughout the PAP in the case of the corrective maintenance strategy, such a result 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 operation time associated with the material removal.

To explain the second outcome, two main reasons can be pointed out. First, the WZ traffic management plan implemented during the whole M&R activities of any M&R strategy was exclusively designed to be efficient in dealing with the traffic demand existing in the year 0 of the PAP. In other others, it is unable to prevent road users and freight from experiencing substantial delays when facing the M&R events forecasted for the predecessor years. Second, either M&R strategy allows to keep the pavement condition throughout the PAP with an IRI level lower than 3 m/km. As mentioned previously this IRI value is the threshold after which the vehicle maintenance and repair costs will start to be incurred by the vehicles owners (Chatti & Zaabar, 2012). This fact is particularly important given that Islam & Buttlar (2012) 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 for the reduction of the total RUC incurred during the usage phase.

In addition to the results introduced in the previous paragraphs, Figures 3 also allow for a straightforward conclusion on the distribution of the LCCs among the highway agency and road users. The recycling-based and the corrective maintenance strategies present similar findings, as the highway agencies are expected to expend about 25% of the life cycle amount that is likely to be spent by road users. On its turn, the traditional reconstruction M&R strategy beside its intermediate position in the ranking of the most costly M&R strategies is the one that would lead to the fairest distribution of the total LCCs among highway agency (46%) and road users (54%).



(a) (b)

Figure 3. PW of the life cycle highway agency costs (a), and RUC (b).

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 the materials extraction and production, 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. Figure 4 presents the costs of the two M&R activities broken down by pavement life cycle phases. Table 14 shows the difference in the costs associated with the recycling-based M&R activity relative to the traditional reconstruction M&R activity, presented in absolute value and percentage. These results should be interpreted in the same way as those displayed in Table 13.

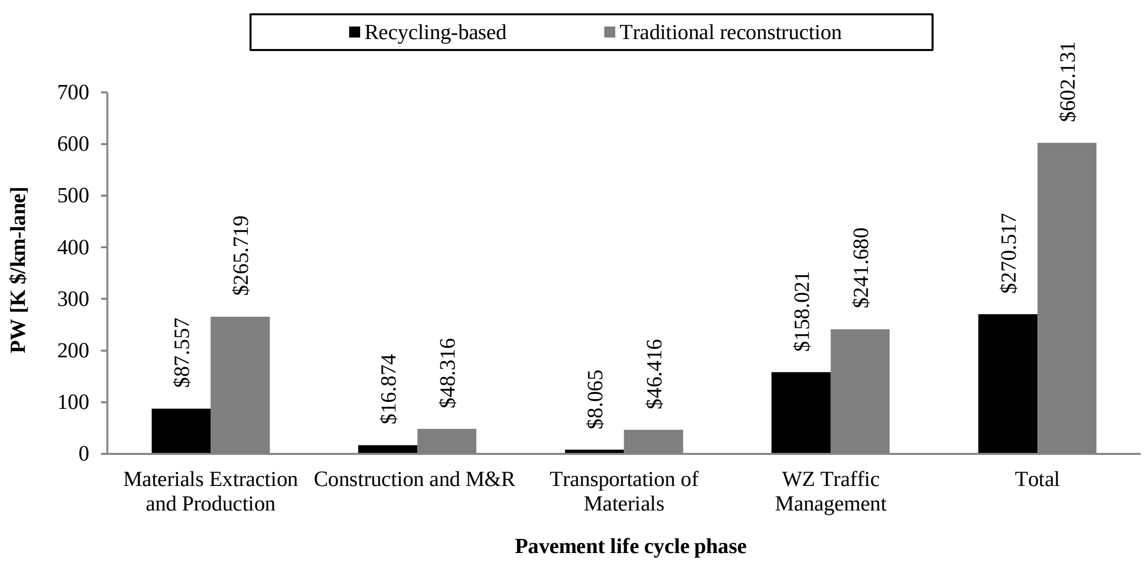


Figure 4. Costs of the recycling-based and traditional reconstruction M&R activities broken down per pavement life cycle phase.

Table 14. Difference between the costs corresponding to recycling-based M&R activity and those of the traditional reconstruction M&R activity (K $/lane-km).

Pavement life cycle phase				Total
Materials extraction and production	Construction and M&R	Transportation of materials	WZ Traffic management	
-178.162 (-67%)	-31.442 (-65%)	-38.352 (-83%)	-83.658 (-35%)	-331.614 (-55%)

By looking at the results presented in Figure 4 and Table 14 from the perspective of the highway agency, it can be seen that the most meaningful cost savings, in absolute value, resulting from applying the recycling-based M&R activity comes from the materials phase. It shows a reduction of $178.162 thousands/lane-km, or 67% of the costs incurred during homologous phase of the traditional reconstruction M&R activity. However, if the analysis is carried out on a relative basis, then the transportation of materials phase would lead highway agencies to the greatest cost savings, as the transportation 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, Figure 4 and Table 14 unsurprisingly reveal that the adoption of the recycling-based M&R activity in lieu of the traditional reconstruction can also be beneficial. Although less expressive than what is experienced by highway agencies, road users are likely to take advantage of a costs reduction that amounts to $83.658 thousands/lane-km (35%).

4.3. *Sensitivity analysis*

In order to examine how variations across a set of parameters and assumptions affect the robustness of the reported outcomes, and thereby, the relative merits of the alternatives being considered and compared, a sensitivity analysis was undertaken.

Based on the costs drivers identified in the previous sections and the critical assumptions common to any LCCA, the potential effects on the LCCs due to the variation in the value of the following parameters were analyzed: (1) discount rate, (2) bituminous materials costs (BMC), (3) TDC and (4) hauling distance of the virgin aggregates. Each single parameter was varied uniformly on a unit-by-unit basis from the established baseline value in the positive and negative direction, while holding all others at their average values. An exception to this methodological procedure was considered in the case of the hauling distances of the virgin aggregates. The influence of this parameter on the results was assessed by considering three distinct values (20km, 50 km and 80 km) in addition to the baseline value (0.6 km).

Figure 5 presents the impacts of varying the discount rate and BMC, ± 60%, on the highway agency costs. It can be seen that the recycling-based strategy's life cycle cost advantage over the remaining M&R strategies is robust even when considerable relative changes in the parameter values were tested against the baseline values. Unless a huge discount rate is considered, the recycling-based strategy is always the preferable from the highway agency's standpoint. In contrast, the relative differences in the economic performance of the remaining M&R strategies denote some volatility as the discount rate and BMC are changed. If the increase in the costs of the BMC exceeds approximately 35% the baseline value, the corrective maintenance strategy would become more attractive than the traditional reconstruction strategy. A similar consequence is observed in that case that the discount rate varies more than approximately -15% (in absolute value) relatively to the baseline value. Finally, Figure 5 also reveals that the highway agency costs are more sensitive to changes in the BMC than in the discount rate, as denoted by the greatest slope of the curves representing the impacts of varying the first input on the highway agency costs.

Figure 6 depicts the sensitivity of changes in discount rate and TDC on RUC. The analysis indicates that overall neither the TDC nor the discount rate are critical parameters when evaluating the relative differences between the RUC over the ± 60% sensitivity range. However, a more careful analysis of the behavior of the curves shows that the disadvantage of the corrective maintenance strategy over the remaining alternatives is attenuated as the discount rate and the TDC increase and decrease, respectively. The corrective maintenance strategy requires more M&R events throughout the PAP but its first M&R event is less time consuming than the homologous event in the competing alternatives. This fact explains why at higher discount rates the economic performance of all M&R strategies tends to become closer. With the regard to the influence of the TDC on the RUC, the results suggest that for the conditions considered in this case study at higher TDC the effect of the number of M&R events prevail over the effect of their duration.

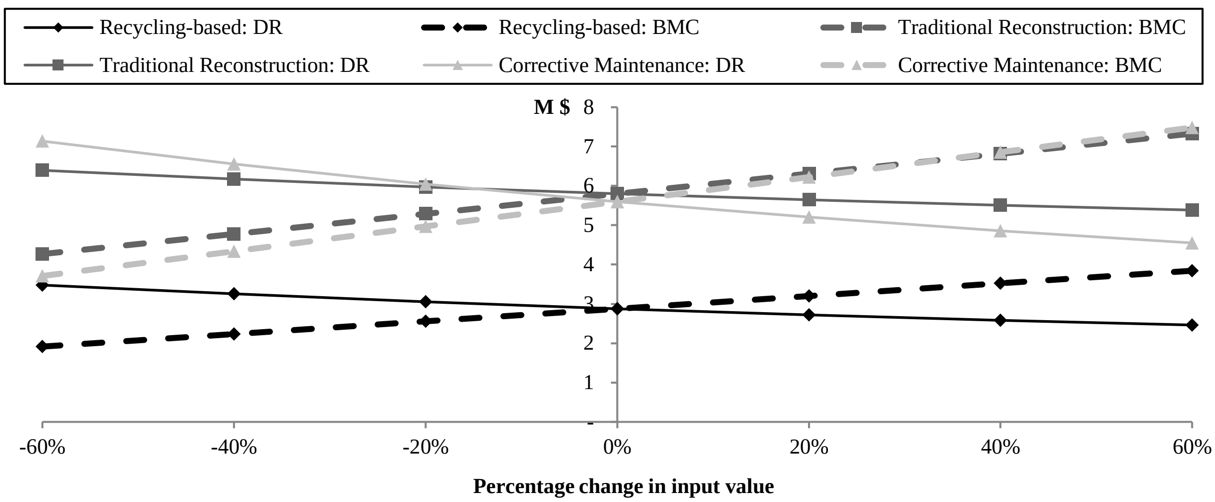


Figure 5. Sensitivity analysis of total highway agency costs.

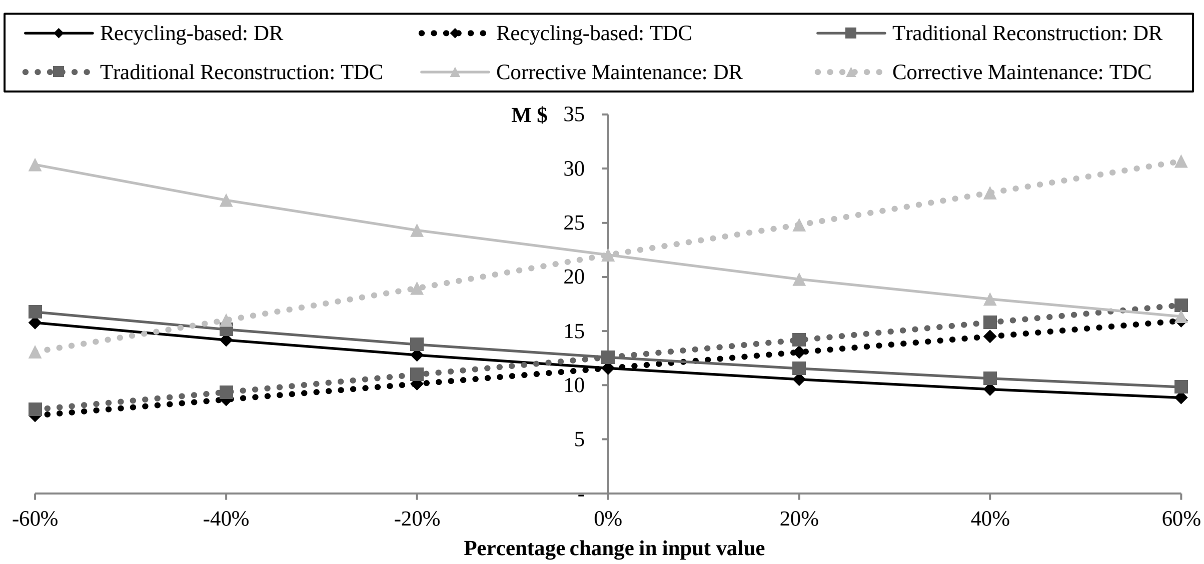


Figure 6. Sensitivity analysis of RUC.

In the vein of the analysis described previously, a similar study was conducted which aims to evaluate how the economic benefits resulting from implement the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity (see Table 14) varies as a function of changes in the value of (1) BMC; (2) transportation distance of the virgin aggregates, and (3) TDC. Comparatively with the previous analyses, the influence of the discount rate on the outcomes was not assessed because the two alternative M&R activities are undertaken in year 0 of the PAP. On the other hand, the analysis includes the assessment of the impacts on the highway agency costs resulting from considering different values of the transportation distance of virgin aggregates. Although not being as important as the BMC, the economic competitiveness of in-place pavement recycling techniques is also affected by material transportation costs and how such costs compare to the cost of new virgin material delivered to the construction site. The recycling project analyzed in this case study did not take full advantage of this common feature of in-place recycling techniques given that quarry that supplied the aggregates consumed during the project was inside the boundary of the asphalt plant facility. To provide insights into the magnitude of the influence of this parameter on the highway agency costs, three distinct transportation distance values of virgin aggregates were considered (20km, 50 km and 80 km) in addition to the baseline value (0.6 km).

Unsurprisingly, the results presented in Figure 7 (a) underline the importance of the BMC in driving the superior economic performance demonstrated by the recycling-based M&R activity. In a theoretical scenario where the costs of the binder and bituminous emulsions rise up to 60% of the baseline values, the option for the recycling-based M&R activity would allow highway agency costs savings of approximately $226 thousands/km-lane, representing an increment of 27% relatively to those corresponding to the baseline scenario. Disregarding the fact that an increase in the BMC would not be disassociated from a likely increase in the costs of other petroleum-derived products (e.g. fuels, oils, lube, etc.), the savings above reported are of such magnitude that they are just slightly lower than the total savings (roughly 248 thousands/km-lane, see Table 14) that highway agency are likely to take advantage during the materials, construction and M&R, and transportation of materials phases for the conditions considered in the baseline scenario.

With respect to the influence of the transportation distance of virgin aggregates on the costs incurred by highway agency during the corresponding pavement life cycle phase, Figure 7 (b) shows that in a plausible scenario where the transportation distance of virgin aggregates is equal to 50 km, the highway agency costs savings increase by 37%. This percentage would increase to 61% if a longer distance (80 km) was considered. Although the importance of the transportation distance of virgin aggregates to the economic advantage associated with the transportation of materials phase is not as expressive as the BMC to the total economic benefit of the recycling-based M&R activity, it should be bear in mind that this analysis only addressed the influence of the transportation distance of virgin aggregates. Additional costs savings are expected to be incurred during this pavement life cycle phase if the transportation distances of the asphalt mixtures were greater than those considered in this case study.

Finally, from the Figure 7 (c) it can be concluded that changes in the TDC lead to similar relative costs savings experienced by the road users during the WZ traffic management phase. For example, when the TDC increase by 60%, the RUC savings increase by 47%. This value is greater than the relative savings (27%) incurred by the highway agency during the materials phase when the BMC increases accordingly.

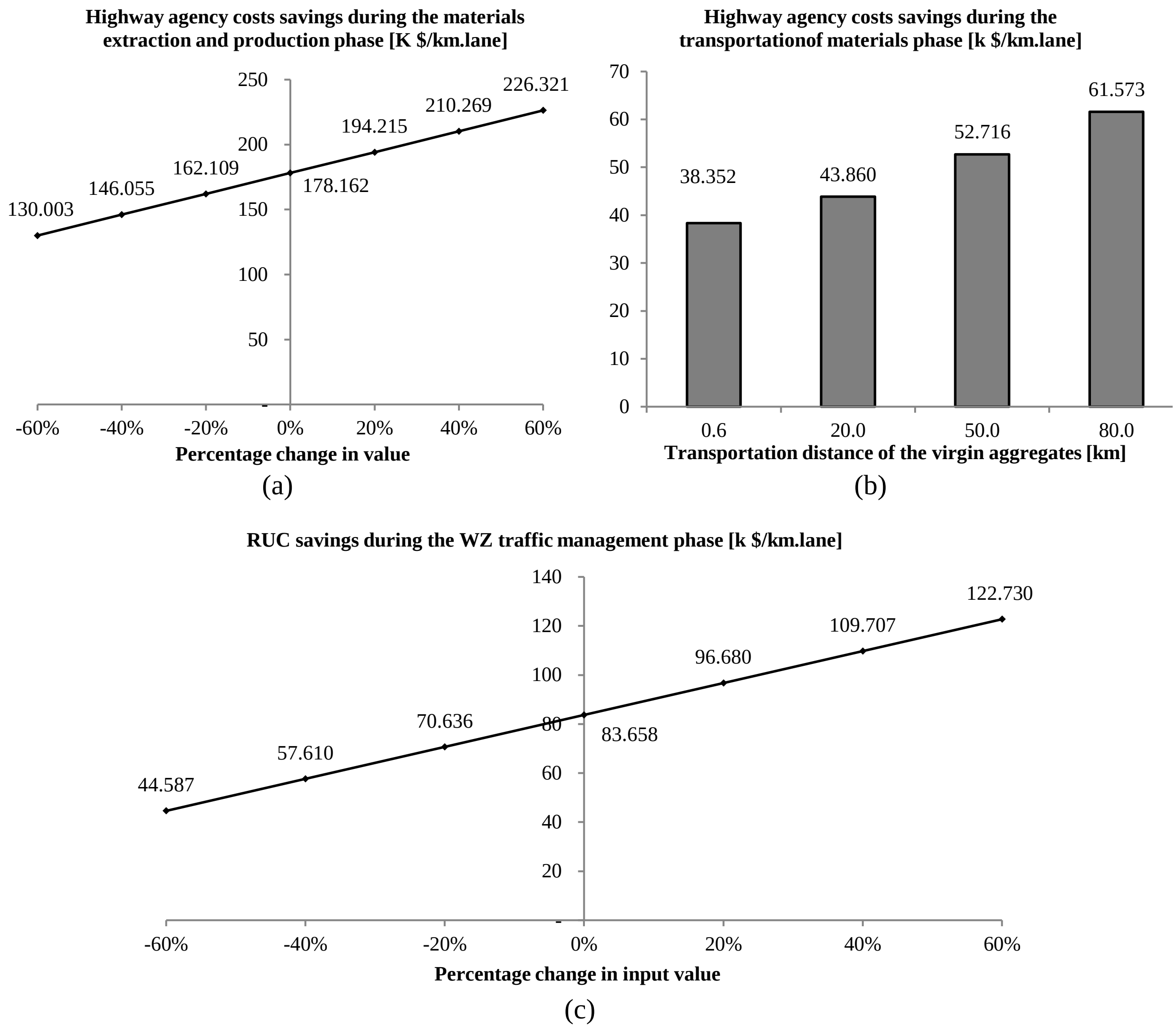


Figure 7. Sensitivity analysis of the economic benefits resulting from applying the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity, due to variability in: (a) bituminous materials costs (BMC); (b) transportation distance of the virgin aggregates, and (3) TDC.

4.4. *Key findings*

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

- the recycling-based M&R strategy is the least costly M&R strategy, allowing life cycle net savings of 21% and 48% relatively to the expenses incurred with the adoption of the traditional reconstruction and corrective maintenance strategies;
- the recycling-based M&R strategy significantly enhance the overall economic performance of the pavements over the life cycle by lowering the costs incurred during the materials transportation and materials extraction and production phases, depending on whether the analysis if carried out from the perspective of relative or absolute values, respectively;

- although the corrective maintenance strategy is the one that requires the greatest number of M&R activities to be implemented throughout the pavement life cycle, it was found to be more cost effective to highway agencies than the traditional construction strategy;
- regardless the type of M&R strategy adopted, the majority of the LCCs incurred by highway agencies and road users are due to the materials extraction and production and WZ traffic management phases, respectively;
- the cost of the bituminous-related materials was found to be the main cost driver of the materials phase costs, whereas the TDCs have revealed a decisive role in determining the WZ traffic management phase's economic performance;
- the life cycle RUC can be as much as 4 times greater than the life cycle highway agency costs;
- a reduction of 67% in the costs incurred by highway agencies during the materials extraction and production phase can be achieved by undertaking the recycling-based M&R activity in lieu of the traditional reconstruction M&R activity;
- the recycling-based strategy's life cycle cost advantage over the remaining M&R strategies is robust even when considerable relative changes in the discount rate, TDC and BMC values were tested against the baseline values;
- if the transportation distance of the virgin aggregates was equal to 50 km, the highway agency costs savings would increase by 37%. This percentage would increase to 61% if a longer distance (80 km) was considered.

5. Summary and conclusions

A shift towards more environmentally and economically responsible behavior in the road pavement management field requires less focus on the outputs of the decisions support tools and more on understanding of how the decision making process occur, and which variables are the most susceptible of influencing this process.

This paper presented the development of a cradle-to-grave, integrated and comprehensive LCC-based decision support tool that can assist decision-makers in determining whether current request for the adoption of more environmental friendly construction and M&R practices leads to an increase in the expenditures stream incurred by the different pavement stakeholders. Rather than relying on embracing inputs, the proposed model allows for the desegregation of the costs of new construction and M&R techniques and materials, not only in terms of the pavement life cycle phases where they are incurred, but also from the perspective of the delivery cost's upstream supply chain.

Through a step-wise and thorough analysis, the proposed LCC model can be applied to calculate and compare several categories of costs supported by the highway agencies and road users arising from assumptions and parameters considered across a wider range of the processes modelled throughout 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 proposed LCC model was applied to a case study of an in-place pavement recycling rehabilitation project. The results of the LCCA of three competing M&R strategies for a pavement segment show that, notwithstanding the exclusivity of each project, the implementation of recycling-based M&R strategies has the potential to be an efficient solution to lower the total LCCs incurred both by highway agencies and road users. From the perspective of the highway agencies, the majority of the recycling-based strategy's life cycle economic advantage over the competing alternatives is expected to be obtained during the materials phase, essentially due to the reduction in the consumption of bituminous-related materials.

However, if the results are analyzed from the road users' perspective, the WZ traffic management phase would outperform the usage phase as the greatest source of RUC savings thanks to the reduction of the TDCs.

In addition, a sensitivity analysis was undertaken to assess the robustness of the outcomes when different input values are considered. The analysis has shown that variances to the key assumptions applied within LCC analysis does not alter the recycling-based M&R strategy's life cycle cost advantage over the remaining M&R strategies.

To guide highway agencies towards an optimized allocation of resources while meeting the environmental concerns, future work on this topic should focus on the development of a framework that integrates in a systematic and parallel way this LCC model with an upgraded version of the LCA model presented by Santos et al. (2014).

6. Acknowledgements and disclaimer

This work has been supported by the Portuguese Foundation for Science and Technology under the Grant [SFRH/BD/79982/2011], by European Regional Developing Funding [CENTRO-07-0224-FEDER-002004- EMSURE - Energy and Mobility for Sustainable Regions] and by the Transportation Pooled Fund TPF-5(268) National Sustainable Pavement Consortium.

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, the Federal Highway Administration, or the constructor. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement. Moreover, this paper does not constitute a standard, specification, or regulation.

7. References

American Society of Civil Engineering (2013). *2013 Report card for America's infrastructure*. Retrieved from the American Society of Civil Engineering website: http://www.infrastructurereportcard.org/a/#p/roads/overview

Amini, A. A., Mashayekhi, M., Ziari, H. & Nobakht, S. (2012). Life cycle cost comparison of highways with perpetual and conventional pavements. *International Journal of Pavement Engineering*, 13, 553-568. http://dx.doi.org/10.1080/10298436.2011.628020

Barnes, G. & Langworthy, P. (2003). *The per-mile costs of operating automobiles and trucks*. (Report No. MN/RC 2003-19). Retrieved from the Minnesota Local Road Research Board (LRRB) website: www.lrrb.org/pdf/200319.pdf

Caterpillar, Inc. (2012). Caterpillar performance handbook, 42nd Ed., Caterpillar, Peoria, IL.

Chan, A., Keoleian, G., & Gabler, E. (2008). Evaluation of life-cycle cost analysis practices used by the Michigan Department of Transportation. *Journal of Transportation Engineering*, 134, 236-245. http://dx.doi.org/10.1061/(ASCE)0733-947X(2008)134:6(236)

Chatti, K., & Zaabar, I. (2012). *Estimating the effects of pavement condition on vehicle operating costs* (National Cooperative Highway Research Program Report No. 720). Transportation Research Board, Washington, D.C. Retrieved from Transportation Research Board website: http://www.trb.org/Main/Blurbs/166904.aspx

Damas, L. (2005). *SQL- Structured Query Language*. Lisboa: FCA- Editora de Informática Lda. (in Portuguese).

Diefenderfer, S. D. & Hearon, A. J. (2010). *Performance of Virginia's warm-mix asphalt trial sections.* Virginia Transportation Research Council. Report VTRC 10-R17. Retrieved from Virginia Department of Transportation website: http:/www.virginiadot.org/vtrc/main/online_reports/pdf/10-r17.pdf

Diefenderfer, B. K., Apeagyei, A. K., Gallo, A. A., Dougald, L. E. & Weaver, C. B. (2012). In-place pavement recycling on I-81 in Virginia. *Transportation Research Record: Journal of the Transportation Research Board*, 2306, 21-27. doi: 10.3141/2306-03

Epps, J., Berger, E. & Anagnos, J. N. (2003). *Treatments. Moisture sensitivity of asphalt pavements- a national seminar, San Diego, California*. Transportation Research Board, Washington, D.C. Retrieved from the Transportation Research Board website: http://www.trb.org/Publications/Blurbs/153655.aspx

European Asphalt Pavement Association [EAPA] & National Asphalt Pavement Association [NAPA], (2011). *The asphalt paving industry: a global perspective (2nd edition).* Retrieved from European Asphalt Pavement Association (EAPA) website: http://www.eapa.org/userfiles/2/Publications/GL101-2nd-Edition.pdf

Fabrycky, W.J. & Blanchard, B.S. (1991). *Life-cycle cost and economic analysis*. New Jersey: Prentice Hall.

Federal Highway Administration (2002). *Life-cycle cost analysis primer* (Report No FHWA-IF-02-047). Retrieved from Federal Highway Administration website: http://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm

Federal Highway Administration (2003). *Economic analysis primer* (Report No FHWA-IF-03-032). Retrieved from Federal Highway Administration website: http://www.fhwa.dot.gov/infrastructure/asstmgmt/primer00.cfm

Federal Highway Administration (2005). *Highway economic requirements system- state version (HERST-ST). Technical report*. Retrieved from Federal Highway Administration website: http://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech00.cfm

Fender, K. J. & Pierce, D. A. (2013). *An analysis of the operational costs of trucking: 2013 update.* American Transportation Research Institute (ATRI). Retrieved from American Transportation Research Institute website: http://atri-online.org/2013/09/04/an-analysis-of-the-operational-costs-of-trucking-2013-update/

Hall, K., Correa, C., Carpenter, S. & Elliott, R. (2003). *Guidelines for life-cycle cost analysis of pavement rehabilitation strategies*. Proceeding of the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C.

Hansen, K. R. & Copeland, A. (2013). *2nd annual asphalt pavement industry survey on reclaimed asphalt pavement, reclaimed asphalt shingles, and warm-mix asphalt usage: 2009-2011.*Information series 138, National Asphalt Pavement Association, MD. Retrieved from the National Asphalt Pavement Association (NAPA) website: http://www.asphaltpavement.org/index.php?option=com_content&view=article&id=946:napa-fhwa-seek-asphalt-mix-producers-input-for-survey&catid=24:napa-news4&Itemid=1308

Harvey, J., Kendall, A., Lee, I.-S., Santero, N., Van Dam, T. & Wang, T. (2010). *Pavement life cycle assessment workshop: discussion summary and guidelines* (Technical Memorandum: UCPRC-TM-2010-03). Retrieved from University of California Pavement Research Center website: http://www.ucprc.ucdavis.edu/PublicationsPage.aspx

Islam, S., and W. Buttlar (2012). Effect of pavement roughness on user costs. *Transportation Research Record: Journal of the Transportation Research Board*, 2285, 47-55. http://dx.doi.org/10.3141/2285-06

Klöpffer, W. (2008). Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95). *International Journal of Life Cycle Assessment*, 13, 89-94. doi:10.1065/lca2008.02.376

Lee, J. C., Edil, T. B., Tinjum, J. M. & Benson, C. H. (2010). Quantitative assessment of environmental and economic benefits of recycled materials in highway construction. *Transportation Research Record: Journal of the Transportation Research Board*, 2158, 138-142. DOI: 10.3141/2158-17

Li, Z. & Madanu, S. (2009). Highway project level life-cycle benefit/cost analysis under certainty, risk, and uncertainty: methodology with case study. *Journal of Transportation Engineering*, 135, 516-526. http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000012

Lindholm, A. & Suomala, P. (2005). Present and future of life cycle costing: reflections from Finnish companies. *The Finnish Journal of Business Administration*, 2, 282-292.

Loureiro, H. (2010). *Visual Basic- curso completo* [Visual Basic- Complete Course]. Lisboa: FCA-Editora de Informática Lda. (in Portuguese)

Mallela, J. & Sadasivam, S. (2011). *Work zone road user costs - concepts and applications* (Report No FHWA-HOP-12-005). Office of Operations (OPS), Federal Highway Administration (FHWA), Washington, D.C. Retrieved from Office of Operations (OPS), FHWA website: http://www.ops.fhwa.dot.gov/wz/resources/publications/fhwahop12005/index.htm

Miliutenko, S., Björklund, A. & Carlsson, A. (2013). Opportunities for environmentally improved asphalt recycling: the example of Sweden. *Journal of Cleaner Production*, 43, 156-165. http://dx.doi.org/10.1016/j.jclepro.2012.12.040

Mirzadeh, I., Butt, A. A., Toller, S. & Birgisson, B. (2013). Life cycle cost analysis based on the fundamental cost contributors for asphalt pavements. *Structure and Infrastructure Engineering.* Advance online publication. http://www.tandfonline.com/doi/full/10.1080/.U4OyQXZTpck#.U4PAF3ZTpck

Morgan, J. G. (2005). *Hot mix asphalt for county roads: private providers or public plants?*. Comptroller of the Treasury, Offices of Research and Education Accountability, State of Tennessee. Retrieved from the Tennessee Comptroller of the Treasury website: http://www.comptroller.tn.gov/AuditsAndReportsSearch/CategorySearchResults.aspx

Office of Management and Budget (2013). *Discount rates for cost-effectiveness, lease purchase, and related analyses*. Table of past years discount rates from Appendix C of OMB Circular No. A-94. Retrieved from the Office of Management Budget website: http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c

Ozbay, K., Parker, N. A., Jawad, D. & Hussain, S. (2003). *Guidelines for life cycle cost analysis* (Report No FHWA-NJ-2003-012). Retrieved from the Center for Advanced Infrastructure & Transportation (CAIT), Rutgers website: http://cait.rutgers.edu/research-reports/guidelines-life-cycle-cost-analysis

Rangaraju, P. R., Amirkhanian, S. & Guven, Z. (2008). *Life cycle cost analysis for pavement type selection* (Report No FHWA-SC-08-01). Retrieved from Department of Civil Engineering, Clemson University website: http://www.clemson.edu/t3s/scdot/pdf/projects/SPR656Final.pdf.

Sakhaeifar, M. S., Brown, E, R., Tran, N. & Dean, J. (2013). Evaluation of long-lasting perpetual asphalt pavement with life-cycle cost analysis. *Transportation Research Record: Journal of the Transportation Research Board*, 2368, 3-11. DOI: 10.3141/2368-01

Salem, O. M., Abourizk, S. & Ariaratnam, S. (2003). Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives. *Journal of Infrastructure Systems*, 9, 6-15. http://dx.doi.org/10.1061/(ASCE)1076-0342(2003)9:1(6)

Salem, O. M., Deshpande, A. S., Genaidy, A., Geara, T. G. (2013). User costs in pavement construction and rehabilitation alternative evaluation. *Structure and Infrastructure Engineering*, 9, 285-294. DOI: 10.1080/15732479.2010.550304

Santos, J. & Ferreira, A. (2012). Pavement design optimization considering costs and preventive interventions. *Journal of Transportation Engineering*, 138, 911-923.http://dx.doi.org/10.1061/(ASCE)TE.1943-5436.0000390

Santos, J. & Ferreira, A. (2013). Life-cycle cost analysis system for pavement management at project level. *International Journal of Pavement Engineering*, 14, 71-84. http://www.tandfonline.com/doi/abs/10.1080/10298436.2011.618535?src=recsys#.U4PE4HZTpck

Santos, J., Bryce, J., Flintsch, G., Ferreira, A., & Diefenderfer, B. K. (2014). A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering*. Accepted for publication. http://dx.doi.org/10.1080/15732479.2014.945095

Swei, O., Gregory, J., & Kirchain, R. (2013). Probabilistic characterization of uncertain inputs in the life-cycle cost analysis of pavements. *Transportation Research Record: Journal of the Transportation Research Board*, 2366, 71-77. http://trb.metapress.com/content/1752746708g81736/

Thenoux, G., González, A. & Dowling, R. (2007). Energy consumption comparison for different asphalt pavements rehabilitation techniques used in Chile. *Resources, Conservation and Recycling*, 49, 325-339. http://dx.doi.org/10.1016/j.resconrec.2006.02.005

Tighe, S., Haas, R. & Ponniah, J. (2007). Life-cycle cost analysis of mitigating reflective cracking. *Transportation Research Record: Journal of the Transportation Research Board*, 1823, 73-79. http://trb.metapress.com/content/x81432q805311w14/

Transportation Research Board. (2000). *Highway Capacity Manual 2000.* Transportation Research Board, Washington, D.C.

United States Army Corps of Engineers (2011a). *Sheboygan harbor strategic navigation dredging, WI. Appendix A- Cost appendix for design project report for Sheboygan harbor Dredged Material Management Plan (DMMP).* US Army Corps of Engineers, Detroit District. Retrieved from United

States Army Corps of Engineers, Detroit District website: http://www.lre.usace.army.mil/Portals/69/docs/PPPM/PlanningandStudies/DraftPlanningStudies/oneSheboyganHrbWIInterimDMMPmainDec2011.pdf.

United States Army Corps of Engineers (2011b). *Construction equipment ownership and operating expense schedule, Region II*. Document EP 1110-1-8, Vol. 2. Washington D.C.: US Army Corps of Engineers.

United States Department of Labor (2011a). *Occupational employment statistics May 2011*. Bureau of Labor Statistics, Department of Labor. Retrieved from the United States Department of Labor website: http://www.bls.gov/oes/2011/may/oes_stru.htm

United States Department of Labor (2011b). *Employer costs for employee compensation – June 2011*. Bureau of Labor Statistics, Department of Labor. Retrieved from the United States Department of Labor website: http://www.bls.gov/schedule/archives/ecec_nr.htm#2011

United States Department of Transportation (2003). *Valuation of Travel Time in Economic Analysis, Revised Departmental Guidance, Memorandum*. Office of the Secretary of Transportation, U.S. Department of Transportation, Washington, DC. Retrieved from Office of the Assistant Secretary for Transportation Policy website: http://www.dot.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic

United States Energy Information Administration (2014a). *Lower Atlantic (PADD 1C) gasoline and diesel retail prices*. Retrieved from United States Energy Information Administration website: http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r1z_a.htm

United States Energy Information Administration (2014b). *Average retail price of electricity to ultimate customers: by state, by provider, annual back to 1990 (Form EIA-861)*. Retrieved from United States Energy Information Administration website: http://www.eia.gov/electricity/data.cfm#sales

United States Energy Information Administration (2014c). *Virginia Natural Gas Prices.* Retrieved from United States Energy Information Administration website: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_sva_a.htm

United States Environmental Protection Agency (2010a) *Exhaust and crankcase emission factors for nonroad engine modeling- compression- ignition* (Report No. NR-009d). Retrieved from United States Environmental Protection Agency website: http://www.epa.gov/otaq/nonrdmdl.htm#model

United States Environmental Protection Agency (2010b). *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Retrieved from United States Environmental Protection Agency website: http://www.epa.gov/otaq/models/moves/index.htm#user.

United States Geologic Services (2013a). *2011 minerals yearbook: cement [Advance Release]*. Retrieved from United States Geologic Services website: http://minerals.usgs.gov/minerals/pubs/commodity/cement/

United States Geologic Services (2013b). *2011 minerals yearbook: stone, crushed [Advance Release]*. Retrieved from United States Geologic Services website: http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

Virginia Department of Transportation (2012). *Business Rules and User's Information, Dashboard 3.0*. Virginia Department of Transportation. Retrieved from Virginia Department of Transportation (VDOT) website: http://dashboard.virginiadot.org/Help/DB%20User%20Guide.PDF.

Walls, J. & Smith, M. (1998). *Life-cycle cost analysis in pavement design - in search of better investment decisions* (Report No. FHWA-SA-98-079), Federal Highway Administration, Washington, D.C. Retrieved from United States Department of Transportation Digital Document Center website: http://isddc.dot.gov/OLPFiles/FHWA/013017.pdf

1. Supplemental material

1.1. *Construction and M&R model*

(i) Model formulation:

$$C_{C.M\&R} = C_{EOw} + C_{EOp} + C_{L} \quad (1)$$

$$C_{EOw} = C_{EOw:C} + C_{EOw:Int} + C_{EOw:Tx} + C_{EOw:Ins} \quad (2)$$

$$C_{EOp} = C_{EOp:FC} + C_{EOp:PM\&FOG} + C_{EOp:R} + C_{EOp:T} + C_{EOp:SWI} + C_{EOp:M} \quad (3)$$

$$C_{EOw:D} = \frac{AC - TC - SV}{AOP \times AYU} \quad (4)$$

$$C_{EOw:L} = \frac{LCV}{LCD} \quad (5)$$

$$C_{EOw:Int} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times IntR}{AYU} \quad (6)$$

$$C_{EOw:Tx} = \frac{ATC}{AYU} \quad (7)$$

$$C_{EOw:Ins} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times InsR}{AYU} \quad (8)$$

$$C_{EOp:FC} = FC \times FCost \quad (9)$$

$$C_{EOp:PM\&FOG} = C_{EOp:FC} \times F_{PM\&FOG} \quad (10)$$

$$C_{EOp:R} = \frac{(AC - TC) \times F_{R}}{AYU} \quad (11)$$

$$C_{EOp:T} = \frac{TC}{TL} \quad (12)$$

$$C_{EOp:SWI} = SWIC \quad (13)$$

$$C_{EOp:M} = MC \quad (14)$$

$$C_{Labor} = \sum_{WCat=0}^{N_{WCat}} n_{Wcat} \times \frac{WB_{WCat}}{WD_{Eff} \times WD \times WH} \times V_{act} \times AF_{WCat,act} \quad (15)$$

(ii) Notation:

$C_{C.M\&R}$ costs supported 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 time

C_{EOw} construction equipment owning costs. They are the same regardless of whether the construction equipment are parked in the constructor’s yard, or operating (or idling) at a given work site

C_{EOp} construction equipment operating costs. They vary in proportion to hours of actual operation

C_L	hourly costs fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits)
$C_{EOw.C}$	hourly cost to protect the asset's value. If the equipment is owned by the constructor this subcategory is named depreciation cost (Equation 3). On the other hand, when the equipment is not owned by the constructor, the most likely scenario is that the equipment is leased. In this case the $C_{EOw.C}$ is named leasing cost (Equation 4), and depending on the clauses set out in the leasing contract, some of the remaining C_{EOw} subcategories may be exempted from a direct and individual accounting
$C_{EOw.Int}$	costs incurred due to the capital invested in an equipment, regardless of whether the equipment is purchased with constructor assets' or financed
$C_{EOw.Tx}$	costs of property tax and license for the equipment
$C_{EOw.Ins}$	costs incurred due to fire, theft, accident, and liability insurance for the equipment
AC	cost of acquisition of the construction equipment
TC	cost of a new set of tires [$]
SV	salvage value of the construction equipment [$];
AOP	average ownership period [years]
AYU	average yearly usage [hr]
LCV	leasing contract value [$]
LCD	leasing contract duration [hr]
$IntR$	interest rate expressed in decimal value
ATC	annual tax cost [$]
$AInsC$	annual insurance cost [$]
TR	tax rate expressed in decimal value
$InsR$	insurance rate expressed in decimal value
$C_{EOp.FC}$	cost of the fuel consumed per each equipment piece at a work site
$C_{EOp.PM\&FOG}$	cost for routine servicing of the construction equipment, as typically specified in the operation and maintenance manuals provided for each construction equipment
$C_{EOp.R}$	cost for equipment repairs, maintenance, and major overhauls performed either in the work site or in the shop
$C_{EOp.T}$	costs of tires replacement
$C_{EOp.SWI}$	costs incurred with high-wear items, such as cutting edges and bucket teeth
$C_{EOp.M}$	costs of construction equipment mobilization and demobilization
FC	hourly fuel consumption during the operation period [liters/hr] estimated according to the methodology adopted by the US EPA's NONROAD2008 model (US EPA, 2010a)
$FCost$	unit fuel cost [$/liter]
$F_{PM\&FOG}$	factor that represent the $C_{EOp.PM\&FOG}$ as a percentage of the hourly fuel cost
F_R	factor that represent the $C_{EOp:R}$ as a percentage of the cost of a new equipment after subtracting the tires cost (TC)

TL	estimated tire life [hr]
$SWIC$	hourly cost of special wear items [$/hr]
MC	hourly cost of equipment mobilization/demobilization [$/hr]
C_L	hourly cost fully incurred by the employer with the human resources required at work site to actually perform a given construction and M&R action (i.e. including wages and benefits).
N_{WCat}	total number of work categories required to perform the construction and M&R action act
n_{Wcat}	number of workers of the category $WCat$ that integrate the crew in charge of performing the construction and M&R action act
WB_{WCat}	total annual employer cost [$] for employee compensation of the category $WCat$, which includes wages, salaries and total benefits
WD	total number of paid working days per year
WD_{Eff}	coefficient representing the ratio between the number of days, per year, that a worker of a given category is actually available for working and the total number of paid working days per year (WD). The numerator of this ratio is obtained from the denominator by deducting the vacation days, the holidays, the sick days, the breaks, the training and meeting days, and other
WH	number of working hours per day
V_{act}	total duration in hours of a construction and M&R action act
$AF_{WCat,act}$	assignment factor between 0 and 1 that represents the time during one hour of a construction and M&R action act that a worker of the category $WCat$ is allocated to that construction and M&R action

1

Table 1.1. Values of the variables corresponding to each piece of construction equipment needed to compute the construction equipment owning and operating costs

Lane	Activity	Process	Name	Brand	Model	AYU [hr]	AOP [years]	AC [$]	SV [$]	$F_{PM\&FOG}$	F_R	$InsR$ [%]	TR [%]	TC [$]	TL [hr]	$SWIC$ [$/hr]	MC [$/hr]
Right	FDR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3	2	-	-	35	10.5
		Reclaiming	Reclaimer	Wirtgen	WR 2400	606	8	523 000	104,600	0.119	1	3	2	4,000	3,000	35	10.5
			Water Tank Truck (only chassis)	Mack	Granite GU713	1,641	8	140,000	28,000	0.119	0.65	3	2	4,000	2,000	-	10.5
			Water Tank (skid-mounted, 4000 gallons	-	-	1,641	8	35,000	7,000	-	-	-	-	-	-	-	-
			Cement Spreader Truck (only chassis)	Mack	Granite GU713	1,641	8	140,000	28,000	0.119	0.65	3	2	4,000	2,000	-	10.5
			Truck mounted Spreader (27 tonnes)	Stoltz	-	1,641	8	50,000	10,000	-	-	-	-	-	-	-	-
		Compacting	6-ton vibratory soil compactor	Caterpillar	CP44	606	8	124,000	24,800	0.102	0.8	3	2	1,600	3,000	-	10.5
		Grading	Motor Grader	Caterpillar	120H	962	8	280,000	70,000	0.144	0.75	3	2	4,800	3,000	-	10.5
	CCPR	Cold Central Plant Recycling	CCPR mobile plant	Wirtgen	KMA 220	606	8	517,000	103,400	0.119	0.9	3	2	-	-	-	10.5
			Wheel loader	Caterpillar	950K	761	8	246,000	61,500	0.111	0.7	3	2	20,000	3,000	-	10.5
		Paving and compacting	Paver	Dynapac	SD2550 C	821	8	340,000	51,000	0.119	1.00	3	2	-	-	-	10.5
			12-ton Double steel-drum vibratory roller	Hamm	HD+ 120 VO	760	8	150,000	22,500	0.102	1.20	3	2	-	-	-	10.5
			14-ton Double steel-drum vibratory roller	Hamm	HD +120 VV	760	8	213,000	31,950	0.102	1.20	3	2	-	-	-	10.5
			10-ton vibratory rubber tire roller	Hamm	GWR10	760	8	109,000	16,350	0.102	1.20	3	2	11,200	1,500	-	10.5

Table 1.1. Values of the variables corresponding to each piece of construction equipment needed to compute the construction equipment owning and operating costs (continued)

Lane	Activity	Process	Name	Brand	Model	AYU [hr]	AOP [years]	AC [$]	SV [$]	$F_{PM\&FOG}$	F_R	$InsR$ [%]	TR [%]	TC [$]	TL [hr]	$SWIC$ [$/hr]	MC [$/hr]
Left	CIR	Milling	Milling Machine	Wirtgen	W 2100	606	8	700,000	140,000	0.119	1	3	2	-	-	35	10.5
		Recycling	Cement Spreader Truck (only chassis)	Mack	Granite GU713	1,641	8	140,000	28,000	0.119	0.65	3	2	4,000	2,000	-	10.5
			Truck Mounted Spreader (27 tonnes)	Stoltz		1,641	8	50,000	10,000	-	-	-	-	-	-	-	-
			Asphalt Distributor Truck (only chassis)	Mack	CHU613	1,641	8	140,000	28,000	0.119	0.65	3	2	4,000	2,000	-	10.5
			Asphalt Heated Tank Trailer (4000 Gallons)	Etnyre			8	65,000	13,000					3,200	2,000	-	10.5
			Cold Recycler	Wirtgen	3800 CR	606	8	900,000	180,000	0.119	1	3	2	-	-	35	10.5
		Compacting	16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3	2	-	-	-	10.5
			16- ton double steel-drum vibratory roller	Hamm	HD 120	760	8	104,000	15,600	0.102	1.20	3	2	-	-	-	10.5
			25-ton vibratory rubber-tire roller	Hamm	GWR 280	760	8	148,000	22,200	0.102	1.20	3	2	11,200	1,500	-	10.5
Both Lanes	Asphalt Paving	HMA and SMA paving and compacting	Paver	Dynapac	SD2550C	821	8	340,000	51,000	0.119	1.00	3	2	-	-	-	10.5
			Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3	2	11,200	1,500	-	10.5
			Breakdown roller	Dynapac	CP 142	760	8	120,000	18,000	0.102	1.20	3	2	11,200	1,500	-	10.5
			Finishing roller	Dynapac	CC324HF	760	8	122,000	18,300	0.102	1.20	3	2	-	-	-	10.5
		Tack Coat Application	Diesel Engine	Perkins	1100 Series	815	8	10,000	1,000	0.102	0.6	-	2	-	-	-	10.5
			Skid steer Load (sweeper)	Bobcat	S630	818	8	38,000	7,600	0.111	0.8	3	2	1,080	350	-	10.5
			Asphalt Distributor Truck (only chassis)	Mack	Granite GU713	1641	8	140,000	28,000	0.119	0.85	3	2	4,000	2,000	-	10.5
			Asphalt Heated Tank (Skid mounted, 3000 Gallons)	Etnyre	-	-	8	55,000	11,000	-	-	-		-	-	-	10.5
	Unbound Layers Removal	Excavation	Excavator	Hitachi	Zaxis 350LC-5	1,092	8	410,000	102,500	0.149	0.8	3	2	-	-	25	10.5

Table 1.2. Values of the variables corresponding to each worker category needed to compute the respective hourly labor cost

$WCat$	WB_{WCat} [$/year][a]	WD [days][e]	WD_{Eff} [e]	WH [hr]
Foremen	71,853.51 [a]	260	0.77	8
Paving Equipment Operator	52,212.26 [b]	260	0.77	8
Laborers	41,061.29 [c]	260	0.77	8
Screed man	52,212.26 [b]	260	0.77	8
Hauling Truck Driver	55,798.19 [d]	260	0.77	8

[a]Value obtained by considering the annual 90th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (Unites States Department of Labor, 2011b).
[b]Value obtained by considering the annual 50th percentile total compensation for the "Paving, Surfacing, and Tamping Equipment Operators" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (Unites States Department of Labor, 2011b).
[c]Value obtained by considering the annual 50th percentile total compensation for the "Construction laborers" occupational group in Virginia. It results from considering the wages and salaries equal to 66.9% of the total compensation (Unites States Department of Labor, 2011b).
[d]Value obtained by considering the annual 50th percentile total compensation for the "Heavy and Tractor-Trailer Truck Drivers" occupational group in Virginia. It results from considering the wages and salaries equal to 66.4% of the total compensation (Unites States Department of Labor, 2011b).
[e]Data source: Wiegmann, Sundararajan & Tao (2011). It corresponds to a "year-round, full-time" hours figure of 2,080 hours.

1.2. *Transportation of materials phase*

(i) Model formulation:

$$C_{TP} = C_{HTOw} + C_{HTOp} + C_{L} \tag{16}$$

$$C_{HTOw} = C_{HTOw:C} + C_{HTOw:Int} + C_{HTOw:Tx} + C_{HTOw:Ins} \tag{17}$$

$$C_{HTOp} = C_{HTOp:FC} + C_{HTOp:PM\&FOG} + C_{HTOp:R} + C_{HTOp:T} \tag{18}$$

$$C_{HTOw:D} = \frac{AC - TC - SV}{AOP \times AYU} \tag{19}$$

$$C_{HTOw:L} = \frac{LCV}{LCD} \tag{20}$$

$$C_{HTOw:Int} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times IntR}{AYU} \tag{21}$$

$$C_{HTOw:Tx} = \frac{ATC}{AYU} \tag{22}$$

$$C_{HTOw:Ins} = \frac{\frac{AC \times (AOP+1) + SV \times (AOP-1)}{2 \times AOP} \times InsR}{AYU} \tag{23}$$

$$C_{HTOp:FC} = FC \times FCost \tag{24}$$

$$C_{HTOp:PM\&FOG} = C_{HTOp:FC} \times F_{PM\&FOG} \tag{25}$$

$$C_{HTOp:R} = \frac{(AC - TC) \times F_R}{AYU} \tag{26}$$

$$C_{HTOp:T} = \frac{TC}{TL} \tag{27}$$

$$C_{Labor} = \frac{WB_{HTD}}{WD_{Eff} \times WD \times WH} \times \frac{L_{HM}}{S_{HM}} \times 2 \qquad (28)$$

(ii) Notation:

C_{TP}	costs supported by the highway agency due to the transportation of the materials
C_{HTOw}	hauling truck owning costs. They are the same regardless of whether the hauling truck is parked in the hauling truck owner's yard, or operating
C_{HTOp}	hauling truck operating costs. They vary in proportion to hours of actual operation
C_L	hourly costs fully incurred by the employer with the hauling truck driver (i.e. including wages and benefits)
$C_{HTOw:C}$	hourly cost to protect the asset's value. If the hauling truck is owned by the constructor this subcategory is named depreciation cost (Equation 19). On the other hand, when the hauling truck is not owned by the constructor, the most likely scenario is that it is leased. In this case the $C_{HTOw:C}$ is named leasing cost (Equation 20), and depending on the clauses set out in the leasing contract, some of the remaining C_{HTOw} subcategories may be exempted from a direct and individual accounting
$C_{HTOw:Int}$	costs incurred due to the capital invested in the hauling truck, regardless of whether it is purchased with constructor assets' or financed
$C_{HTOw:Tx}$	costs of property tax and license for the hauling truck
$C_{HTOw:Ins}$	costs incurred due to fire, theft, accident, and liability insurance for the hauling truck
$C_{HTOp:FC}$	cost of the fuel consumed by the hauling trucks
$C_{HTOp:PM\&FOG}$	cost for routine servicing of the hauling truck, as typically specified in the operation and maintenance manuals provided for each hauling truck
$C_{HTOp:R}$	cost for hauling trucks repairs, maintenance, and major overhauls
$C_{HTOp:T}$	costs of tires replacement
FC	fuel consumption [liters/km] estimated according to the United States Environmental Protection Agency (US EPA) Motor Vehicle Emissions Simulator (MOVES) (United States Environmental Protection Agency [US EPA], 2010b) as detailed by Santos et al. (2014)
TL	estimated tire life [km]
L_{HM}	distance of the hauling movement [km] (1 way)
S_{HM}	Average speed of the hauling movement [km/hr]

The meaning of the remaining variables is the same as that presented in Supplemental material 1.1 Construction and M&R phase.

Table 1.3. Values of the variables corresponding to each hauling truck needed to compute the materials transportation costs

Name	Brand	Model	AYU [km]	AOP [years]	AC [$]	SV [$]	$F_{PM\&FOG}$	F_{Repair}	$InsR$ [%]	TR [%]	TC [$]	TL [km]
Dump truck	Mack	Granite GU 713	166,000	10	140,000	60,000	0.119	0.65	3	2	4,000	322,000
Water tank truck	Mack	Granite GU 713	166,000	10	175,000	35,000	0.119	0.65	3	2	4,000	322,000
Cement tank truck	Mack	Granite GU 713	166,000	10	190,000	38,000	0.119	0.65	3	2	4,000	322,000
Asphalt distributor tank truck	Mack	Granite CHU 613	166,000	10	205,000	41,000	0.119	0.65	3	2	7,200	322,000
Bituminous emulsions distributor tank truck	Mack	Granite GU 713	166,000	10	195,000	39,000	0.119	0.65	3	2	4,000	322,000

Acronyms: Equal to those specified in the formulation referring to the Construction and M&R phase

1.3. *WZ traffic management phase*

Table 1.4. Values of the main parameters used in the computation of the unit cost of travel time for passenger cars

Name of the parameter	Value of the parameter	Data Source
Proportion of PC on personal travel [%]	93.7	National Household Transportation Survey [NHTS] (http://nhts.ornl.gov/tools.shtml)
Average vehicle occupancy of PC for personal travel [person/veh]	1.67	National Household Transportation Survey [NHTS] (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type [%]	70	United States Department of Transportation [US DOT] (2003)
Median annual household income of all US households [$]	50 054	DeNavas-Walt, Proctor & Smith (2012)
Hourly time value of a person on personal time [$/person.hr]	16.85	-
Hourly time value of a vehicle on personal travel [$/veh.hr]	28.13	-
Proportion of PC on business travel [%]	6.3	National Household Transportation Survey [NHTS] (http://nhts.ornl.gov/tools.shtml)
Average vehicle occupancy (AVO) of PC for business travel [person/veh]	1.24	National Household Transportation Survey [NHTS] (http://nhts.ornl.gov/tools.shtml)
Hourly value of personal travel time as a percentage of wage rate for an intercity travel type [%]	100	United States Department of Transportation [US DOT] (2003)
Total hourly wages and benefits of all civilian workers [$]	29.98	Unites States Department of Labor (2011b)
Hourly time value of a person on business time [$/person.hr]	29.98	-
Hourly time value of a vehicle on business travel [$/veh.hr]	37.18	-
Weighted average of hourly time value of PC [$/hr]	**28.70**	-

Table 1.5.Values of the main parameters used in the computation of the unit cost of travel time for trucks

Name of the parameter	Value of the parameter	Data Source
AVO of single-unit trucks [person/veh]	1.025	Federal Highway Administration [FHWA] (2005)
AVO of combination-unit trucks [person/veh]	1.12	Federal Highway Administration [FHWA] (2005)
Average wages and benefits for single-unit truck drivers	21.87	Unites States Department of Labor (2011b)
Average wages and benefits for combination-unit truck drivers	26.13	Unites States Department of Labor (2011b)
Hourly time value of single-unit trucks [$/hr]	**22.42**	-
Hourly time value of combination-unit trucks [$/hr]	**29.27**	-

Table 1.6. Values of the main parameters used in the computation of the cost of freight inventory delay

Name of the parameter	Value of the parameter	Data Source
Percentage of empty loaded single-unit trucks [%]	29	Alam, Fekpe & Majed (2007)
Percentage of empty loaded combination-unit trucks [%]	24	Alam, Fekpe & Majed (2007)
Average payload of single-unit trucks [lb]	27 859	Alam & Rajamanickam (2007)
Average payload of combination-unit trucks [lb]	42 527	Alam & Rajamanickam (2007)
Average prime bank lending rate [%]	3.25	Board of Governors of the Federal Reserve System (http://www.federalreserve.gov/releases/H15/data.htm #fn2)
Average value of commodities shipped by truck [$/lb]	1.52	Federal Highway Administration [FHWA] (2005)
Hourly value of freight shipped by truck [$/lb.hr]	7.36×10^{-06}	-
Hourly freight inventory costs for single-unit trucks [$/hr]	**0.21**	-
Hourly freight inventory costs for combination-unit trucks [$/hr]	**0.31**	-

1.4. *References*

Alam, M., Fekpe, E. & Majed, M. (2007). *FAF² Freight traffic analysis*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Retrieved from Office of Freight Management and Operations (HOFM), FHWA website: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports7/index.htm

Alam, M., & Rajamanickam, G. (2007). *Development of truck payload equivalent factor*. Office of Freight Management and Operations (HFMO), Federal Highway Administration (FHWA), Washington, D.C. Retrieved from Office of Freight Management and Operations (HOFM), FHWA website: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports9/index.htm

DeNavas-Walt, C., Proctor, B. D. & Smith, J. C. (2012). *Income, poverty, and health Insurance coverage in the United States: 2011* (Report No. P60-243), US Census Bureau, September 2012. Retrieved from U.S. Census Bureau website: http://www.census.gov/library/publications/2012/demo/p60-243.html

Federal Highway Administration (2005). *Highway economic requirements system- state version (HERST-ST). Technical report*. Retrieved from Federal Highway Administration website: http://www.fhwa.dot.gov/asset/hersst/pubs/tech/tech00.cfm

Santos, J., Bryce, J., Flintsch, G., Ferreira, A., & Diefenderfer, B. K. (2014). A life cycle assessment of in-place recycling and conventional pavement construction and maintenance practices. *Structure and Infrastructure Engineering*. Accepted for publication. http://dx.doi.org/10.1080/15732479.2014.945095

United States Department of Labor (2011b). *Employer costs for employee compensation – June 2011.* Bureau of Labor Statistics, Department of Labor. Retrieved from the United States Department of Labor website: http://www.bls.gov/schedule/archives/ecec_nr.htm#2011

United States Department of Transportation (2003). *Valuation of Travel Time in Economic Analysis, Revised Departmental Guidance, Memorandum*. Office of the Secretary of Transportation, U.S. Department of Transportation, Washington, DC. Retrieved from Office of the Assistant Secretary for Transportation Policy website: http://www.dot.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic

United States Environmental Protection Agency (2010b). *Motor Vehicle Emission Simulator (MOVES). user guide for MOVES2010b* (Report EPA-420-B-12-001b). Retrieved from United States Environmental Protection Agency website: http://www.epa.gov/otaq/models/moves/index.htm#user.

Wiegmann, J., Sundararajan, A. & Tao, Z. (2011). *Decision making for outsourcing and privatization of vehicle and equipment fleet maintenance* (National Cooperative Highway Research Program Report No. 692). Transportation Research Board, Washington, D.C. Retrieved from Transportation Research Board website: http://www.trb.org/Main/Blurbs/165623.aspx