Life Cycle Assessment of Sustainable Road Pavements: Carbon Footprinting and Multi-attribute Analysis

Filippo Giustozzi

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Civil Engineering

Gerardo W. Flintsch, Committee chair
Karen P. DePauw
Antonio A. Trani
Maurizio Crispino

June 11, 2012
Blacksburg, Virginia

Keywords: life cycle assessment, pavement maintenance, carbon footprinting, multi-objective optimization, pavement management.

Life Cycle Assessment of Sustainable Road Pavements: Carbon Footprinting and Multi-attribute Analysis

Filippo Giustozzi

ABSTRACT

Sustainability is increasingly becoming a significant part of strategic asset management worldwide. Road agencies are providing guidelines to assess the relative sustainability of road projects. Unfortunately, environmental features of a road project are still considered as stand-alone evaluations, an added value. Very little has been done to integrate environmental impacts as a part of pavement management systems and other decision support tools to choose between different strategies. In this way, being awarded with a "green" certificate for a specific road project could result in the belief that recognition would correspond to the optimal strategy. Furthermore, a road project awarded with a "green" rating during the construction phase does not mean that the project results "green" if a life cycle approach is considered. Indeed, the most environmental friendly strategies may not be the ones with the highest performance. Using "greener" materials or performing recycle-related practices may lead to a lower performance over the life cycle and therefore produce an increase in maintenance needed, which could in turn result into more congestion due to work zones and higher total emissions. Therefore, construction and maintenance strategies should be analyzed according to three main parameters: cost, performance or effectiveness, and environmental impacts.

The cost analysis part takes into account outflows over the service life of the pavement according to the well-known Life Cycle Cost Analysis methodology. The cheapest maintenance technique over the analysis period was expounded and sensitivity analyses to involved factors were conducted. Performance assessment was developed according to experimental on site data gathered and analyzed over several years to develop deterioration pavement models. Effectiveness of maintenance treatments is further provided and compared to the volume of traffic. In addition, environmental impacts related to maintenance and rehabilitation strategies were analyzed. Emissions were computed over the life cycle of the pavement from the manufacture of raw materials for the initial construction, placement, and maintenance phase.

Finally, an optimization procedure was developed for including environmental impacts into a Pavement Management System. A methodology to set a multi-attribute approach system, computing costs, performance, and eco-efficiency over the life cycle of the pavement, is therefore proposed.

TABLE OF CONTENTS:

LIST OF FIGURES:

LIST OF TABLES:

Chapter 1. Introduction

Although a significant number of environmental protection measures concerning industrial products and processes have emerged over the past few years, similar procedures have only just started to appear in road construction and related practices. An effort for understanding what a “sustainable pavement” would imply in terms of emissions and energy consumption is therefore required. Since environmental impact assessment of major projects is becoming mandatory in many countries, various studies are attempting to evaluate environmental impacts of different pavement materials, technologies, or processes during the road’s life cycle. To support these efforts, there is a need to measure and describe different aspects of sustainability related to pavements.

Assessing the carbon footprint of a product or a project, that is, computing the total amount of pollutants involved and converting them into an equivalent quantity of carbon dioxide, is gaining interests throughout the community. “Low carbon,” “green,” “recycled,” and “sustainable” items are often promoted by the media, and reducing the amount of pollutants emitted in the atmosphere is becoming a common goal in different fields.

Environmental certification approaches have been developed during the last decade to certify companies, buildings and products (i.e.; Energy star© 2011, U.S. Green Building Council 2009). Moreover, road infrastructure accounts for more than 6,506,204 km (both paved and unpaved roads) in the United States, over a comprehensive surface of 9,826,675 square km. Huge amounts of materials, mainly non-renewable or high impact resources (virgin aggregates, bitumen, concrete, polymers, etc.), are consumed every year for construction, maintenance and rehabilitation activities on roads. Finding the way towards a low carbon road pavement over its life cycle represents a great opportunity to reduce greenhouse gasses emissions worldwide and ensure sustainability in infrastructure. Moreover, reducing material consumption through the implementation of recycling practices reflects another useful way to achieve the goal previously stated (Horvath 2003).

Although computing impacts and emissions due to road activities is a step in the right direction, the environmental assessment cannot represent a stand-alone evaluation of a road project or material. It should always be linked with the performance and the costs of the infrastructure over the life cycle. A potentially environment friendly strategy, in fact, may not be the best performing strategy and could therefore lead to continuous maintenance and rehabilitation interventions, therefore wasting funds and increasing user delays.

Consequently, three aspects (cost, performance, and environment) have to be included in the decision support process in order to assist road authorities and municipalities in enhancing the management of their resources. An optimization of those three variables through a multi-attribute analysis that minimizes environmental impacts and costs while maximizing the performance over the life cycle is therefore needed.

The present dissertation focuses on the life cycle assessment of road materials and road-related construction and maintenance practices to understand their costs, performance, and environmental impacts over the service life of the pavement. A multi-attribute approach is developed to incorporate impacts assessment into the pavement management decision process.

1.1 Sustainability in Road Pavements

Transportation-related projects and systems usually have to face different and competing goals. Adding sustainability can be helpful for better balancing strategies and improving the decision process with new objectives.

Sustainability is usually defined by *the triple bottom line* concept, which includes taking into account three primary aspects: *social* (people), *environmental* (ecology), and *economic* (profit) (Hacking 2008). Assessing sustainability achieves the fulfillment of social and economic needs, both present and future, and the responsible use of natural resources while preserving or improving the well-being of the environment on which life depends (FHWA 2011).

The idea of sustainable development was described in a White House Council (1981) on Environmental Quality report stating that "if economic development is to be successful over the long term, it must proceed in a way that protects the natural resource base". The United Nations acknowledged in 1987 the sustainable development as "the development which meets the needs of current generations without compromising the ability of future generations to meet their own needs".

Since economic and natural resources are gradually decreasing during present times, sustainable approaches in transportation are made necessary for improving the quality of life and serving the transportation needs without impacting future generations to accomplish their needs (Brundtland 1987).

Furthermore, assessing sustainability on various fields and disciplines can help with developing innovative processes, assuring wide participation, meeting or anticipating new requirements and setting new standards, finding programmatic barriers, rewarding excellence and communicating benefits and goals (FHWA 2010).

1.2 Computing Environmental Impacts: a Life Cycle Assessment

1.2.1 Overview

Life cycle assessment (LCA) of materials and processes, also known as life cycle analysis, is a methodology to assess environmental impacts related with all the stages of a product's life from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use phase, repair and maintenance, up to disposal or recycling) (Azapagic 1999).

The goal of LCA is to compare the environmental effects of products and services in order to improve processes, support policies and provide a robust basis for deciding between alternatives. The term “life cycle” refers to the notion that the assessment requires the analysis of the raw material production, manufacture, distribution, use and disposal including all intervening transportation steps involved in the product's life.

Two main types of LCA can be acknowledged. The *attributional LCA* seeks to establish the impacts associated with the production and the use of a certain product, or with a specific service or process, at a point in time (typically the recent past). The *consequential LCA*, instead, seeks to identify the environmental consequences of a decision or a proposed change in a system under study (oriented to the future), which means that market and economic implications of a decision may have to be taken into account (Ekvall 2004).

The procedures for conducting life cycle assessments are part of the ISO 14000 environmental management standards (EMAS) - ISO 14040:2006 and 14044:2006 (Tibor 1995).

According to the ISO standards, an LCA is carried out in four distinct stages. These are often mutually dependent in that the outcomes of one stage will affect how other stages are completed.

Usually, an LCA starts with an explicit and consistent statement of the *goal and scope of the study*, which explains the context of the study and describes how and to whom communicate results. This is a key step in the overall analysis. The goal and scope part therefore include some technical details that provide constraints on the subsequent work: the *functional unit* clearly defines what is being studied providing a reference to which the inputs and outputs can be associated; the *system boundaries*; *assumptions and limitations* made; and the *impact categories* chosen.

Life cycle *inventory analysis* (LCI) involves the analysis of the inventory of flows from and to the surrounding environment for a specific product system. Inventory flows take account of water, energy, and raw materials, but also pollutant releases to air, land, and water. In order to develop the inventory, a flow model of the technical system is created adopting data on inputs and outputs. It is typically illustrated with a flow chart that comprises the activities that are going to be assessed in the supply chain and the technical system boundaries. The data must be connected to the functional unit previously defined. The outcomes obtained from the inventory is a LCI that informs about all inputs and outputs involved in the study, in the form of simple flows to and from the environment.

The inventory analysis is usually followed by the *impact assessment*. This phase of LCA evaluates the implication of possible environmental impacts based on the LCI flow results. Life Cycle Impact Assessment (LCIA) is constituted by the following elements: choice of impact categories, indicators, and characterization models; and impact measurement, where the LCI flows are converted into common equivalence units in order to be summed to provide an overall total impact. However, in addition to these basic steps, other LCIA elements – such as normalization, grouping, and weighting – can be conducted depending on the goal and scope of the LCA study. During the normalization process, the results of the impact categories are usually compared with the total impacts in the field of interest. Grouping consists of sorting and ranking the impact categories. Sometime instead, the environmental impacts are weighted relative to each other so that they can then be summed to obtain a single value for the total environmental impact.

Life cycle *interpretation* is a systematic way to identify, quantify, and check information coming from the results of the life cycle inventory and/or the life cycle impact assessment. Usually, the outcomes are summarized during the interpretation phase providing a set of conclusions and recommendations for the study. According to ISO standards (ISO 14044:2006), the interpretation should contain the identification of significant issues based on the results of the LCI and LCIA, the evaluation of the overall analysis considering its completeness, sensitivity and consistency, and conclusions, limitations and recommendations. A key factor of performing life cycle interpretation is to define the level of confidence in the final results and communicate them in an accurate manner. In order to interpret outcomes from an LCA, the accuracy of results as well as the achievement of goals has to be deeply investigated.

The methodology proposed in the thesis takes into account carbon emissions and aims to develop a sort of environmental database (or inventory) for road pavement's materials and related construction, maintenance, and recycling practices.

1.2.2 Carbon Footprinting

A carbon footprint corresponds to the measure of the environmental impacts related to our activities, particularly climate change. A carbon footprint corresponds to the total amount of greenhouse gasses (GHG) emitted over the life cycle of a specific product (Wiedmann 2007). The whole manufacturing processes, and their related emissions, for transforming the initial raw material into the final marketable product, are usually considered into the carbon footprint assessment. These include hauling, application, and disposal. Sometime they can also include the recycling stage. In the present dissertation, emissions from the manufacture of raw materials (cradle-to-gate analysis), equipment utilized during the construction stage, maintenance practices, preservation strategies over the life cycle, and construction procedures, are converted into carbon equivalent emissions to compute their carbon footprints.

A single footprint considers the six GHGs identified by the Kyoto Protocol: carbon oxides (CO_x), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbon (PFC), and sulfur hexafluoride (SF_6). These gasses absorb infrared radiation and can therefore affect the climate when they are released in the atmosphere (UK Carbon Trust 2010). In order to simplify the calculations, the six gasses are combined into a single index, the carbon footprint's unit measure: the equivalent carbon dioxide (CO_2e). The CO_2e allows a direct and easy comparison between different emissions sources in terms of equivalent carbon dioxide, considering the wide range of GHGs. The conversion from a certain greenhouse gas into a unit of equivalent carbon dioxide is carried out multiplying the amount of that GHG by its Global Warming Potential (GWP) on a specific time interval, usually 100 years.

The GWP is the measure of the global warming produced by a GHG trapped into the atmosphere for a specific time interval (20, 100, or 500 years) (Lashof 1990). Its potential of warming up the planet is compared to the CO_2 warming potential, assumed equal to 1. For example, the GWP related to the methane is 25, nitrous oxide is 298, hydrofluorocarbon (HFC-23) is 14800, and sulfur hexafluoride is 22800 (Solomon 2007). Even if accurate chemical analyses are available on almost every pollutant in the atmosphere, carbon footprint analysis is still a challenging task. A comprehensive database of emissions produced on every single process for converting raw material into the final product, is still far to be completed, especially on road-related materials and processes.

Finally, new standards are coming out to benefit organizations, governments, project proponents and stakeholders worldwide by providing clarity and consistency for quantifying, monitoring, reporting and validating or verifying GHG inventories or projects.

1.2.3 Embodied Energies

Embodied energy is defined as the sum of energy inputs (fuel, power, materials, human resources, etc.) that is used in the process for creating a new marketable product, from the point of extraction and refining materials, bringing it to market, and disposal/re-purposing of it (Hammond 2008). It is an accounting method which aims to find the overall sum of the energy required for an entire product over its life cycle: raw material extraction, transport, manufacture, assembly, installation, disassembly, and disposal.

Applying different calculation methods will produce different outcomes in terms of scale and purpose of application and therefore the type of energy embodied. An international agreement on the appropriateness of data scales and methodologies is still pending. A wide range of embodied energy values can be obtained for any given material and analysis. There is no comprehensive global embodied energy public dynamic database, and embodied energy calculations may therefore omit important data. This is the main reason why carbon footprints are mainly investigated in the present thesis.

For instance, moving a product from the manufacturer to the consumer may (or may not) include the embodied energies spent for the road construction and maintenance other than transportation itself. Such omissions can be a source of significant methodological error in embodied energy evaluations. Without estimating the embodied energy error, it is challenging to calibrate any sustainability index, and so the value of any given material, process or service. For these reasons, several embodied energy assessments set boundaries and fixed constraints in the analyses.

LEED (U.S. Green Building Council 2009) and SBTool (Larsson 2007), international initiatives for a sustainable built environment, are rating procedures in which the embodied energy of a product or material is evaluated, along with other factors, to assess environmental impacts of buildings. Embodied energy is an innovative concept for which researchers have not yet agreed absolute universal values because of the many variables that can be taken into account. Most of them agree that making comparisons between products and processes represents a more efficient procedure with than computing their absolute values. For this reason, comparative lists (e.g., University of Bath Embodied Energy & Carbon Material Inventory [Hammond 2008]) contain average absolute values, and describe the variables which have been taken into consideration when compiling the lists.

Typical embodied energy units of measurement are MJ/kg (megajoules of energy spent to make a kilogram of a specific product). The conversion between MJ and CO_2e is not straightforward, though possible, because different types of energy (oil, wind, solar, nuclear and so on) emit different amounts of carbon dioxide, so the actual amount of carbon dioxide emitted to produce a product will be dependent on the type of energy used in the manufacturing process.

1.2.4 Material Conservation

Pavement construction and maintenance consumes a significant amount of non-renewable resources and energy. The size of the energy and material investment suggests that improving the environmental understanding and economic aspects of the use of virgin versus recycled materials may lead to a more sustainable road construction sector. Beyond some clear benefits such as a lower amount of materials to landfills, other benefits are strictly dependent upon specific features also related to the performance and cost of construction activities. Manufacturing, processing, and transportation are very important to balance costs and benefits of recycling.

Recycled materials for pavement construction mainly come from demolition of old civil engineering structures, and waste materials from industry. Recycled materials used in construction activities may be categorized according to their source (Horvath, 2003): *industrial* byproducts (steel slag, glass, rubber, coal fly ash, etc.), *road* byproducts (reclaimed concrete pavement and reclaimed asphalt pavement materials), and *demolition* byproducts (crushed concrete, bricks, etc.). The incorporation of recycled materials in road construction and the substitution for virgin materials is perceived as an opportunity to save resources and avoid the impacts associated with their extraction and transportation. Nehdi (2001) has identified 43 types of secondary materials used in road construction: almost half of them were industrial byproducts. Retaining materials from landfills can be converted into economic benefits because of the avoided cost of dumping material into landfills. Furthermore, the rising price of sand and gravel highlights the importance of recycling as a cost saving measure for future investments (Horvath 2003). However, a more detailed assessment is needed for a comprehensive cost-benefit analysis. Other advantages, in fact, are not always easy to quantify. Transportation to the construction site can entail high fuel consumption and therefore major costs and less energy savings, if the distance to provide recycled materials exceeds a certain mileage.

Furthermore, even if the economic assessment is positive some poor mechanical properties or technical requirements established by the road authorities may limit or avoid the use of recycled materials. In addition, if a certain material achieves the technical requirements but the overall life-time of the pavement is reduced due to its use, then a life-cycle cost analysis can establish whether or not using virgin or recycled material is appropriate.

Recycling materials coming from industrial waste or demolition activity raise environmental concerns about the potential for certain components to leach into the soil and groundwater at concentrations that can be dangerous to human health. The environmental effects of processing, re-manufacturing, and transporting recycled materials should also have been taken into account.

The use of byproducts needs to be assessed in terms of their potential environmental consequences and how they compare to the materials they are substituting (Horvath 2003).

1.3 Cost Assessment: Life Cycle Cost Analysis

The Federal Highway Administration has set the following definition for Life-Cycle Cost Analysis in Pavement Design: “a process for evaluating the total economic worth of a usable project segment by analyzing initial cost and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring and resurfacing costs, over the life of the project segment” (U.S. Congress 1998).

In other words, it can be stated that Life Cycle Cost Analysis is an engineering-economic technique adopted to compare and evaluate alternative infrastructure investment options, by considering the whole costs, both from agencies and users, incurred during a common analysis period. LCCA is generally used by transportation authorities and road agencies as a decision-support tool to select the lowest cost strategy among different investment alternatives.

LCCA begins by developing project alternatives highlighting initial construction activities and consequent maintenance and rehabilitation (M&R) interventions, which are necessary to guarantee a specific level of performance. Costs related to M&R practices over the years of the analysis period are then estimated accounting for both agency and facility users' expenditures, and converted to their present value through a common economical technique known as "discounting." However, the final decision in the entire decision-making process does not depend only on LCCA outcomes, but it also considers several other aspects both political and financial related.

LCCA techniques are widely used by agencies and road authorities for establishing funding levels and allocating resources. However, some uncertainties regarding when and how LCCA should be applied and what kind of assumptions should be made still remain. Whether or not to consider user costs is still a controversial point in the analysis.

Usually, small transportation authorities and officials prefer short-term plans instead of evaluating the effectiveness of long-term investments, especially when local and low-traffic roads are involved. The initial construction cost is too often considered the most important factor that influences agencies decisions, while the future benefits and cost are often disregarded. Future M&R activities are part of the alternative as much as the initial construction is and, without maintenance and rehabilitation, the investment will not provide a continuous use to the public over the years. A broader application of this important engineering-economic tool should be therefore encouraged, particularly when investments require significant investments.

There are two different approaches when conducting a Life Cycle Cost Analysis (Rahman 2010). The first, the *deterministic approach*, assigns to every input parameter a fixed value directly chosen by the analyst. These values are usually developed by looking at historical data, similar analysis or relying on professional experience. The outcomes are then verified through sensitivity analyses, which can reveal if the results are subjected to some uncertainty. Unfortunately, this approach cannot establish the related degree of uncertainty.

The second approach, *probabilistic LCCA*, states that all the input values can be defined by a frequency distribution. A sampling distribution of possible values is developed for each input parameter. Through several iterations a probabilistic distribution of the outputs is developed. In this way, the most effective strategy can be determined for any given risk level and, when interpreting probabilistic LCCA results, decision-makers can choose the level which they feel more comfortable with.

Finally, it can be inferred that probabilistic analysis accounts for uncertainty in input parameters and allows for the simultaneous consideration of different assumptions in many variables. Nevertheless, this procedure is not applied by many agencies because of the effort required for running it. The deterministic LCCA is more often applied because it can be carried out relatively easily with an electronic spreadsheet and it is well understood.

The first step for developing a Life Cycle Cost Analysis is to identify the number of competing pavement design strategies to be compared and characterize them in terms of initial design, maintenance and rehabilitation activities.

When first constructed or just after rehabilitation, pavements are in good condition and provide a high level of performance. Then traffic, time, weather conditions, and other factors, cause functional and structural deterioration and, consequently, performance decreases rapidly. Hence, maintenance and rehabilitation (M&R) interventions are necessary to reduce the deterioration trend and enhance pavement condition and safety. Transportation agencies usually decide the optimal timing to perform M&R based on the chosen level of serviceability and funds availability.

As a consequence, competing alternatives in a Life Cycle Cost Analysis will be characterized by different activities spread over time. Since the main goal of LCCA is to quantify the impact of initial and future cost decisions over a long period of time, a common time horizon needs to be set. This horizon is called *analysis period* and should be established at the beginning of the analysis.

Costs considered in LCCA include those incurred by both, the agency and the users of the road net system, as a result of agency construction, maintenance and rehabilitation activities. User costs comprise three different groups of costs: Vehicle Operating Costs (VOC), Travel Time Costs (TTC) and Accident Costs (AC), incurred during normal in-service conditions and during construction work zones. Current LCCA practice does not typically consider user costs and, consequently, the analysis takes into account only agency costs. In some cases, this could lead to the wrong decision as slight differences in vehicle operating costs, caused by differences in roughness for instance, may result in huge differences in VOC over the life of a pavement (Hicks

1999). The Federal Highway Administration reports that “User costs are greatly influenced by current and future roadway operating characteristics. They are directly related to the current and future traffic demand, facility capacity and the timing, duration and frequency of work zone-induced capacity restrictions” (Smith 1998).

1.3.1 Agency Costs

Agency costs include all the costs incurred directly by the agency over the life of the project, including initial construction, maintenance, and rehabilitation activities. Construction costs are those needed to bring the road facility into initial service and their estimation involves the calculation of the required material quantities. These quantities, which are function of layers thickness and pavement width, are then multiplied by their unit prices. Maintenance expenditures include those costs necessary to maintain the asset above certain desirable performance and safety levels. There are various maintenance activities that can be carried out on a road, including maintenance of pavement, shoulders, drainage system, etc. For LCCA purposes, only those categories which directly affect the performance of a pavement should be considered.

Agency costs should also include the remaining value of the investment at the end of the analysis period, which represents a negative cost and may be computed using the *Remaining Service Life* (RSL) method. It represents the remaining life in a pavement alternative at the end of the analysis period converted into a monetary value.

Design alternatives are compared over equivalent analysis periods, but very often their service lives exceed the analysis period. Any service life exceeding the analysis period is known as Remaining Service Life and this value may vary significantly among competing alternatives.

1.3.2 User Costs

Best-practice LCCA requires including both the costs incurred by the agency and those incurred by the road users over the life of the project. In the LCCA process, user costs are those differential costs incurred by users among competing alternative road improvements, and associated maintenance and rehabilitation strategies, over the analysis period.

User costs can be described as the sum of two separate components: In-service Road User Costs and Work Zone Road User Costs. In-service costs are associated with in-service standard road conditions and reflect user costs basically as a function of the pavement performance (roughness). The work zone component includes user costs associated with using the road facility during periods of construction, maintenance, and rehabilitation activities, which generally restrict the road capacity and disrupt the normal traffic flow. They depend on work zone length, time period and traffic management.

Both of the categories include three user cost groups: Vehicle Operating Costs (VOC), Travel Time Costs (TTC) and Accident Costs (AC).

Vehicle Operating Costs are mainly due to road surface conditions (and particularly roughness), road geometry and driver behavior. They are evaluated separately for the different vehicle types as the sum of several factors: fuel consumption, oil consumption, tire consumption, vehicle utilization, parts consumption, labor hours, capital costs and overheads. Various methods are available in technical literature to compute VOC (e.g., World Bank Highway Design and Maintenance Standard Model HDM-4 [Kerali 2000]).

If the pavement performance curves of the competing alternatives are similar, there is a very small difference between Vehicle Operating Costs. Thus, they can be disregarded. However, this should be recognized as a simplification. If pavement performance curves substantially differ, significant VOC differentials can be developed.

Travel Time Costs vary, generally, by vehicle class and trip purpose (business or personal) and are, therefore, estimated separately for working passenger-hours and non-working passenger-hours. They are primarily a function of demand for use of a certain road facility with respect to its capacity and, with less influence, of road serviceability. As a consequence, there should be a small difference for TTC among competing alternatives during normal operating conditions. O the contrary, work zone user delay costs may be significantly different for maintenance and rehabilitation activities.

Accident Costs represent the damage undergone by material goods and the travelling public when an accident occurs. Three different levels of damage, and consequently of unit costs, can be identified: property damage, injury and fatality. Accident costs are then estimated by multiplying the unit cost per accident type by the crash rate per vehicle-km travelled, by the vehicle-km travelled. In-service accident costs depend primarily on the functional class of the road and thus they should not be expected to differ among competing alternatives in a LCCA. Work zone AC, depend on the work zone length and traffic organization.

It can be stated that incorporating road user costs into a LCCA procedure enhances the accuracy of the results, although it generally also represent a challenge.

When computed, user costs are often so large that they substantially exceed agency costs, particularly in high-traffic and congested areas. Most Departments of Transportation have been reluctant to rely on user cost estimates for various reasons. The main concern is the difficulty in evaluating user delay time. Although several literature sources on the value of traveler time exist, much of this time does not have a clearly-defined market value. In the same way, uncertainties exist about the relationship between agency activities and accident rates or vehicle operating costs. In addition, user costs do not charge agency finances as do agency costs. These aspects, in combination with the uncertainties associated with the calculation of the actual values, typically lead transportation decision-makers to give less weight (often none) to user costs than to agency costs. This limits the ability to find the lowest total cost solutions over the life cycle.

1.4 Performance Assessment: Life Cycle Performance Analysis

Benefits in Life Cycle Performance Analyses are generally all those advantages (also cost reductions) that are accrued by road users because of a particular road pavement’s condition. Pavement performance over the life cycle reflects the deterioration of the pavement when exposed to traffic, climate, and material decay over time. In order to estimate the benefits of a specific strategy, it is primarily necessary to identify all the factors and pavement characteristics that directly affect them. These factors could be numerous, such as roughness, level of service, appearance, color, light reflections, etc. Nevertheless, roughness and pavement serviceability are the ones with the biggest influence. It could be noticed, for instance, that increasing roughness usually results in reduced operating vehicle speeds, increasing Travel Time, Vehicle Operating Costs and discomfort.

As frequently happens in LCCA, it may be very hard or even inappropriate to attribute monetary value to the benefits provided by a pavement alternative. For this reason, benefits can be evaluated simply by measuring the area under the pavement performance curve for each alternative. This method is known as the *Area-Under-Curve* Method (Zimmmerman 1995).

Usually, when developing a Life Cycle Performance Analysis, the pavement performance curves resulting from competing strategies are different, depending on initial design characteristics, frequency and type of maintenance and rehabilitation, traffic and weather conditions.

The benefit provided by each pavement alternative can be quantified by calculating the area under the performance curve, eventually deducting the portion under the chosen threshold (figure 1.1).

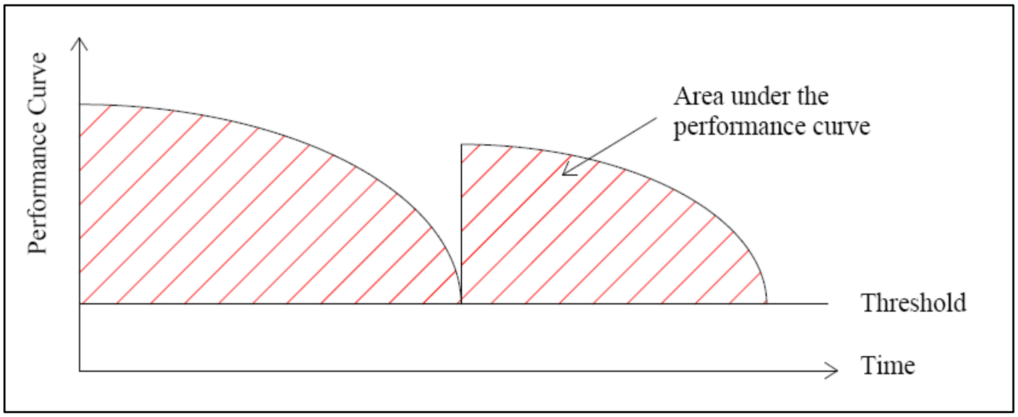


Figure 1.1: Area-Under-Curve Method

Several indices can be chosen to describe performance trends over the analysis period (i.e.; Present Serviceability Index, Pavement Condition Index, Structural Condition Index, Composite Condition Index, etc.). Commonly, the performance curve is expressed in terms of Present Serviceability Index (PSI) versus time (or Pavement Condition Index vs. time) and the benefit is therefore computed as follows:

$$Benefit = \int_0^z (PSI - PSI_T)dt \tag{1.1}$$

where z = analysis period; PSI = present serviceability index for each year; PSI_T = threshold chosen for present serviceability index; t = time elapsed since the beginning of the analysis year. The previous quantity is suitable in the comparison of different strategies. Sometimes, benefits for each M&R alternative could be computed as follow:

$$Benefit = AuC \cdot AADT \cdot L \tag{1.2}$$

where: *AuC* is the area under curve as calculated in the previous equation [i.e.; PSI * years]; *AADT* is the annual average daily traffic [vehicles/day]; *L* represents the length of the road section considered [i.e.; km].

Every M&R treatment carried out over the analysis period can be quantified by the "jump" in the performance curve. The incremental measurement of a performance indicator computed at the time just before and just after maintenance would be an instantaneous "*performance jump*" (PJ) due to certain maintenance activity/treatment. The PJ magnitude is generally a function of the time and type of maintenance intervention undertaken: a higher PJ indicates a greater improvement to the pavement serviceability. This approach has been developed in many research works and different models for various treatments can be found in literature (Labi 2005). Unfortunately, the practice of measuring performance before and after maintenance activities is not common in road agencies and data availability is very limited. Performance jumps, for instance, can be assessed: (1) through real scale field measurements, which result in a more accurate estimate but limited to the proper conditions of the site (pavement structure and materials, traffic, weather conditions), or (2) deduced using data and models available in literature for that specific treatment (Wu 2010).

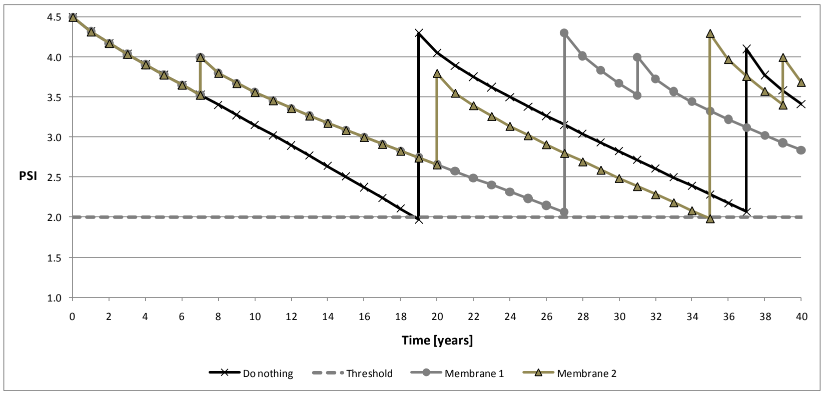


Figure 1.2: Performance Jumps of several M&R strategies, an example

It is very important to assess the optimal timing over the life cycle to schedule maintenance and rehabilitation activities on road pavements. Applying the same treatment twice over the life cycle can produce different overall performance depending on the time of application. Sensitivity analyses are therefore always recommended.

Estimating the Area-Under-Curve can be done in several mathematical ways. A common method is the *trapezoid method*: the area under the performance curve is divided into n-trapezoids, one for each year of the analysis period. The area of each trapezoid is therefore computed according to the following formula (if PSI is used as a performance indicator):

$$Area\ (trapezoid\ 1) = \frac{(PSI_{@year\ 0} + PSI_{@year\ 1}) \cdot 1year}{2} \quad (1.3)$$

That is, extending to all trapezoids:

$$Area\ Under\ Curve = \sum_{i=0}^{n} \frac{(PSI_i + PSI_{i+1}) \cdot 1year}{2} \quad (1.4)$$

As a general outcome, specific maintenance strategies on road pavements (i.e.; preventive maintenance) results in the pavement having better conditions over the analysis period. The improved performance will therefore reduce normal operating user costs (strictly related to the pavement conditions), improving user satisfaction.

1.5 Multi Criteria Decision Making

Several optimization methods are available in the literature for choosing between different alternatives taking into account multiple parameters. An ideal pavement management system (PMS) should help preserve all pavement sections at a high level of service, with adequate structural condition, and requiring a reasonable low budget. In addition, environmental impacts due to material consumption (especially non-renewable resources such as virgin aggregates or bitumen), construction equipment, hauling (to/from and within the construction site), use-phase (users delays, rolling resistance and related fuel consumption, etc.), and final disposal or recycling, should be minimized. Therefore, the perfect maintenance and rehabilitation strategy to be implemented into a PMS would be the one that maximize performance over time, minimizing costs (both agency and user costs), and minimizes the impacts on the environment over the life cycle of the pavement.

Unfortunately, many of these objectives are usually in conflict. For example, frequent maintenance interventions will typically improve the performance but, on the other hand, they result in higher traffic delays and congestion for users, therefore increasing their operating costs. Frequent maintenance will also require higher material consumption, use of equipment, lane closures, and traffic disruptions, therefore producing higher environmental impacts. Moreover, it is generally believed that lowering the budget will result in a poorer condition of the whole pavement network. However, several studies (Cuelho 2004; Geoffroy 1996; Labi 2003; Labi 2005; and Hass 1994) identified "*preventive maintenance*" approaches, for instance, as significant contributors for saving money while enhancing the performance of the pavement over the service life.

Decision processes in programming of pavement maintenance alternatives should involve multi-objective considerations in order to address these conflicting requirements. However, the current practice in pavement management is based on single-objective optimization, usually considering costs as a stand-alone evaluation for choosing among alternatives. Other parameters involved into the decision process are imposed as constraints in the analysis (i.e.; minimum level of service required, maximum amount of resources to be used, etc.). Outcomes obtained by subjectively setting limits and boundaries are therefore sub-optimal if compared to the results obtained using multi-objective optimization methods (Fwa 2000). When dealing with a single-objective optimization problem the superiority of one solution respect to another can be easily determined by comparing the objective function values of the two solutions. The optimal solution will be the one providing the best value of the objective function. Unfortunately, more than one optimal solution can be defined in multi-attribute optimization problems since there is not a unique "best" solution (i.e.; a dominating solution). In this kind of approaches, a family of optimal solutions, non-dominated solutions, can be defined and it is known as the Pareto optimal solution set (Goldberg 1989).

Furthermore, a curve (for the case of two-objective problems) or a surface (for the case of three or higher multi-objective problems) can be identified that includes all non-dominated solutions. This curve, or surface, is defined as the Pareto frontier. A Pareto optimal solution cannot be improved with respect to any objective without worsening at least one other objective; it represents a trade-off between conflicting requirements. Consequently, since finding out a unique multi-objective solution able to optimize each objective function at the same time is almost impossible, then a reasonable solution can be chosen within a set of reasonable solutions, each of which is not dominated by other solutions even if the objectives are satisfied.

1.6 Dissertation overview

1.6.1 Problem statement

Achieving sustainability, although promoted by media and researchers worldwide, still represents a challenging issue because of two main reasons: (1) there are still questions about how it should be measured, and (2) there are no commonly accepted approaches to incorporate it into comprehensive decision support processes, such as pavement management systems (PMS) or infrastructure management systems (IMS).

The sustainability of a product, material, or project can be quantified, for instance, by measuring the environmental impacts of the several processes for transforming the raw materials into the final product or carrying out that particular work. Environmental impacts are usually measured through the computation of the greenhouse-gasses (GHG) emitted in the atmosphere during the whole process, known as the carbon footprint.

Carbon footprinting analyses are not easy to develop mainly because standards have not been set for road pavements until now. Different procedures and constraints can therefore be adopted achieving different results depending upon the inputs.

Assessing the environmental sustainability of a certain material, maintenance strategy, or project, cannot be a stand-alone procedure. Instead, it should be included into a more comprehensive life cycle analysis. Cost and performance analyses of competing strategies should be enhanced with a multi-attribute approach that includes environmental impacts and eco-efficiency. Probably the most effective approaches for assessing what a “sustainable pavement” or a “green project” would entail is through multi-attribute analysis and comprehensive rating systems.

1.6.2 Objectives

The main objectives of this dissertation are: (1) to propose an objective methodology to simultaneously assess costs, performance, and environmental impacts of road related practices, strategies, and materials, and (2) to implement a procedure for including eco-efficiency values into a more comprehensive decision support system.

Specifically, the research covers the following topics:

1- Analysis of costs and performance over the pavement life cycle according to several initial construction, and maintenance and rehabilitation activities;

2- Current methods for assessing sustainability and measuring environmental impacts (carbon footprint analyses) on road pavements;
3- Environmental impacts assessment of road material production, maintenance strategies, and construction operations (construction and maintenance phase) over the pavement life cycle;
4- Relative significance of constraints and parameters involved into the environmental analysis (sensitivity analysis);
5- Mathematical approaches for incorporating environmental impacts into the decision support process according to multi-criteria analyses.

1.6.3 Research Approach

The following tasks were completed in order to achieve the overall objectives of the investigation.

- A critical and extensive review of technical papers and books in order to acquire a deeper knowledge of the most recent advances in the topics, which was summarized in the previous section. The review suggested that although a great quantity of relevant articles is available about costs and performance analysis of road pavements over the life cycle, only a small number of paper cover the environmental life cycle assessment of roads. Apparently, widely-accepted methods for environmental assessment are available for buildings and industrial products, but a minimum amount was linked to road pavements. Sustainability concepts for transportation infrastructures only started to arise in the last two years.
- Analysis of current techniques and methodologies to assess costs, performance, and the environmental impacts over the life cycle of a product. Starting from the cost analysis, through the performance investigations, to the environmental assessments of road materials and practices, many theoretical studies and practice exercises were reviewed. The most commonly available materials in road pavement were investigated to know their costs and performance. Furthermore, for each parameter, several sensitivity analyses have been run to investigate how it could be affected by changing cost and performance-related factors: discount rate, analysis period, time of application, etc. The dissertation proposes a new procedure for computing environmental impacts of road works through

carbon footprinting, and applies the procedure for different materials' manufacture techniques, maintenance and rehabilitation strategies, and construction practices.

- Analysis of performance, and in particular of maintenance effectiveness, was conducted by investigating real pavement sections throughout the State of Virginia. Data available from the Virginia Department of Transportation were investigated and several maintenance types were evaluated according to different traffic levels for developing deterioration curves. The Area-under-Curve was estimated taking into account real pavement data.
- Through the carbon footprint method road materials and related practices impacts were assessed. The amounts of equivalent carbon emitted into the atmosphere to carry out a unit length of maintenance (or rehabilitation) treatment, manufacture a ton of a certain material, and adopt a certain machine during construction, for instance, were calculated. In particular, different available design mixes were investigated for materials and treatments, and different brands were analyzed for the construction equipment.
- The three parameters (costs, performance, and environmental impacts), independently assessed, were finally included into a single comprehensive evaluation. A considerable amount of potentially feasible maintenance and rehabilitation strategies were generated, combining the three aspects over the life cycle of the pavement, for selecting the strategy in the decision making process that optimizes the objectives: minimize costs and environmental impacts while maximizing performance.

1.6.4 Dissertation organization

The dissertation follows a manuscript format which includes a collection of papers; each manuscript is used as an individual chapter of the dissertation. They represent the research work in which the author was involved at Virginia Tech during the duration of the doctoral studies.

A general introduction is provided in **Chapter 1**. The general contents of the dissertation, the problem statement, the research objectives, and the research approach, are presented here.

Chapter 2 – *Cost Assessment:* "*Life cycle cost analysis of a new composite material for bridge pavement waterproofing*" illustrates the methodology used for conducting life-cycle cost analysis. The paper, published in the proceedings of the Fifth International IABMAS Conference (Philadelphia, USA, 11-15 July 2010), investigates costs over the pavement life cycle related to maintenance and rehabilitation strategy. In particular, a new composite membrane for pavement waterproofing was tested and a full scale test area was developed. The Life Cycle Cost Analysis was aimed at setting up a procedure for the evaluation of the long term cost-benefits associated with that maintenance strategy. The net benefit (in term of unit saved per unit spent) was computed and sensitivity analyses to the factors involved were conducted.

Chapter 3 – *Performance Analysis: "Effectiveness of Preventive Maintenance Treatments on Road Pavements"* introduces the methodology adopted for comparing the performance of pavement maintenance and rehabilitation policies. The paper analyzes and quantifies the benefits of adopting a preventive maintenance approach on road pavements. A considerable amount of pavement sections were therefore analyzed in the state of Virginia (USA) and the effectiveness of various maintenance treatments was evaluated in order to quantify the extension of life provided. Post-treatment deterioration curves were developed according to the experimental data gathered. Since effectiveness of treatments was found to be affected by traffic levels and structural capacity of pavements, several deterioration models were developed. Research findings can be generalized to be applied to a variety of pavement maintenance situations encountered by road agencies. This chapter has been accepted for publication in the proceedings of the Seventh International Conference on Maintenance and Rehabilitation of Pavements (MAIREPAV 7, Auckland, New Zealand, August 28-30, 2012).

Chapter 4 – *Environmental Assessment:* "*Environmental Assessment of Road Construction Methods for a Low Carbon Pavement"* introduces the methodology used to assess the economic impact based on carbon footprinting. It illustrates the approach with a carbon footprint assessment of two construction methods for road foundation/sub-base layers. The analysis showed that re-use of in situ soils through mechanical stabilization can help contractors and companies to reduce their environmental impacts when building foundation layers for road pavements. The paper shows that soil stabilization uses less equipment, has less material handle and supply, and consumes less virgin aggregates, thus providing a considerable eco-advantage in terms of emissions produced. This chapter was published in the Transportation Research Board Compendium of Papers (91st Annual Meeting, Washington DC, USA, January 22-25, 2012).

Chapter 5 – *Environmental Assessment:* "*Recycling Practices for Achieving Environmental Sustainability in Road and Airport Pavements"* presents another application of the environmental assessment methodology proposed. It shows how more sustainable pavements can be achieved with innovative construction techniques and materials. In particular, the analysis shows that a long-lasting and well-performing pavement can be built with more than 85 % of recycled materials. The environmental analysis of a case study shows that a reduction of almost 35% of emissions could be achieved using recycling practices. Furthermore, pavement performance is analyzed and monitored as well in order to show that recycling does not necessarily result in lower performance. This chapter was submitted for publication in the proceedings of the 5th International Conference of the Società Italiana Infrastrutture Viarie (SIIV), "Sustainability of Road Infrastructures" (to be held in Rome, Italy, 29-31 October 2012).

Chapter 6 – *Performance and Environmental Analysis:* "*Environmental Analysis of Preventive Maintenance Treatments on Road Pavements"* proposes a methodology to compare the eco-effectiveness of pavement preservation and rehabilitation strategies. For the case study considered, pavement preventive maintenance strategies were shown to be eco-effective, in addition to providing enhanced average performance over the life cycle. Moreover, the paper shows that a preventive maintenance strategy could save up to almost 44% of CO_2e emissions over a 50-years analysis period compared to a major rehabilitation and reconstruction approach. This chapter was published in the proceedings of the 8th International Conference on Managing Pavement Assets (Santiago, Chile, November 15-19, 2011).

Chapter 7 – *Multi-Attribute Approach:* "*Multi-Approach Life Cycle Assessment of Road Pavements for Achieving Environmental Sustainability"* makes a first attempt on combining the three decision variables (cost, performance and environmental impacts) into the decision-making process. The paper, which was published in the International Journal of Life Cycle Assessment (Volume 17, Number 4, 2012, p 409-419, DOI: 10.1007/s11367-011-0375-6), proposes a multi-attribute decision support methodology to compare pavement preservation and rehabilitation strategies. Costs, performance, and environmental impacts are combined to develop a multi-attribute decision index. The case study considered suggested that pavement preventive maintenance strategies can be eco-effective, well-performing and cheaper over the life cycle than major rehabilitations. A large amount of emissions and energy could be saved by adopting the optimal maintenance plans on road pavements.

Chapter 8 – *Multi-Attribute Approach:* "*Multi-Approach Life Cycle Assessment Optimization to Incorporate Environmental Impacts into PMS"* presents a more advanced method for combining the three assessment criteria. The paper introduces an optimization procedure for including environmental impacts into a Pavement Management System. A methodology to set a multi-attribute approach decision support process, computing costs, performance, and eco-efficiency, is proposed. The method can be useful for road authorities and municipalities for enhancing the decision support systems and choosing between several asset management alternatives.

Chapter 9 – *Findings, Conclusions and Recommendations for Future Research* summarizes the key findings and conclusions of the dissertation and provides recommendation for future research on sustainability assessment of road pavements.

1.6.5 Significance

Since environmental assessment of roads is a relatively new concept that is expanding worldwide, it is important to have a systematic way of comparing different materials, processes, and strategies in order to optimize decision-support systems. Setting an efficient procedure to compute carbon footprints, energy and material consumptions, and to incorporate environmental features in a multi-attribute analysis can lead towards more effective resources allocation (Flintsch 2009). In particular, the results obtained from the analysis can be customized depending on the need of that particular administration or road authority just by assigning different weights to the parameters involved in the decision process (Wu 2008). For example, a “greener” investment policy would assign a major weight for strategies oriented towards the use of recycled materials, the valorization of in-situ resources, or the application of specific “low pollution” treatments instead of prioritizing budget and performance. A totally different procedure can be adopted by a municipality with a lack of funds for carrying out road construction or maintenance activities. An “equal-weight” assessment could be done in order to optimize the whole available resources without favoring (or disregarding) any of the decision criteria. Decision and policy makers could benefit from both the above mentioned procedures.

Furthermore, carbon footprinting of road materials and related practices can represent a first step towards creating a “sustainable road database” and a step forward to the environmental certification of products, processes, and methodologies related to road infrastructures.

1.7 References

Azapagic A. and R. Clift (1999). *Life cycle assessment and multi-objective optimization*. Journal of Cleaner Production, 7(2): p. 135-143.

Brundtland G.H. (1987). *Our common future*. World commission on environment and development, p. 8-9.

Cuelho E., Freeman R.B. (2004). *Cost-effectiveness of crack sealing materials and techniques for asphalt pavements*. Montana Department of Transportation, Research Section, USA

Ekvall T. and B.P. Weidema (2004). *System boundaries and input data in consequential life cycle inventory analysis*. The International Journal of Life Cycle Assessment, 9(3): p. 161-171.

Energy star© (2011). National Association of State Energy Officials. 1414 Prince Street, Suite 200, Alexandria, VA 22314. www.naseo.org

FHWA (2010). *Sustainable Highways*. [cited May 2012]; Available from: www.sustainablehighways.org.

Flintsch G.W., Wu Z., Chen C., and Medina A. (2009). *Incorporating Sustainability Considerations into the Transportation Asset Management Process*. Transportation Research Board Annual Meeting, Washington DC, USA.

Fwa T., Chan W., and Hoque K. (2000). *Multi-objective optimization for pavement maintenance programming*. Journal of Transportation Engineering.

Geoffroy D.N, (1996). *NCHRP Synthesis of Highway Practice 223: Cost-Effective Preventive Pavement Maintenance*. Transportation Research Board, National Research Council, Washington D.C.

Goldberg D. E. (1989). *Genetic algorithms in search, optimization and machine learning*. Addison-Wesley, Reading, Mass.

Haas R., Hudson W.R., Zaniewski J.P. (1994). *Modern pavement management*. Krieger Publishing Company. ISBN: 0894645889

Hacking T. and P. Guthrie (2008). *A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment*. Environmental Impact Assessment Review. 28 (2-3): p. 73-89.

Hammond G. and C.I. Jones (2008). *Embodied energy and carbon in construction materials.* Energy, 161(2): p. 87–98.

Hicks R., J.R. Lundy, and J.A. Epps (1999). *Life cycle costs for asphalt-rubber paving materials*. Rubber Pavements Association, Tempe, Arizona.

Horvath A. (2003). *Life-Cycle Environmental and Economic Assessment of using recycled materials for asphalt pavements*. Dept. of Civil and Environmental Engineering, University of California.

Kerali H.G.R., J. Odoki, and E. Stannard (2000). *Overview of HDM-4*. World Bank, Washington DC, USA.

Labi S. and Sinha K.C. (2003). *The effectiveness of maintenance and its impact on capital expenditures*. Publication FHWA/IN/JTRP-2002/27. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2003. DOI: 10.5703/1288284313331

Labi S. and K.C. Sinha (2005). *Life-cycle evaluation of flexible pavement preventive maintenance*. Journal of Transportation Engineering. 131: p. 744.

Larsson N. (2007). *Rating systems and SBTool*. The International Initiative for a Sustainable Built Environment.

Lashof D.A. and D.R. Ahuja (1990). *Relative contributions of greenhouse gas emissions to global warming*.

Nehdi M. (2001). *Ternary and quaternary cements for sustainable development*. Concrete International, 23(4): p. 35-42.

ISO 14044 (2006). *Environmental Management–Life Cycle Assessment–Requirements and Guidelines*.

Smith M. and J. Walls (1998). *Life-Cycle Cost Analysis in Pavement Design*. Report No. FHWA-SA-98-079. FHWA, Washington, DC.

Solomon S. (2007). Climate Change - *The physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge Univ. Pr.

Tibor T. and I. Feldman (1995). *ISO 14000 a guide to the new environmental management standards*. Irwin Professional Publishing, Burr Ridge, IL (USA).

Rahman S. and D. Vanier (2010). *Life cycle cost analysis as a decision support tool for managing municipal infrastructure*. National Research Council Canada, NRCC-46774.

U.K. Carbon Trust (2010). *Carbon footprinting: the next step to reduce your emissions*.

U.S. Congress (1998). *Transportation Equity Act for the 21st Century*.

U.S. Green Building Council (2009). *LEED 2009 for New Construction and Major Renovations*. Washington, DC. United States Green Building Council.

Zimmerman K.A. (1995). *Pavement management methodologies to select projects and recommend preservation treatments*. Vol. 222. Transportation Research Board.

Wiedmann T. and J. Minx (2007). *A definition of 'Carbon Footprint'*. ISA UK Research Report, 7(01).

Wu Z. (2008). *Hybrid multi-objective optimization models for managing pavement assets.* Virginia Polytechnic Institute and State University.

Wu Z., Groeger J., Simpson A., and Hicks R. (2010). *Performance Evaluation of Various Rehabilitation and Preservation Treatments*. Office of Asset Management, Federal Highway Administration, Washington, D.C.

Chapter 2. Life cycle cost analysis of a new composite material for bridge pavement waterproofing

M. Crispino[1], G. Flintsch[2], F. Giustozzi[3]

Abstract: One of the most critical issues related to bridge management and preservation is deck water-proofing. Infiltration of water into the bridge deck through unsealed cracks could result in accelerated loss of structural adequacy. Actions like crack sealing and general waterproofing can slow the deterioration and help reduce the life-cycle costs. An effective protection system against water infiltration is necessary for a functional and efficient bridge management plan. However, benefits associated with such maintenance activities are seldom ever considered. Consequently, many road bridge authorities do not include preventive maintenance activities in their bridge management programs. Recent research has resulted in the development of new technologies in the field of crack sealing and surface waterproofing. In this context, a new composite material for waterproofing interlayer membranes, to be "cold applied" (with great benefit for the environment and for workers) was tested in full scale experiments. This paper presents the main characteristics and the performance of this new technology, when applied to bridge decks. A life-cycle cost analysis quantitatively shows the savings to the road bridge authority and the benefits to the users (because of the improved condition of the bridge surface). The methodology applied is general and can be extended to other similar technologies.

---

[1] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

[3] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

2.1 Introduction

Preventive maintenance applied at the right time during a structure's service life has been proven to provide a significant improvement in its performance and reduce the deterioration rate thus increasing the structure service life.

Bridges play an important role in transportation systems by addressing adverse topography or overpassing natural obstacles, connecting various pieces of infrastructures. Given their importance, it is necessary to apply proper maintenance actions in order to extend the remaining life of existing bridges and minimize their repair and rehabilitation costs.

Bridge management is a long-term and expensive activity. In order to apply a proper long-term maintenance strategy, it is necessary to understand the existing condition of the structure, predict the future deterioration, choose the optimum maintenance actions and their application times, and predict their expected effects (Frangopol & Matsumoto, 2006).

A key challenge for bridge managers is prioritizing the maintenance of the bridges under their jurisdiction to obtain the best cost-benefit efficiency.

2.2 Bridge Deck Waterproofing

One critical issue related to bridges management and preservation is deck waterproofing. Providing an effective protection against water is a key aspect of a functional and efficient bridge management plan. In this context, the authors collaborated to develop a new composite material for bridge deck waterproofing through full scale experiments and evaluate of the long term benefits of this technology through a comprehensive analysis of the whole life cycle costs (LCCA) of the bridge surface.

Infiltration of water into the bridge deck through unsealed cracks could result in accelerated loss of structural adequacy.

Water, air pollution, harsh environment (e.g. sea bridges) and the use of de-icing salt during winter maintenance can damage the concrete structures. In particular when rain water penetrates the deck, it may leach out calcium hydroxide and salt formed by chemical reaction of the calcium compounds of the cement paste. Porosity increases and the concrete structure is damaged. Permeable concrete due to inappropriate concrete consolidation and/or high water-cement ratio also facilitates the infiltration of water, and repeated freezing and thawing cycles may cause the concrete structure to deteriorate.

Corrosion of steel reinforcement is produced by carbonation, chlorides and cracks. Carbonation lowers the pH-value that protects the steel against corrosion, chloride attacks steel especially at low cover thicknesses in the presence of oxygen. Water infiltration also causes cracks and interlayer saturation that could lead to, under traffic action, the progressive detachment of the surface layer and the development of new cracks and potholes.

As a result, waterproofing bridges through a preventive maintenance approach proves to be essential in order to obtain higher performances and long bridge deck service lives (FHWA, 1996, Peshkin, 2004, Crispino, 2008).

Materials and techniques for bridge surface waterproofing have to be properly adapted to the distress characteristics; for this purpose two different cracking types are therefore distinguished: isolated and diffuse cracking.

Isolated cracks are rehabilitated in accordance with two treatments: crack filling and crack sealing. Crack filling is used for “non-working” cracks, which are not affected by significant movements due to thermal and traffic loads. Cracks are first cleaned with compressed air and then generally filled up with bituminous materials. Crack sealing is used mainly for “working” cracks, subjected to deflection and thermal strains wider than 2 mm, usually transversally directed. The method requires the shaping of the crack to define its geometry and the subsequent sealing with a bituminous sealant (FHWA, 1996).

On the other hand, diffuse cracks are mitigated through maintenance strategies such as surface treatments, thin layer or rehabilitation treatments such as overlays or layer reconstruction, in some cases with interlayers having waterproofing and reinforcing functions (e.g. membranes or geosynthetics) (Galehouse, 1996, Zinke, 2005, Crispino, 2008).

Many investigations have tried to develop durable, cost-effective, and fast applied maintenance treatments to help Agencies involved in bridge management. In this context, an innovative preventive treatment for diffuse cracking through a new composite membrane, directly applied over the cracked surface, was developed and analyzed. The research included full scale experiments, performance predictions, and a life cycle cost analysis to evaluate long-term benefits.

2.3 Composite Waterproofing Interlayer Membrane Development

2.3.1 Introduction

The tested composite waterproofing membrane is made of a self-adhesive bituminous compound rein-forced with a crossover glass-fiber mesh.

The main distinctive characteristic of such membrane is the self-adhesive power, which allows “cold application.” This feature provides full adherence between the layers without even applying bituminous emulsions as tack coat.

The membrane is very thin, about 1.5-2 mm, and it has a self-adhesive lower side opposite to a thermo-adhesive upper side; this particular structure aims to assure a full adhesion to both the old “cold” cracked surface (concrete, asphalt concrete,…) below and the new hot asphalt wearing course applied above.

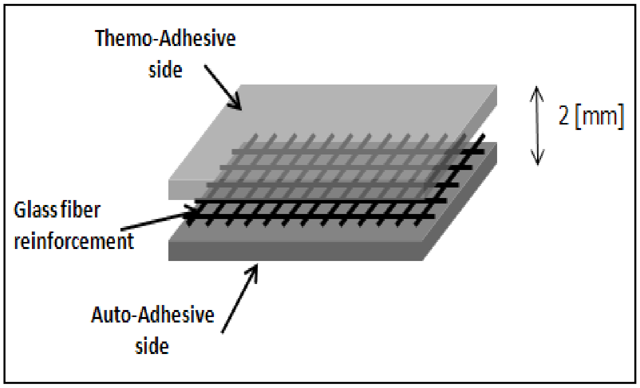


Figure 2.1: Composite waterproofing membrane

The membrane presents an orthotropic mechanical behavior: recent laboratory investigations have in fact shown an average transverse tensile resistance of 21.1 kN/m and an average longitudinal tensile resistance of 21.6 kN/m. This new innovative material was tested in full scale in order to evaluate its effectiveness in bridge pavement waterproofing and cracks reflection prevention.

2.3.2 Full scale tests

The full-scale test areas included three different road bridges with three different traffic levels. They included parts of: (1) a local mountain road with low traffic, (2) a provincial road with medium traffic level, and (3) a highway with heavy traffic (Fig. 2.2). All test sites showed high and severe surface deterioration. Experiments aimed at evaluating the cost-effectiveness of the waterproofing interlayer membrane in the rehabilitation of a damaged bridge deck pavement affected by diffuse cracking.

Figure 2.2: a) Full scale test area, highway; b) Full scale test area, local mountain road.

Different techniques were tested in order to evaluate the membrane efficacy for bridge deck waterproofing; the most interesting technique involved the application of the membrane directly on the existing pavement surface (or on existing concrete bridge deck), properly cleaned but without milling the distressed asphalt layer, and the subsequent laying of a traditional 3 cm asphalt wearing course layer.

Pre-application distress surveys of the test areas were conducted in order to characterize the surface cracking status and establish a database with the position, extension, and severity of each crack. The existing surface was carefully cleaned using a brushing machine, before applying the membrane without using a bituminous emulsion. A traditional asphalt wearing course layer (3 cm) compacted as usual completed the application.

Because of the strong adhesion between membrane and existing surface, the paver did not have any “attachment” problems while passing on the membrane during the paving stage. The entire maintenance operation was completed with a productivity of approximately 350 m²/h.

Test areas are being subjected to periodical monitoring by visual inspections in order to capture the development of distresses as the sections are subjected to traffic in service.

The heavy traffic over the highway bridge, part of a toll road system, was measured by the national road agency. After almost five months after application, there was practically no cracking. According to the following monitoring campaigns, the last one after almost two years from the application, the road surface condition has remained unchanged. There was no significant cracking after two years. In order to verify the waterproofing potential, a vapor barrier test has been done according to UNI-EN 1931 standard; transmission properties of steam were verified on road field samples obtained by coring. Test results are summarized in Table 2.1, using the following symbols: S, sample thickness; g, flux density of steam; w, steam permeance; δ, steam permeability; μ, factor of resistance to steam diffusion.

Table 2.1: Vapour barrier test [UNI-EN 1931]

Sample S	[μm]	g [Kg/(m^2/s)]	w [Kg/(m^2*h*Pa)]	δ [Kg/(m^2*s*Pa)]	μ
1	2000	6.078E-09	6.006E-12	67.74	33870
2	2000	4.789E-09	4.732E-12	85.98	42988
3	2000	5.157E-09	5.096E-12	79.84	39918
Mean		**5.34E-09**	**5.28E-12**	**77.85**	**38925**

The long lasting uncracked waterproofed surface has once again confirmed how important water is in pavement decay.

2.4 Life Cycle Cost Analysis

Preventive maintenance is increasingly being adopted by road agencies. This practice is based on the premise that a road asset should not be left to deteriorate up to the point where major rehabilitation is needed and that it can be beneficial to carry out preventive maintenance in the period between major rehabilitation events.

LCCA is a process to evaluate the economic effectiveness of different investments alternatives over a certain time period and identify the most cost-effective one. The selection of an appropriate maintenance strategy for an asset should consider all of the costs and benefits that will be incurred as a result of the selection of that strategy.

The authors set up an evaluating procedure for the different maintenance strategies in order to quantify the long-term implications of a preventive maintenance strategy. The procedure and the evaluation of long-term benefits due to the use of a waterproofing interlayer bituminous membrane are presented in the following sections.

2.4.1 LCCA for bridge deck pavement waterproofing technology

The prediction of the time to reach a given structural damage level is an important issue in planning strategies for the maintenance and repair of existing structures. Therefore having an accurate prediction of the major parameters defining structural performance and its evolution over time basing on limited monitoring activities is very important (Biondini, Frangopol, 2006).

Taking into account both agency and user costs during the whole bridge pavement life cycle, a non-intervention ("Do Nothing") alternative has been compared to different "Preventive Maintenance" strategies in order to quantify the long-term benefits of pavement waterproofing. Pavement treatment effectiveness models are in fact vital for pavement engineering and management.

A long enough analysis period has been chosen in order to allow the evaluation of the long-term costs for each alternative; superior performances in the short term may not necessarily translate to superior performances in the long term.

The usual asset analysis period range is always between 30 and 40 years, including at least one complete reconstruction for each option (FHWA, 1998). However, a sensitivity analysis on the period has been taken into account at the end.

2.4.1.1 Different strategies definition

Different maintenance strategies are characterized by maintenance plans that include the description, scheduled time, and costs of each intervention. However, an approach involving both cost and benefit analysis is generally preferred for measuring maintenance effectiveness (FHWA, 1998, NCHRP, 1989). In the determination of benefits, the measure of effectiveness may involve the use of a surrogate variable to represent maintenance effectiveness; the variable used could usually be time-based, load-based, or a combination of the two. According to this, a performance decay model has been associated to each alternative describing the pavement characteristics evolution during the analysis period.

The IRI (International Roughness Index) has been taken as a measure of the performance, assuming a starting value of 1.0 (m/km), related to new pavement condition, and a threshold value of 4.0 (m/km) indicating a damaged pavement condition. The Life Cycle Time of the pavement was defined as the time for the IRI index, starting with a value of 1.0, to reach the threshold value, at which full reconstruction is considered necessary. The assumed decay model is described by the following equation:

$$IRI_t = \mathrm{f}(\mathrm{IRI}_{\mathrm{t-1}}; \mathrm{k}) \qquad (2.1)$$

where t = pavement age, k = decay rate.

The model defined is the same for both the alternatives "Do-Nothing" and "Preventive Maintenance", with a different decay rate individually defined for each option based on practical field experience and comparable case study analyses, considering their limitations (Geoffrey, 1996, Solaimanian, 2002, Crispino, 2004a,b, Crispino, 2008). It should be noted that the decay rate should assume different values within the same maintenance alternative depending upon the surface age (deterioration rate) at the intervention time and intervention type. This approximation has been taken into account during the calculations.

The expected service life improvement values, according to different analyses concerning preventive maintenance treatments (Zaniewsky, 1996, Hicks, 1999, Zaniewsky, 2000, MDOT, 2000, Yildirim, 2004), are included in a range between 1 and 5 years, depending on the application context, pavement conditions and treatment individual characteristics. However the service life improvement given by the waterproofing membrane, because of the particular application that includes an asphalt wearing course layer (at least 3 cm) above the membrane, should be at least equal, but in most cases higher, to an HMA overlay's improvement.

Preventive maintenance triggers have to be defined taking into account cracking models, in order to set the optimal schedule for each maintenance activity concerning pavement waterproofing technologies (Galehouse, 1998).

The cracking model is considered linear and described by the following equation:

$$A_f(t) = t_o + F_f * t \qquad (2.2)$$

where: A_f = cracked area (ratio between the percentage of cracked area and the pavement surface), t_o = time of first crack initiation, F_f = cracking rate (percentage of cracked area per year) (Crispino & al., 2004a).

Cracking evolution depends on traffic volumes and composition, pavement characteristics and environmental conditions.

Treatment schedules for “Preventive Maintenance” alternatives have been defined through cracking and decay models previously reported, referring to the whole analysis period, determining the time and the characteristics of each treatment. Once the treatment timing scheme was known, it was possible to identify the Service Life related to each alternative as well as the Residual Service Life, that is the remaining pavement life at the end of the analysis period. Scheduling the activities represents the starting point for the life cycle cost evaluation related to each maintenance strategy.

2.4.1.2 Life Cycle Costs

Both agency and user costs were taken into account in calculating the life cycle cost for each maintenance strategy.

Monetary agency costs are all those costs associated with the alternative that are directly incurred by the agency during the analysis period and can be expressed in monetary terms. User costs are all those costs associated with the alternative that are incurred by road users over the analysis period and can be expressed in monetary terms. It should be noted that costs were evaluated referring to a sample bridge section, considered representative for the whole infrastructure and only those costs that are significantly different for the diverse alternatives need to be considered in the life cycle cost analysis, e.g. engineering and administration costs may be eventually cut out if they are equal in all alternatives. The analysis was developed in terms of constant costs, e.g., activity cost would not change over the period in which the life cycle analysis is performed.

Using a discount rate, commonly utilized in engineering economics to refer to the rate of change over time in the true value of money, taking into account fluctuations in investment interest rates and inflation, the costs were converted into present costs and summed, in order to determine life cycle costs of each alternative.

2.4.1.2.1 Agency costs

Agency costs include initial rehabilitation design and construction costs, follow-up rehabilitation design and construction costs, annual maintenance costs, traffic control costs during construction work and either demolition-and-removal costs or residual value of the pavement structure at the end of the analysis period.

During analysis the costs previously described could be resumed and identified as follows: construction costs (Cc), maintenance costs (Cm), reconstruction costs (Cr) and pavement residual serviceable life value (RV). Their sum outlines the agency costs:

$$Ac = Cc + Cm + Cr - RV \tag{2.3}$$

Construction costs were not assumed to be the same for all the different alternatives; maintenance costs were instead estimated considering supplying and application costs of each treatment, according to the following formula:

$$Cm = (S_{ci} + A_{ci}) * ARS * P_a \tag{2.4}$$

where: S_{ci} = supplying cost (per unit area), A_{ci} = application cost (per unit area) of the maintenance treatment i, ARS = Road Section Area, P_a = percentage of test area subjected to maintenance treatment. Due to its nature, the “Do-Nothing” alternative does not consider maintenance costs. Reconstruction costs were defined for both “Do-Nothing” and “Preventive Maintenance” alternatives; typical road renewal operations like milling of distressed pavement, disposal of new materials, supplying and application of bituminous emulsion, laying and compaction of new asphalt concrete layers are later on calculated, according to the formula:

$$Cm = (S_{cr} + A_{cr}) * ARS \tag{2.5}$$

where: S_{cr} = supplying cost for reconstruction operations (per unit area), A_{cr} = application costs for reconstruction operations (per unit area), ARS = Road Section Area.

Agency costs also include the residual value (RV), also called salvage value in literature, defined as the economic value that could be attributed to an alternative at the end of the analysis period. In this case the economic benefit derived from the remaining bridge pavement life at the end of the analysis period should be analyzed:

$$RV = C * (RSL/SL) \tag{2.6}$$

where: C = sum of maintenance and reconstruction costs for a single life cycle that is the period between two consecutive reconstructions, RSL = residual service life, SL = expected pavement service life according to the related decay model. A summary table of agency costs is hereafter provided (Tab. 2.2).

Table 2.2: Agency costs

	C_c	C_m	C_r	RV
Do-Nothing	-	-	$C_r=(S_c+A_c)ARS$	$RV=C(RSL/SL)$
Preventive Maintenance	-	$C_m=(S_c+A_c)ARS*P_a$	$C_r=(S_c+A_c)ARS$	$RV=C(RSL/SL)$

2.4.1.2.2 User Costs

User costs are the costs incurred by the road users over the project life and include: vehicle operating costs, time costs due to delays, and accident costs. These costs are usually associated with pavement serviceability (roughness in particular) and road works but, in order to compare the “Do-Nothing” and “Preventive Maintenance” strategies, costs due to the pavement condition have not been computed.

Assuming in fact a well-timed preventive maintenance treatment as hypothesis, the related IRI index reduction due to the preventive maintenance doesn’t produce a relevant comprehensive impact on the whole life cycle cost (FHWA, 1998).

Work zones involve two kinds of costs: the additional travel time that they cause the user and the additional vehicle operating costs in relation to normal service conditions. Vehicles are forced to decelerate and, if travelling in a work zone with an insufficient capacity, they will stop and queue, increasing fuel consumption and extra travel time.

Users cost characterization required a full work zone description (project year, length, duration and timing of lanes closures, speed limitations, capacity and number of open lanes, etc.), traffic spectrum report (volumes, distribution and composition) and time value estimation for each road user category that depends on trip type, purpose and vehicle class.

Unit users costs were calculated through the following formula (Kaan, 2004. Witczak, 1994.):

$$Cu = C_{o,i} + C_{d,i} + C_{a,i} \tag{2.7}$$

where $C_{o,i}$ = vehicle operative costs, $C_{d,i}$ = costs due to delays, $C_{a,i}$ = accident costs; all referred to the treatment i.

Vehicle operative costs due to work zones were turned into monetary values through the assessment of fuel and tire consumption, increasing of maintenance costs and loss of time according to the FHWA method (FHWA, 2004). NCHRP Report 1-33 “Procedure for Estimating Highway User Costs, Air Pollution and Noise Effect” has been taken as a reference, updating defined costs at the analysis year.

User delay costs usually dominate user costs and represent one of the most critical aspects in estimation because a determination of the value of time (for each user category) is required. Based on scientific and practical experience analysis (NCHRP, 1-33) the values of time were estimated and increased to better reflect the current/base year value (FHWA, 1998), assuming a different time charge for each traffic component depending also on the traffic control plans associated with the alternatives (NCHRP, 1993, 1995).

Accident costs were evaluated according to their consequences and localizations, considering specific analysis based on the observed territorial context, i.e. presence of intersections and tunnels, traffic composition, accident rates in the area, and local criticality. Different crash costs have been assumed in relation to their severity (slight, serious or fatal injuries) based on accident data and statistics (Crispino, 1998, FHWA, 1989, 1994).

Quickness of application and ability to immediately be opened to traffic characterized this “low impact” preventive maintenance treatment for bridge deck pavement waterproofing; road occupation in space and time was limited. For these reasons the related user costs (in terms of delay due to road works) were not taken into account. A summary table of user costs is provided (Tab. 2.3).

Table 2.3: User costs

	Normal Operation Costs	Work Zone Costs	
		Preventive Maintenance	Reconstruction
Do-Nothing	-	-	$Cu = \Sigma i\ (Co,i + Cd,i + Ca,i)$ *(FHWA)*
Preventive Maintenance	-	-	$Cu = \Sigma i\ (Co,i + Cd,i + Ca,i)$ *(FHWA)*

2.4.1.2.3. Life Cycle Costs modeling

Alternatives considered in a life-cycle cost analysis must be compared using a common measure of economic worth in order to let the analysts determine which alternative is the most cost-effective. The method used in the analysis is the "present worth" that makes use of the conversion of all cash flows, using a discount rate, to an equivalent single sum at time zero. In this way Life Cycle Cost (LCC) of each alternative could be determined. The predicted schedule of activities and their associated agency and user costs composed the life cycle cost stream for each alternative, usually represented into expenditure stream diagrams.

Life Cycle Cost Analysis's results were compared through a "Saving Factor" defined as follows. Life Cycle Cost of the "Preventive Maintenance" alternative is given by the formula:

$$LCC_{pm} = LCC_{dn} + C_{pm} - S_{pm} \qquad (2.8)$$

where: LCC_{pm} = Life Cycle Costs for "Preventive Maintenance" alternative, LCC_{dn} = Life Cycle Costs for "Do-Nothing" alternative, C_{pm} = cost of the preventive maintenance treatments, S_{pm} = savings due to preventive maintenance. "S_{pm}" index depends on preventive maintenance costs (C_{pm}) through a Saving Factor (SF), according to the formula:

$$LCC_{pm} = LCC_{dn} + C_{pm} - SF * C_{pm} \qquad (2.9)$$

According to the equation (9) Saving Factor SF could be expressed as follow:

$$SF = [(LCC_{dn} - LCC_{pm}) + C_{pm}]/C_{pm} \qquad [\text{Euro/Euro}] \qquad (2.10)$$

In this way SF exemplifies the net benefit earned for each unit spent in preventive maintenance.

2.4.2 Case Study: interlayer membrane for bridge deck pavement waterproofing

The Authors carried out a theoretical LCCA in order to estimate the long-term benefits of "Preventive Maintenance" strategies (PM), making use of a waterproofing interlayer membrane vs. a "Do-Nothing" alternative (DN). The analysis was developed considering a sample road bridge (with unitary length), with a transversal section constituted by two traffic lanes of 3.75 m width for each direction.

A linear cracking model was considered, assuming a cracking rate value of 7.14% (cracked area/years) and fixing the preventive maintenance trigger for the treatment in the 9th year of pavement life in the case of a single membrane application during the pavement life cycle. Applications occurred at 5th and 12th years of pavement life when applying the membrane interlayer twice during the pavement life cycle.

Decay models for each one of the two alternatives were defined. “Do-Nothing” decay model was based on a previous road survey (FHWA, 1998. Crispino, 2004) considering IRI index:

$$IRI_{year\text{-}t} = \min\left[4; IRI_{year\,(t-1)} + 0{,}1\right] \qquad (2.11)$$

Bridge deck pavement Service Life for “Do-Nothing” alternative has resulted in a period of 16 years. The decay model for “Preventive Maintenance” strategies differs from the “Do-Nothing” alternative due to the waterproofing membrane effect: in particular a range of expected bridge pavement life improvement between 1 and 5 years was considered for each PM application. Consequently, Service Life between 17 (=16+1) and 21 (=16+5) years was observed applying the membrane once and between 18 (=16+1+1) and 26 (=16+5+5) applying it twice.

Agency and User costs were defined considering reconstruction, preventive maintenance operations and residual service life value, according to the hypothesis and methods previously described. Costs were discounted and summed in order to obtain the Life Cycle Cost for each alternative; results are expressed through the “Saving Factor”, defined as described before and showed in Fig. 2.3.

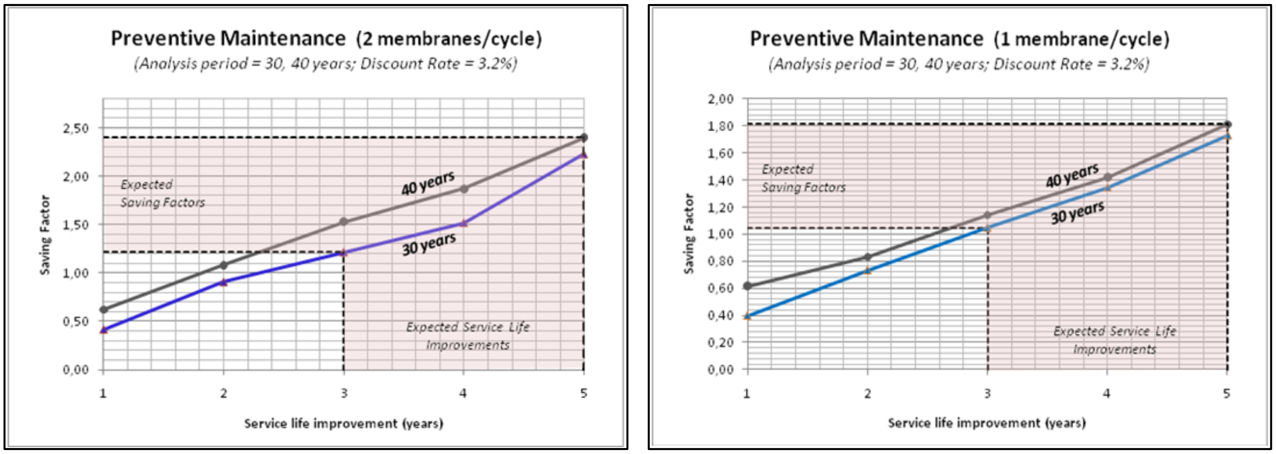


Figure 2.3: Savings due to preventive maintenance with waterproofing membrane

The result, derived from both economic analysis and practical experience, showed significant benefits due to the adoption, on bridge deck surface, of preventive maintenance treatment with waterproofing membrane, allowing a remarkable overall saving.

The analysis showed a net benefit due to the Preventive Maintenance treatments included between 1.10 and 1.80 units for every unit spent on preventive maintenance (single membrane application during pavement life cycle) and between 1.20 and 2.40 (double membrane application during pavement life cycle), according to service life improvements between 3 and 5 years, a result fully consistent with the results of the full scale experiment.

A sensitivity analysis of results to discount rate was finally developed to estimate the variability of the benefits/cost ratio, considering a range of discount rate values between 1% and 5%, in accordance with analysis periods of 30, 40, 50 and 60 years. Results showed that the Saving Factor is minimally affected by the discount rate variation, presenting a variance of the Saving Factor values of 0.0035. Analysis period instead affects the outcome more; results are in fact mainly related to the Residual Service Life value and to the schedule of Preventive Maintenance treatments in the analysis period.

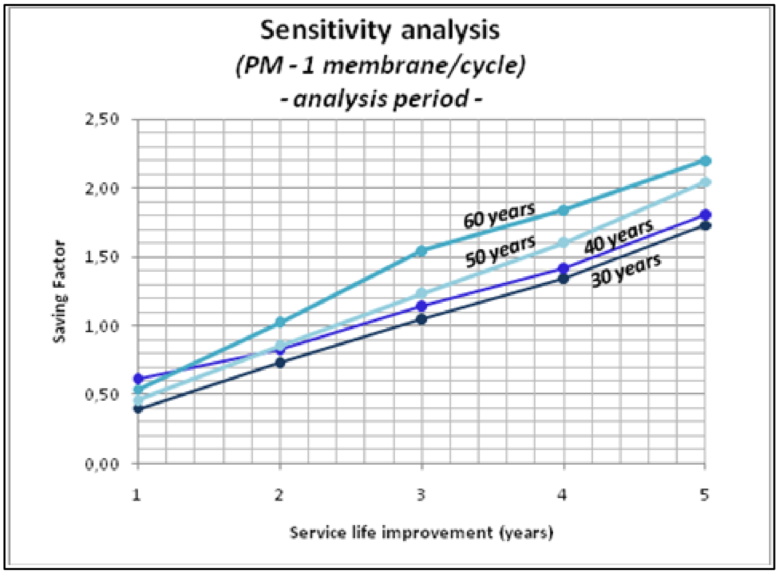


Figure 2.4: Sensitivity analysis to analysis period

2.5 Conclusions

The critical aspect related to pavement waterproofing treatments (membranes, crack sealing, tapes, etc.) is the evaluation of their long-term benefits, which should exceed their initial costs.

A new composite membrane for pavement waterproofing was tested at Politecnico di Milano. A full-scale experiment consisting of the application of such membrane on three different bridges with different traffic levels, whose pavements were affected by diffuse and severe cracking, allowed the performance of bridge deck waterproofing using membrane interlayer to be evaluated in terms of service life extension. This experiment, through visual inspections over about two years, has shown that the waterproofing system limits surface cracking.

The Life Cycle Cost Analysis was aimed at developing a procedure for the evaluation of long term preventive maintenance benefits in general terms. The procedure was then applied for two different preventive maintenance strategies related to those tested in the full scale test area. The improvement given by the treatments to the service life of the pavement was fixed in a range of 1-5 years and the expected long-term benefits were evaluated according to an analysis period of 30 and 40 years.

Results showed that the maintenance strategies with waterproofing membrane assures a net benefit (in term of unit per unit spent), according to a service life improvement between 3 and 5 years.

Saving Factor (index defined for the evaluation of PM long term benefits) results can be used independently from discount rate values and affected only by the analysis period.

On the basis of the results obtained it can be concluded that bridge pavement waterproofing can be considered not only as a technical solution to protect both the pavement and the bridge but also a cost-saving strategy for the Agency to able to delay expensive rehabilitation interventions.

2.6 References

Al Monsour et al. (1994). *Economic Analysis of Effectiveness of Pavement Preventive Maintenance*, Transportation Research Board.

Biondini F, Frangopol D. (2006). *Probabilistic Service Life Assessment and Maintenance Planning of Concrete Structures*, Journal of Structural Engineering.

Center for Transportation Studies (2000). *Best Practice Handbook on Asphalt Pavement Maintenance*. University of Minnesota.

Crispino, M. (2004a). *Development of a Pavement Management System in the Province of Milan: the validation of Pavement Performance Curve,* SIIV, Firenze.

Crispino, M. (2004b). *First experience in developing a PMS for a province road network in Italy*, 6th International Conference on Managing Pavements, Brisbane.

Crispino, M. (2008). *Improving Pavement Waterproofing in Italy*, 23rd ARRB Conference – Research Partnering with Practitioners, Adelaide.

Crispino et al. (2009). *Life cycle analysis of a new composite material for pavement waterproofing*, MAIREPAV 6, Turin.

Dohr G. et al. *Bridge deck waterproofing with bitumen sheets*.

Frangopol D. et al. (2006). *Reliability-based life-cycle bridge management using structural health monitoring*, IABMAS 06, Porto, Portugal.

FHWA Federal Highway Administration (1996). *Pavement Maintenance Effectiveness – Preventive Maintenance Treatments*, US Department of Transportation.

FHWA Federal Highway Administration (1998). *Life Cycle Cost Analysis in Pavement Design*, US Department of Transportation.

FWHA Federal Highway Administration (2004). *Life Cycle Cost Analysis - Real Cost*, US Department of Transportation.

Galehouse J. (1998). *Innovative Concepts for Preventive Maintenance*, Transportation Research Board.

Geoffoy, D.N. (1996). *Cost-Effective Preventive Pavement Maintenance*, Transportation Research Board.

Hall K. et al. (2003). *Guidelines for Life-Cycle Cost Analysis of Pavement Rehabilitation Strategies*, Transportation Research Board.

Jian-Zhong P. (2005). *Study of the road performance of waterproof materials for concrete bridge decks*, SATC, 2005.

Kaan, O. et al. (2004). *Life Cycle Cost Analysis: State of the practice vs State of the art*, Transportation Research Board.

Labi S, Sinha K. C. (2003). *Life Cycle Evaluation of Highway Pavement Preventive Maintenance*, Transportation Research Board.

Lamptey G. et al. (2008). *Decision support for optimal scheduling of highway pavement preventive maintenance within resurfacing cycle*, Decision Support System.

McKell W. (1975). *Field evaluations of waterproof membrane systems for bridge decks*, Virginia Dept. of Transportation.

Morgado J., Neves J. (2009). *Accounting For User Cost When Planning Pavement Maintenance And Rehabilitation Activities*, Mairepav 6, Torino.

NCHRP 133, (1972). *Procedure for Estimating Highway user Costs, Air Pollution, and Noise Effects.*

Peshkin, D.G. et al. (2004). *Optimal Timing of Pavement Preventive Maintenance Treatment Application*, Transportation Research Board.

Solaimanian et al. (2002). *Comparison of hot poured crack sealants to emulsified asphalt crack sealants*, 81st Annual Meeting of Transportation Research Board, Washington D.C.

Witczak M. (1994). *Probabilistic-Based MCP (Micro-Computer Program) for LCCA for Asphalt Concrete Pavements*, University of Maryland.

Zhang H. et al. (2008). *An integrated life cycle assessment and life cycle analysis model for pavement overlay systems*, IALCCE 08, Varenna, Italy.

Zinke S. (2005). *Evaluation of Pavement Crack treatments Literature Review*. Connecticut Advanced Pavement Laboratory, Final report.

Chapter 3. Effectiveness of Preventive Maintenance Treatments on Road Pavements

F. Giustozzi[1], M. Crispino[2], G. Flintsch[3]

ABSTRACT: Transportation departments worldwide have usually allocated resources for building new infrastructures; recently, the focus has instead moved towards maintaining and preserving existing assets and allocating funding in a more effective way. Several studies have already determined that carrying out maintenance on pavements retaining high performance effectively results in savings from both cost and performance perspectives: a preventive maintenance approach.

Indeed, maintenance, if applied at the right time using the right treatment, is able to extend the service life of a pavement; acting proactively on pavement deterioration therefore represents a key role for optimizing maintenance and rehabilitation strategies. Although several references discuss the advantages of a preventive maintenance approach, a very small amount of data on its short and long-term effectiveness is available. In common practice, pre-established treatments are therefore often applied regardless of the type of distress, traffic, and timing of the intervention, thus wasting resources without guaranteeing any substantial improvement in pavement performance.

The present paper aims to analyze and quantify the benefits of adopting a preventive maintenance approach. A considerable amount of pavement sections were analyzed in the state of Virginia (USA) and the effectiveness of various preventive maintenance treatments was evaluated in order to quantify the extension of life provided to pavements. Post-treatment deterioration curves were developed according to the experimental data gathered.

Since effectiveness of treatments was also found to be affected by traffic levels and structural capacity of pavements, several deterioration models were plotted. Research findings can be

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

exported and generalized to be applied to a variety of pavement maintenance situations encountered by road agencies.

3.1 Introduction

Presently, one of the most critical problems that affect the infrastructure system is the optimization of available resources, which are usually very limited, to preserve high system performance. Keeping road pavements at a high level of performance entails an effective maintenance plan over their service lives. Maintenance, if scheduled at the proper time and adopting the right treatments, can significantly reduce the overall costs while preserving the asset at higher performance over the long-term. An effective pavement management system (PMS) that continuously monitors the current road conditions is therefore desirable for predicting future deterioration, properly schedule maintenance activities, and correctly allocate budget.

Unfortunately, a vast majority of road authorities and municipalities do not collect any sort of pavement data on maintenance effectiveness in current practice. The quality control of road pavement projects has been historically focused on achieving minimum standards just after the placement but almost nothing has been recorded during the pavement service life. Moreover, a general lack of monitoring and therefore a significant unawareness of long-term pavement behavior typically results in a budget allocation based on experience, which is frequently ineffective. Instead, road agencies assign funds for pavement maintenance and rehabilitation (M&R) on an “overall” budget scheme: a fixed amount of funds is equally spread over the years of the maintenance contract. In this way a surplus or a lack of money, but mainly a loss of funds, for pavement maintenance treatments are therefore expected and the budget allocation results to be often inadequate. Thus, the common practice seems to be oriented towards a corrective approach for maintaining pavement assets in order to postpone outflow costs: deteriorate first, react later. The long-standing philosophy of “if it is not broke, then don’t fix it” still has many supporters.

The final result is that pavement assets are deteriorating faster than expected and the lack of adequate and previously allocated funding does not allow proper reaction.

Recently, maintenance techniques oriented towards the preservation of existing pavement assets are becoming popular. The main reason is the general understanding that available funding levels and a corrective approach do not result in pavement assets that perform at the level of service demanded by the general public (Peshkin et al. 2004). For instance, a report by the Federal Highway Administration (FHWA 2005) assesses that the actual condition of highway pavements on the National Highway System in the US is such that the cost to maintain the system at current condition levels is nearly $50 billion annually. However, the United States currently spends only $25 billion per year, and the estimated cost to upgrade the entire system and bring it up to a "good" level of service is almost $200 billion. It is therefore clear that there is a need for optimizing available resources through the adoption of different types of maintenance approaches. One of the most popular, especially in the United States, is represented by the preventive maintenance (PM) approach: act now for extending the pavement service life later.

Specific treatments applied when the pavement still retains high performance which intent is to slow down the deterioration while reducing the need for routine maintenance and major rehabilitations over the service life. Several studies have shown that PM strategy results into a cost effective and high performing alternative (Cuelho & Freeman 2004) (Geoffroy 1996) (Labi & Sinha 2005) (Hass et al. 1994).

The State-of-the-Practice in pavement preventive maintenance includes several treatments according to the various scenarios that can be faced by road agencies and municipalities. A non-exhaustive list can be summarized as follows (Galehouse 1998): crack sealing/filling, fog seal, chip seal (single and double course), slurry seal, micro-surfacing, thin and ultra-thin overlay, hot in-place recycling. Several descriptions of PM treatments are provided in literature to which it is referred (i.e.; Peshkin et al. 2004; Cuelho et al. 2006; Peshkin et al. 2011; NAPA 2009).

3.2 Performance Assessment of Preventive Maintenance Treatments

Preventive maintenance is usually associated with better performance of the pavement asset although very little experimental data are available on its effectiveness. Deterioration models of pavement PM strategies are therefore simply based on the extension of life provided by treatments according to literature (Wood et al. 2009); for instance, micro-surfacing is acknowledged to provide an extension of pavement service life between 3 and 6 years if applied once on a life cycle, slurry seal from 2 to 5 years, etc. Uncertainties related to this kind of approach can heavily affect long-term planning of M&R strategies: expecting to pay for certain treatments, and therefore allocating a budget for a specific year and then having the pavement deteriorating earlier is not acceptable. Therefore, ignoring how the pavement is going to deteriorate over the service life entails significant weaknesses in budget allocation. The ability to forecast future pavement conditions has potential economic benefits when implemented in pavement management systems. In addition, some PM treatments have been proven to be ineffective under specific boundary conditions (high traffic levels, specific weather conditions, application on inappropriate materials, etc.); an assessment of the effectiveness of PM treatments under several working conditions is thus needed.

The present paper provides post-treatment deterioration models analyzing the effectiveness of some PM treatments over a long-term analysis period. Results for micro-surfacing and slurry seal are presented in the following sections.

3.2.1 Pavement data collection

Monitoring of after-treatment pavement conditions and the resulting collection of pavement data was conducted by the Virginia department of transportation over more than 1400 pavement sections throughout the State. Sections were surveyed from 2007 up to 2010. Data analysis and post-processing were carried out directly by the authors. Furthermore, data presented in the paper are related only to flexible pavements.

For each section surveyed the database provides the following information:

- location (district, route name, direction, lane mile, etc.);
- traffic (daily truck number, traffic category, equivalent single axle loads-ESAL, etc.);
- pavement (construction year, materials adopted for the surface layer);
- PM treatment (year of treatment application, treatment type, pavement condition indices after a specific period of time).

In particular, pavement conditions were reported according to two main indices and then grouped into one comprehensive final performance index. For asphalt pavements, individual distress data was aggregated into the Load-related Distress Rating (LDR) and the Non-load-related Distress Rating (NDR). LDR incorporates pavement distresses that occur as a result of vehicle load related damages (e.g. fatigue cracking, rutting, etc.) while NDR evaluates distresses (e.g. transversal and longitudinal cracking, longitudinal joint separation, bleeding, etc.) considered to be primarily non-load related - i.e., caused by weathering of pavement surface, materials and/or construction deficiencies. Both indices are on a scale of 0 to 100, with 100 representing a pavement with no visible distresses.

The resulting index is the Combined Condition Index (CCI), calculated as the lowest between LDR and NDR (thus having the same scale between 0 and 100), and it is used as the main reference index to evaluate the actual condition of the pavement. For the sake of the analysis CCI values were grouped into five condition ranges: excellent, good, fair, poor and very poor. In general, pavement sections with a CCI value below 60 are considered ‘deficient’ and should be therefore proposed as candidates for medium-high severity M&R treatments.

The Combined Condition Index can be easily linked to more well-known and adopted indices such as the Pavement Condition Index (PCI).

3.2.2 Assumptions made in the analysis

Several assumptions were made in the analysis and they are hereafter presented.

- The effectiveness of PM treatments was evaluated in a time frame ranging from 0 to 10 years where year-0 represents the time when the treatment was applied, year-1 denotes the first year after the treatment application and so on. Although older data were also available, the authors decided not to use them because of their lower quantity and poor reliability. Indeed, available traffic data were not so accurate for the remote past, making it hard to assess a relationship between PM treatment effectiveness and traffic levels. However, the ten-year time span analyzed seemed to be appropriate for interpolating a deterioration trend and predicts future performance values.
- The pavement condition just after the treatment was assumed to be equal to the maximum admissible (CCI = 100). Indeed, it was assumed that preventive maintenance was performed when the pavement conditions ended up having a CCI ≥ 80. Therefore, every time a PM treatment was applied then the pavement would be completely restored (maximum performance).
- Two different types of roads were considered (interstate and primary roads) in order to investigate the effectiveness of PM treatments according to different structural capacities of the pavement. Interstates usually have a structural number (SN) (AASHTO 1993) between 6 and 7, while primary roads between 5 and 5.5.

- Levels of traffic were grouped into intervals of 1000 ESALs each. It should be noted that data for interstate roads included traffic between 2000 and 6000 ESALs, primary roads traffic was instead lower than 2000 ESALs.

An example of available data for primary roads is reported in Figure 3.1.

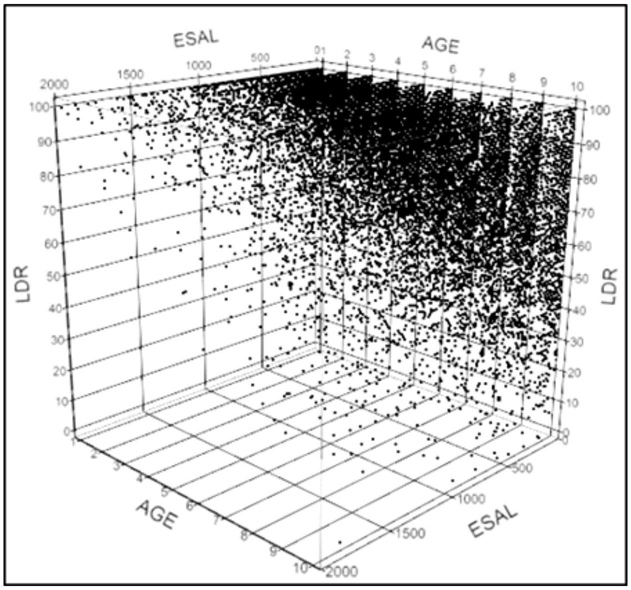


Figure 3.1: Data distribution as function of LDR, time, and ESAL for primary roads.

3.2.3 Microsurfacing

Particularly well-known and largely applied worldwide (i.e.; more than 30 states in the United States, UK, Australia, New Zealand, Germany, South Africa, etc.), microsurfacing has been proven to be one of the most cost-effective PM treatments (ISSA 2010). However, although some studies computing the effectiveness of the treatment are already available in literature (Labi & Sinha 2003) (Peshkin & Hoerner 2005), treatment performance still relies on a general range of extensions of service life provided to the pavement. Influence of traffic on the effectiveness of the treatment, for instance, still remains an a posteriori consideration, a limited insight.

Microsurfacing is a cold-mix of polymer modified asphalt emulsion, aggregates, filler, water, and other additives, properly proportioned, mixed, and spread on the pavement surface as a thin layer (usually less than 1 cm thick). It does not need a final compaction and it is therefore very fast to apply, with high productivities and low user costs caused by delays (re-opening to traffic is usually achieved in less than 2 hours in specific application conditions). A chemically controlled curing process finalizes the application procedure. It was proven to address a great variety of distresses such as rutting, lack of friction, weathering, raveling, and cracking, caused by a mix of UV rays, traffic, and oxidation. In addition, water infiltration is also restricted by sealing the pavement surface.

The following section presents results obtained from the data collection previously described for two types of microsurfacing: type II and type III. The difference is related to the gradation of the aggregates adopted in the mixture with type III having a lower passing at the biggest sieves and therefore resulting to be coarser than type II. Type III microsurfacing is usually adopted on high-volume roads (i.e.; interstates and highways). Latex-modified asphalt emulsion was adopted.

3.2.3.1 Data analysis: microsurfacing

Treatment effectiveness data are reported for interstates according to four groups depending on the ESAL value; only microsurfacing type III was applied to interstates. Figure 2 presents an example of the available data for the interval 4000-5000 and 5000-6000 ESAL. Furthermore, data for primary roads were grouped all together and both types of microsurfacing were applied.

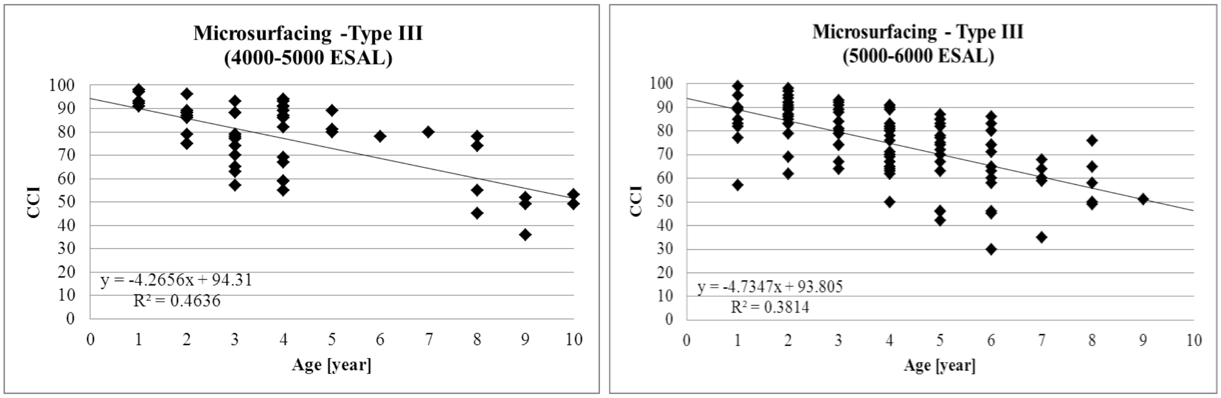


Figure 3.2: Data analysis for type III microsurfacing on interstates

Data were interpolated according to linear regressions but no significant changes in reliability were identified by adopting other types of trend lines. It should also be noted that interpolating data linearly did not provide an equation with an intercept equal to 100. This feature is strongly dependent on the available data; however, the main outcome is represented by the slope variance since road agencies and municipalities aim to predict the future conditions of the pavement, not the actual. As expected, slope is always negative.

Post-treatment deterioration models are summarized in table 3.1 for all traffic levels.

Table 3.1: Post-treatment deterioration models for microsurfacing

Microsurfacing – Type III (interstate)			*Microsurfacing – Type III (primary)*		
ESAL	Post-Treatment deterioration models	R^2	ESAL	Post-Treatment deterioration models	R^2
2000-3000	CCI = - 3.7083 x + 96.531	0.40	0-2000	CCI = - 3.4743 x + 87.129	0.23
3000-4000	CCI = - 4.1288 x + 100.44	0.45	*Microsurfacing – Type II (primary)*		
4000-5000	CCI = - 4.2656 x + 94.31	0.46	0-2000	CCI = - 4.9408 x + 96.851	0.75
5000-6000	CCI = - 4.7347 x + 93.805	0.38			
without grouping traffic	CCI = - 4.2824 x + 96.386	0.57			

3.2.4 Slurry Seal

One of the most common PM treatments is the slurry seal. It consists of a mixture of asphalt emulsion, aggregates, filler, and water; additives for specific purposes can be also added. The entire application process is realized on site through specific equipment that mixes the previous components and adds the emulsion at the end. As with microsurfacing, slurry seals are spread over the pavement surface but the curing process is temperature related. After the emulsion breaks a cohesive mixture is therefore realized and the slurry becomes a hard, dense-graded mixture strictly bonded to the pavement surface. The new thin layer has therefore the thickness of the largest aggregates used in the mixture gradation. Since the curing process is correlated to temperature then re-opening to traffic is highly influenced by the weather conditions during the application. High curing temperatures allow a short re-opening (almost one hour) while in cooler conditions a longer time should be expected (several hours).

Slurry seals are useful for addressing several types of distresses: raveling, oxidation, low severity rutting (mostly due to post compaction effects), and low levels of cracking, for instance. However, a very small mitigation effect has been shown when applying slurry seal on pavements with high severity rutting, cracking, potholes, and large patching (Caltrans 2007).

Currently, three groups of slurry seals are acknowledged depending on their aggregate gradation (Caltrans 2006): Type I is the finest and it is usually adopted for low volume roads and parking lots; Type II is used on moderate to heavy traffic to address raveling and oxidation, mainly; Type III is usually implemented on heavy traffic routes for fixing low rutting and restoring friction. Rate of application also depends on slurry type, increasing when aggregate size increases.

The following section presents results obtained from the data collection previously described for two types of slurry seals: type II and type III. Type III slurry seal was adopted both on interstate and primary roads while type II slurry seal was only used on primary roads.

3.2.4.1 *Data analysis: slurry seal*

Treatment effectiveness data are reported hereafter for interstate and primary roads. Since interstate data were only available for a specific interval of ESAL (4000-5000), mainly because of the particular county or district that applied slurry seal on interstates, no traffic intervals were taken into account. However, since results related to high traffic conditions are presented, it can be reasonably assumed that the treatment performance is consequently higher for lower volume roads. Primary roads data were grouped together and both types of slurry seals were applied.

Figure 3.3 illustrates an example of the available data for interstate and primary roads.

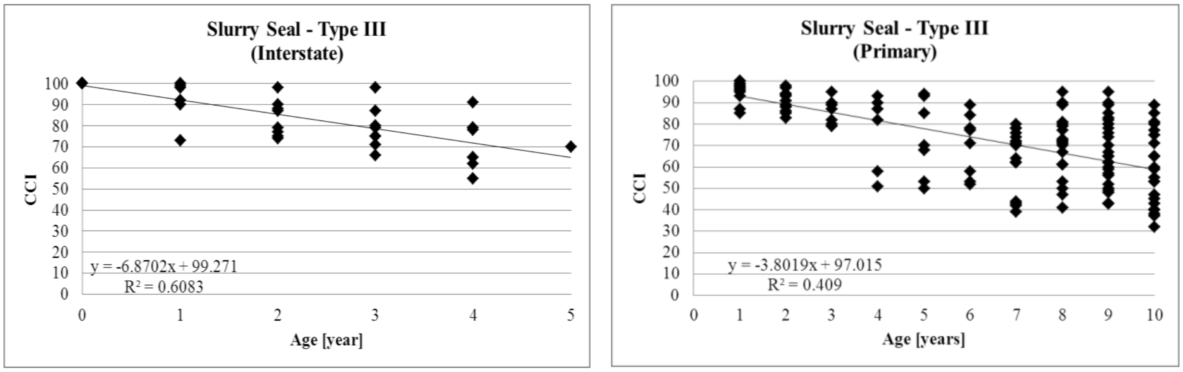


Figure 3.3: Data analysis for type III slurry seal (interstate and primary roads)

Post-treatment deterioration models are summarized in table 3.2.

Table 3.2: Post-treatment deterioration models for slurry seal

Slurry Seal – Type III (interstate)			*Slurry Seal – Type III (primary)*		
ESAL	Post-Treatment deterioration models	R^2	ESAL	Post-Treatment deterioration models	R^2
4000-5000	CCI = - 6.8702 x + 99.271	0.61	0-2000	CCI = - 3.8019 x + 97.015	0.41
			Slurry Seal – Type II (primary)		
			0-2000	CCI = - 7.5508 x + 102.9	0.84

3.3 Discussion

Tables 3.1 and 3.2 show pavement deterioration after conducting a preventive maintenance activity.

Table 3.1 provides a clear trend where increasing the amount of traffic also corresponds to an increase in the deterioration slope; the pavement is therefore deteriorating faster when the traffic volume increases and PM effectiveness is consequently decreasing. This aspect seems to be confirmed if the same treatment (i.e.; microsurfacing type III) is applied to a different kind of road (i.e.; primary road); indeed, the same material applied to primary roads having a lower volume of traffic results in a pavement deteriorating generally slower. Thus, pavement structure (i.e.; the structural number, layer thicknesses) cannot be considered as a main factor affecting the post-treatment effectiveness of PM treatments. Indeed, whenever correctly designed, pavements' structural behavior does not seem to be affected by preventive maintenance treatments, which mainly provide a "superficial" action.

In addition, microsurfacing type II provides a lower post-treatment performance than type III for same roads and same traffic.

Furthermore, as widely assessed in literature, table 3.2 shows how slurry seals generally perform worse than microsurfacing for a similar traffic. Same considerations can also be made regarding slurry seal's effectiveness and the pavement structure and traffic.

3.4 Conclusions

The paper presented an evaluation of preventive maintenance effectiveness on road pavements. In particular, microsurfacing and slurry seal applications were taken into account and post-treatment deterioration models were developed according to real pavement sections data.

Deterioration trends, besides numerically quantifying the performance over a specific time span, showed that traffic was a main variable affecting the treatments' effectiveness. Further investigations should therefore be conducted to evaluate the correlation between the pavement structure and its influence on results. Other variables, such as climate conditions for instance, have to be considered and further investigated.

Moreover, other preventive maintenance treatments should be analyzed and compared. The aim should be to define a long-term preventive maintenance strategy based on the real effectiveness of treatments instead of relying on "average" extensions of service life provided by the treatments.

3.5 References

AASHTO (1993). *Guide for Design of Pavement Structures*. American Association of State Highway and Transportation Officials, Washington, D.C., USA.

Caltrans (2006). *Standard Specifications, Section 37-2 Slurry Seal*. California Department of Transportation. http://www.dot.ca.gov/hq/esc/oe/specs_html/2006_specs.html

Caltrans (2007). *Flexible Pavement Preservation, Chapter 8 - Slurry Seals*. Maintenance Technical Advisory Guide 2nd edition, California Department of Transportation. Volume I.

Cuelho E, Freeman RB (2004). *Cost-effectiveness of crack sealing materials and techniques for asphalt pavements*. Montana Department of Transportation, Research Section, USA.

Cuelho E., Mokwa R., Akin M. (2006). *Preventive Maintenance Treatments of Flexible Pavements: a Synthesis of highway Practice*, Montana Department of Transportation, Research Section, USA.

FHWA - Federal Highway Administration (2005). *Pavement Preservation Definitions*. Memo, Federal Highway Administration, Washington, DC. www.fhwa.dot.gov/pavement/preservation/091205.pdf

Galehouse L. (1998). *Innovative Concepts for Preventive Maintenance*. Transportation Research Record: Journal of the Transportation Research Board. Volume 1627/1998, p.1-6. DOI: 10.3141/1627-01

Geoffroy, D.N (1996). *NCHRP Synthesis of Highway Practice 223: Cost-Effective Preventive Pavement Maintenance*. Transportation Research Board, National Research Council, Washington D.C.

Haas R, Hudson WR, Zaniewski JP. (1994). *Modern pavement management*. Krieger Publishing Company. ISBN: 0894645889

International Slurry Surfacing Association - ISSA (2010). *Recommended Performance Guideline for Microsurfacing.* Report A143. Annapolis, MD, USA.

Labi S., Sinha K.C. (2003). *The effectiveness of maintenance and its impact on capital expenditures*. Publication FHWA/IN/JTRP-2002/27. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. DOI: 10.5703/1288284313331

Labi S., Sinha K.C. (2005). *Life-cycle evaluation of flexible pavement preventive maintenance*. Journal of Transportation Engineering;131:744.

National Asphalt Pavement Association - NAPA (2009). *Thin Asphalt Overlays for Pavement Preservation* by Newcomb D. Information Series 135. Lanham (MD), USA.

Peshkin D., Hoerner T., Zimmerman, K. (2004). *Optimal Timing of pavement Preventive Maintenance Treatment Applications*. Report 523 - National Cooperative Highway Research Program (NCHRP), Washington D.C., USA.

Peshkin D., Hoerner T. (2005). *Pavement Preservation: Practices, Research Plans, and Initiatives*. NCHRP Project No. 20-07, Task 184. American Association of State Highway and Transportation Officials.

Peshkin D., Smith K., Wolters A, Krstulovich J., Moulthrop J., Alvarado C. (2011). *Preservation Approaches for High-Traffic-Volume Roadways*. The Second Strategic Highway Research Program, Report S2-R26-RR-1. Transportation Research Board, Washington, D.C.

Wood T., Watson M., Olson R., Lukanen E., Wendel M. (2009). *Preventive Maintenance Best Management Practices of Hot Mix Asphalt Pavements*. Report No. MN/RC 2009-18, Minnesota Department of Transportation, Office of Materials and Road Research.

Chapter 4. Environmental Assessment of Road Construction Methods for a Low Carbon Pavement

F. Giustozzi[1], G. Flintsch[2], M. Crispino[3]

ABSTRACT: Emissions reduction and energy certifications of products are critical current issues. Both industry trends and the general public opinion are showing an increased concern about what is "sustainable," "green" or "energy-efficient." Many processes and raw materials especially referring to industrial products have been analyzed to determine their environmental impacts, and "green certifications" and "eco-labels" are starting to be used by industries and companies, especially in Europe.

This paper presents a methodology designed to compute the carbon footprint of the stabilization of *in situ* soils with hydraulic binders and compares the results with the traditional supply of non-renewable resources used to build road foundation layers. The analysis is conducted by computing the emissions related to all processes (and equipment) involved in both *in situ* and traditional methods. A sensitivity analysis of the hauling distance of virgin aggregates (the most critical activity in the traditional process) assesses the influence of transportation activities on the entire construction process.

The analysis shows that improving *in situ* soils through cement stabilization can save more than 80% in emissions if compared to the supply of traditional granular layers (assuming embodied energies are not considered). A "sustainable road pavement" should certainly consider the reuse of *in situ* soils to limit emissions during construction activities.

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

[3] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

4.1 Introduction

Several environmental certification approaches have been developed during the last decade for companies, buildings, and products (U.S. Green Building Council 2009). New rating systems and tools are also becoming popular for assessing the eco-impact of road pavement projects (Anderson 2011, FHWA 2010). A comprehensive assessment that includes an environmental perspective aside from costs and performance would allow a complete evaluation of road projects and maintenance strategies. Choosing between different construction and maintenance alternatives should not be just a matter of traditional costs evaluation.

Since millions of dollars ($21.72 billion were spent in 2009 for road maintenance and services in the U.S. [FHWA 2011]) and a vast amount of non-renewable resources are used every year for the construction and maintenance of roads, a calculation of the emissions produced during a certain design/maintenance strategy is important. Emissions analysis could represent a step forward for selecting the right design material while preserving the environment. Similar results in terms of cost and performance may be achieved using more eco-efficient alternatives, which consume less energy and produce less pollution.

Moreover, stabilizing *in situ* soils with cement or lime allows reduction of materials supplies and new soil consumption, thus limiting soil handling across the construction site and increasing productivity. Furthermore, the reuse and the valorization of existing soils limit waste materials and the amount of virgin aggregates required. Life-cycle assessments of this topic, widely available in literature, confirm the advantage of reusing and valorizing *in situ* soils through soil stabilization. The use of cementitious materials as hydraulic binders for soil stabilization, for instance, allows the enhancement of the mechanical properties of soils, thus enabling them to meet the structural requirements usually demanded from a foundation (or sub-base) layer. Enhancements achieved through stabilization include better soil gradation, reduction of swelling potential or plasticity index, improvement in durability and strength, increase of the shrinkage limit, reduction of clay/silt-sized particle, and increase of the resilient modulus (Department Of The Army, The Navy and The Air Force 1994, Bahar 2004). The outcome is a moisture-resistant material that provides high durability and resistance to leaching over time.

Furthermore, hydraulic binders have proven effective in stabilizing a variety of soils, including granular materials resulting from construction and demolition activities (C&D), waste materials from the disposal of asphalt pavements (RAP), and crushed concrete. Even if existing *in situ* soils are not appropriate to be stabilized as they are, recycled materials can be added afterwards in order to create a suitable mixture to be treated. The benefits of reusing *in situ* soil in this way are enhanced by the eco-advantages of valorizing waste materials and saving landfills and energies associated with disposal.

4.2 Objective

This paper presents a methodology designed to compute the carbon footprint of the stabilization of *in situ* soils with hydraulic binders and compares the results with the traditional supply of non-renewable resources used to build road foundation layers. A sensitivity analysis of the hauling distance of virgin aggregates is also provided for assessing the influence of transportation activities on the entire construction process.

4.3 Environmental Assessment

The methodology adopted takes into account carbon emissions in order to develop an environmental assessment of construction strategies for road pavements. Emissions from the manufacture of raw materials (from-cradle-to-gate analysis), equipment utilized during the construction stage, and construction procedures were converted into carbon equivalent emissions (ATHENA™ Institute 2006) to compute a carbon footprint for each alternative.

A carbon footprint corresponds to the total amount of greenhouse gasses (GHG) emitted during the life cycle of a specific product. All manufacturing processes and their related emissions used to transform the initial raw material into the final marketable product are considered in the carbon footprint assessment. These processes include hauling, laying down, and disposal.

A single footprint considers the six GHGs identified by the Kyoto Protocol: carbon oxides (CO_x), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbon (PFC), and sulfur hexafluoride (SF_6). These gasses absorb infrared radiation and can therefore affect the climate when they are present in the atmosphere. In order to simplify the calculations, the six gasses are combined into a single index, or a carbon footprint's unit measure: the equivalent carbon dioxide (CO_2e). The CO_2e allows a direct and simple comparison between different emissions sources in terms of CO_2e, considering in the meanwhile the range of GHGs. The conversion from a certain GHG into a unit of CO_2e is conducted by multiplying the amount of that GHG by its Global Warming Potential (GWP) during a specific time interval (usually 100 years [U.S. Energy Information Administration 1995]).

The GWP is the measure of the global warming produced by a GHG trapped in the atmosphere for a specific time interval (20, 100, or 500 years). Its potential of warming up the planet is compared to the CO_2 warming potential and is assumed equal to 1. For example, the GWP related to CH_4 is 25, N_2O is 298, HFC-23 is 14800, and SF_6 is 22800 (IPCC 2007). Even if accurate chemical analyses are available for almost every pollutant in the atmosphere, carbon footprint analysis is still a challenging task. A comprehensive database of emissions produced from every single process designed to convert raw material into the final product is still far from completion.

However, it is common practice to limit calculations to emissions related to fuel consumption by the fuel type adopted during the various processes. In the following sections, these emissions are estimated for the various processes (e.g., materials manufacture, equipment, and construction) in order to assess the carbon footprints of two different road construction methods (i.e., *in situ* and traditional).

4.3.1 Methodology

4.3.1.1 Materials

The only way to correctly compute emissions related to the manufacture of raw road materials is knowing every single quantity of emissions produced during every phase of an extremely complex and articulate process. For example, emissions from bitumen should include: emissions due to oil extraction, transportation to the plant, refining of crude oil into bitumen, transportation and storage in depots, etc. Since emissions vary considerably depending upon the production method utilized, several literature sources were analyzed and referenced to determine average values. The different literature data available were averaged to compute the final values of emissions due to the manufacture of raw materials.

Table 4.1 summarizes the outcomes from the literature review, highlighting the different sources adopted. The spread for some of the parameters is rather high, as shown by the range value provided in the table. Where no range value is provided it is because only one literature source (i.e., one data) was available. All entries listed in the table consider all stages and processes to obtain the final product as ready-to-use.

Table 4.1: CO_2e emissions due to the manufacture of raw materials

Material	**Emission – CO_2e** (kg/ton material)	**Range** (min-max)	**Literature sources**
Bitumen emulsion [60 %]	221.0	210 - 230	(ATHENA™ Institute 2006, Asphalt Institute and Eurobitume 2008, Stripple 2001)
Crushed aggregates	7.5	4.3 - 10	(Stripple 2001, ATHENA™ Institute 2006, ATHENA™ Institute 1999, Häkkinen 1996, WRAP 2010)
Pit-run aggregates	5.3	2.5 - 10	(Stripple 2001, ATHENA™ Institute 1999, Häkkinen 1996, Hammond 2011)
Cement	1079.6	830 - 1429	(Stripple 2001, Marceau 2007, Häkkinen 1996, Hammond 2011)
Quicklime	2500	-	(Stripple 2001)
Water	0.29	0.28 – 0.30	(Stripple 2001, Hammond 2011)

4.3.1.2 Equipment and Construction

Several pieces of equipment currently used in road construction sites were analyzed to provide a calculation of emissions. Soil stabilizers, rollers, graders, dozers, excavators, loaders, and trucks were investigated to identify and quantify emissions produced during the road construction activities.

Two different processes were analyzed and compared: 1) Building foundation layers stabilizing *in situ* soils with hydraulic binders and 2) Supplying virgin aggregates from a source outside the construction site. The total amount of motive power and the fuel consumption necessary to conduct the works on a sample road unit (e.g., a lane-kilometer) were estimated. The primary source of pollution in a construction site, in fact, is due to the engine exhaust system of the equipment. However, the actual quantity of instantaneous fuel consumed while constructing pavement layers on a sample road unit is difficult to estimate. In fact, a variety of stochastic aspects could affect the assessed value such as: working experience and behavior of the operator, inability to directly measure the instant fuel consumption, multiplicity of available engines and brands, etc. Therefore, the method adopted and the simplifications made during the analysis are hereafter explained.

First, the analyst should identify the number and the type of machines utilized to conduct the work. Then, he/she should estimate the time each piece of equipment is used on the sample road unit (lane-kilometer) considering the productivity data stated on the technical specifications of the machines. Obviously, the total amount of equipment adopted on a lane-kilometer during a site application is conditioned by the time the contractor has to finish the work.

For the purpose of this paper, a sample work process was adopted. The specific machines, their quantity, and usage hours chosen are summarized in Tables 4.2 and 4.3 for the two materials/processes. The calculations were made as follows:

1. Analyze engines from the major manufacturers to identify the fuel consumption needed to conduct a sample unit of a specific action (e.g., soil stabilization, grading, rolling, etc.).
2. Use a mathematical relationship (U.S. Environmental Protection Agency) to convert the calculated fuel consumption into emissions produced.
3. Compute the total amount of CO_2e for each equipment model based on the type and amount of fuel consumed.

Table 4.2: *In Situ* soil stabilization

Materials		**Unit**	**Embodied Emissions** CO_2e (kg/ton material)	**Carbon Footprint** CO_2e (kg)
Soil (*in situ*)	1050	m^3	-	-
Cement (2.5%)	47.25	T	1079.6	51011.1
Water	Not considered		0.288	-

Machines*						
**equipment considered are standard types and medium performance models*	**Working Time** (h)	**N°**	**BSFC** maximum torque (g/kWh)	**P** maximum torque (kW)	**Fuel Consumption** (L)	**Carbon Footprint** CO_2e (kg)
Spreader	1.2	1	215	135	41.86	111.51
Soil stabilizer	2.3	1	208	420	241.50	643.33
Grader	0.5	1	210	95	11.99	31.94
Roller 1 (tamping)	1.5	1	215	135	52.33	139.40
Roller 2 (pneumatic)	2.0	1	215	90	46.51	123.90
					TOTAL	**1050.08**

Table 4.3: Supplying virgin aggregates

<table>
<tr><th colspan="2">Materials</th><th colspan="2">Unit</th><th colspan="2">Embodied Emissions CO_2e (kg/ton material)</th><th>Carbon Footprint CO_2e (kg)</th></tr>
<tr><td>Soil</td><td>1050</td><td colspan="2">m^3</td><td colspan="2">-</td><td>-</td></tr>
<tr><td>Virgin Aggregates</td><td>1050</td><td colspan="2">m^3</td><td colspan="2">≈ 6.5</td><td>12967.5</td></tr>
<tr><td colspan="7">Machines*</td></tr>
<tr><td><i>*equipment considered are standard types and medium performance models</i></td><td>Working Time (h)</td><td>N°</td><td>BSFC maximum torque (g/kWh)</td><td>P maximum torque (kW)</td><td>Fuel Consumption (L)</td><td>Carbon Footprint CO_2e (kg)</td></tr>
<tr><td>Excavator</td><td>5.83</td><td>1</td><td>205</td><td>145</td><td>208.29</td><td>554.86</td></tr>
<tr><td>Loader</td><td>2.92</td><td>1</td><td>215</td><td>120</td><td>90.55</td><td>241.22</td></tr>
<tr><td>Grader</td><td>1</td><td>1</td><td>210</td><td>95</td><td>23.98</td><td>63.88</td></tr>
<tr><td>Roller 1 (single drum)</td><td>1.5</td><td>1</td><td>215</td><td>130</td><td>50.39</td><td>134.23</td></tr>
<tr><td>Roller 2 (pneumatic)</td><td>2.5</td><td>1</td><td>215</td><td>90</td><td>58.14</td><td>154.89</td></tr>
<tr><td></td><td>Hauling Distance (km)</td><td>N°</td><td>BSFC (km/L)</td><td colspan="2">Fuel Consumption (L)</td><td>Carbon Footprint CO_2e (kg)</td></tr>
<tr><td>Truck to/from the quarry (20 km)</td><td>3520</td><td>-</td><td>3</td><td colspan="2">1173.33</td><td>3125.63</td></tr>
<tr><td>Truck to/from the storage site (2 km)</td><td>176</td><td>5</td><td>1.5</td><td colspan="2">586.67</td><td>1562.83</td></tr>
<tr><td colspan="5"></td><td>TOTAL</td><td>5837.54</td></tr>
</table>

Technical specifications obtained directly from manufacturers of the different engine types provided curves for relating the brake specific fuel consumption (BSFC; g/kWh of fuel) to the engine rotation speed (revolutions per minute [rpm]). Torque and power curves determined the relationship between the nominal power supplied by the engine (in kW) and its rotation speed. The amount of fuel consumed was then calculated using Equation 4.1. Different amounts of fuel could be computed depending on the engine rotation speed and the nominal power supplied during a specific instant. Thus, it was assumed that the engine was run at the rotation speed that provided the maximum torque while conducting the work. This circumstance is desirable from an environmental standpoint; in fact, the BSFC of an endothermic engine is next to the minimum value at the maximum torque because it is more efficient at that running speed.

$$F\,[L] = BSFC\left[\frac{g}{kW \cdot h}\right] \cdot P[kW] \cdot T[h] \cdot 1/\gamma\left[\frac{L}{g}\right] \qquad (4.1)$$

Where:

F = fuel consumed,

$BSFC$ = basic specific fuel consumption,

P = engine power when the rotation speed provides the maximum torque, and

γ = density of the fuel (diesel density = 0.832 kg/L).

The Code of Federal Regulations (2005) provides values for carbon content per gallon of gasoline and diesel fuel:

- Gasoline carbon content per gallon: 2,421 g
- Diesel carbon content per gallon: 2,778 g

The Intergovernmental Panel on Climate Change guidelines (IPCC 2007) for calculating emissions inventories require that an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO_2. For all oil and oil products, the oxidation factor used is 0.99 (99 percent of the carbon in the fuel is eventually oxidized, while 1 percent remains un-oxidized [U.S. Environmental Protection Agency 2005]). Moreover, to calculate the CO_2 emissions from a liter (or gallon) of fuel, the carbon emissions were multiplied by the ratio of the molecular weight of CO_2 (m.w. 44) to the molecular weight of carbon (m.w. 12): 44/12.

CO_2 from 1 gal gasoline = 2,421 g x 0.99 x (44/12) = 8,788 g = 8.8 kg/gal = 2.3215 kg/L

CO_2 from 1 gal diesel = 2,778 g x 0.99 x (44/12) = 10,084 g = 10.1 kg/gal = 2.6639 kg/L

Finally, the fuel consumption was multiplied by the specific amount of CO_2e produced in the combustion of 1 L of diesel (Equation 2) in order to calculate the total quantity of emissions from the machines used for building a foundation layer on a lane-kilometer of road pavement.

$$CO_2\, emissions\, [g] = F[L] \cdot \alpha \, \left[\frac{g}{L}\right] \tag{4.2}$$

Where:

α = specific amount of CO_2 emitted during the combustion of 1 L of diesel = 2,663.9 g/L.

In conclusion, outcomes from the emissions calculations of construction equipment were compared with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation

(GREET) Fleet Footprint Calculator (Wang 2007). Comparisons found a difference in resulting emissions due to construction activities of less than 17.5%, mainly imputable to the dissimilarity of truck models adopted during the two analyses.

4.3.2 Carbon Footprinting of Building Foundation Layers

This section presents the calculations used to compute the carbon footprints of two construction processes for foundation layers: stabilizing *in situ* soils and supplying virgin aggregates from outside. Several assumptions were made during the analysis:

- The sample road unit taken as a reference was a lane in width and 1 km in length (0.62 mi).
- The productivity for each machine was assumed equal to the one indicated in the technical specifications provided by the manufacturer.
- Engines were assumed to work in a range next to the maximum torque condition, thus maximizing the engine efficiency and the fuel consumption.
- The same intervention thickness was adopted for both construction methodologies (30 cm, 11.81 in.).
- The initial scraping and the spray of the bituminous emulsion for protecting the layer were not considered during the carbon analysis being common operations for both methodologies.
- The hauling distances for the soil stabilization method are almost equal to zero, being everything solved inside the construction site.

Bringing new aggregates from outside makes the hauling distances a major entry in the emissions list; a distance equal to 20 km (12.4 mi) from the quarry site was assumed for the calculations. However, a sensitivity analysis was provided at the end of the manuscript.

4.3.2.1 In Situ Soil Stabilization

The working procedure can be summarized as follows:

1. Initial scraping for assuring a smoother ride and grass removal;
2. Spreading of the cement powder on the soil upper surface;
3. *In situ* mixing of soil and cement (or lime), eventually adding water; and
4. Grading and compaction.

The machines used were: a scraper, a spreader, a soil stabilizer, a grader and rollers (tamping and pneumatic). The operating times for each machine to conduct the work on a lane and resulting emissions are indicated in Table 4.2.

The total amount of materials involved in the construction process was considered to determine the environmental impacts as discussed in previous paragraphs. A 2.5% of cement (by weight of dry soil) was assumed to be added for stabilizing the soil. Considering a stabilization depth of 30 cm (11.81 in.), a lane width of 3.50 m (11.48 ft), and a length of 1 km (0.62 mi), the total amount of soil to be stabilized was equal to 1,050 m^3 (1,373 yd^3). Therefore, the amount of cement needed was almost 47.25 T.

The amount of water needed to reach the maximum Proctor density was not considered during the analysis because its environmental impact is small (0.29 kg/ton of CO_2e), and the total amount is strongly variable with the relative humidity conditions of the site. The emissions due to the transportation of the cement were disregarded during the analysis because of their small relative weight on the total carbon footprint. Several trucks, in fact, can easily transport all cement needed during a single trip.

4.3.2.2 Traditional Method – Using Virgin Aggregates

The working procedure can be summarized as follows:

1. Initial scraping for assuring a smoother ride and grass removal;
2. Soil digging for a depth of 30 cm (11.81 in.);
3. Loading trucks for removing the previously excavated soil and sending it to the storage site;
4. Grading and compaction of the subgrade, unloading trucks coming from the quarry with virgin aggregates;
5. Laying down and grading of the foundation material; and
6. Final compaction.

The machines used were: a scraper, excavators, trucks, loaders, a grader and rollers (single drum and pneumatic). The operating times to conduct the various activities on a lane and resulting emissions are indicated in Table 4.3.

The total amount of materials were obtained considering an intervention depth of 30 cm (11.81 in.), a lane width of 3.50 m (11.48 ft), and a length of 1 km (0.62 mi). The total amount of soil to be removed was equal to 1,050 m^3 (1,373 yd^3). Therefore, at least the same amount of virgin aggregates were needed as that of the total amount of soil to be stabilized during the *in situ* process. In order to compute the number of excavators and trucks required to conduct the work, some productivity considerations were made.

If an excavator with a bucket capacity of 1.5 m^3 (1.96 yd^3) and a cycle time (loading and unloading) of 20 s was assumed, then 4.5 m^3 (5.88 yd^3) of soil could be loaded into the trucks every minute. Considering a truck loading capacity equal to 12 m^3 (15.68 yd^3), then the excavator could load the truck in almost 4 minutes (3 minutes for loading and 1 minute for maneuvering). Therefore, a productivity of 180 m^3/h (235.4 yd^3) could be assumed for each excavator (a double productivity could be supposed for the loaders).

The number of trucks that should serve an excavator is a function of the hauling distance to/from the storage site and to/from the quarry. In the following calculation, hauling distances of 2 km (3.11 mi) and 20 km (12.43 mi) were assumed to/from the storage site and to/from the quarry, respectively. It was therefore assumed that virgin aggregates were already transferred from the quarry to the storage site before the construction activities began.

A truck was supposed to consume 1.0 L of diesel every 3 km (0.15 gal/mi) when traveling on roads (trip to/from the quarry) and 1.0 L every 1.5 km (0.07 gal/mi) when traveling on yard tracks (trip to/from the storage site). Therefore, five trucks were supposed to serve an excavator considering a cycle time of almost 20 minutes (loading soil – 4 minutes; hauling – 5 minutes; unloading soil – 1 minute; loading aggregates – 4 minutes; hauling – 5 minutes; unloading aggregates – 1 minute*)*.

4.4 Discussion

Tables 4.2 and 4.3 show the eco-advantage of stabilizing *in situ* soils if compared to supplying new materials from outside (almost 82% of emissions saved). Aside from the time saved conducting the work on the same road sample unit, the main eco-advantage is decreased materials handling. In particular, hauling to/from the quarry is the main cause of a higher carbon footprint (almost 53% of the total amount).

It is important to note that if the impact of producing the raw materials is also considered during the analysis, the soil stabilization method will likely result in the worse eco-efficiency as cement has a higher environmental impact than aggregates. That is, producing 1 T of cement is almost

160 times more polluting than extracting 1 T of quarry aggregates. Considering feedstock energies highly increases the total amount of emissions and energies evaluated during the analysis, as is widely assessed in technical literature. Feedstock energies are usually larger than process-related energies and can change the expected results of the study if considered. In particular, for the case study provided in this paper, 97% of the entire soil stabilization emissions are due to the emissions involved in the manufacture of cement, and 69% of the total emissions resulting during the traditional method are related to the manufacture of virgin aggregates.

For the purpose of this analysis and taking into account all the uncertainties about considering embodied energies during life-cycle assessments, only construction activities and related machines were assessed. Moreover, if embodied emissions of raw materials are considered during an analysis then a life-cycle analysis should be conducted. Foundation layers made by cement-treated soils may in fact be more durable than the granular layer. Thus, a cement-treated foundation can improve the service life of the entire pavement and can provide less major rehabilitations across the life cycle and less related emissions.

4.5 Sensitivity Analysis

In order to investigate the influence of transportation on the total emissions produced, a sensitivity analysis was conducted by changing the hauling distance to/from the quarry. It is noted that the transportation influence on the total amount of emissions seems to have a logarithmic trend, increasing faster for hauling distances smaller than 25 km (15.5 mi) and slowing down afterwards.

It can also be inferred that for a hauling distance of 5 km (3.1 mi) from the storage site and the quarry, the total amount of emissions related to the traditional method is 3.5 times higher than the stabilization of *in situ* soils. For more distant quarries (up to 50 km from the construction site) and maintaining constant the distance from the storage site, the total emissions results of the traditional method are almost 10.5 times higher than the soil stabilization.

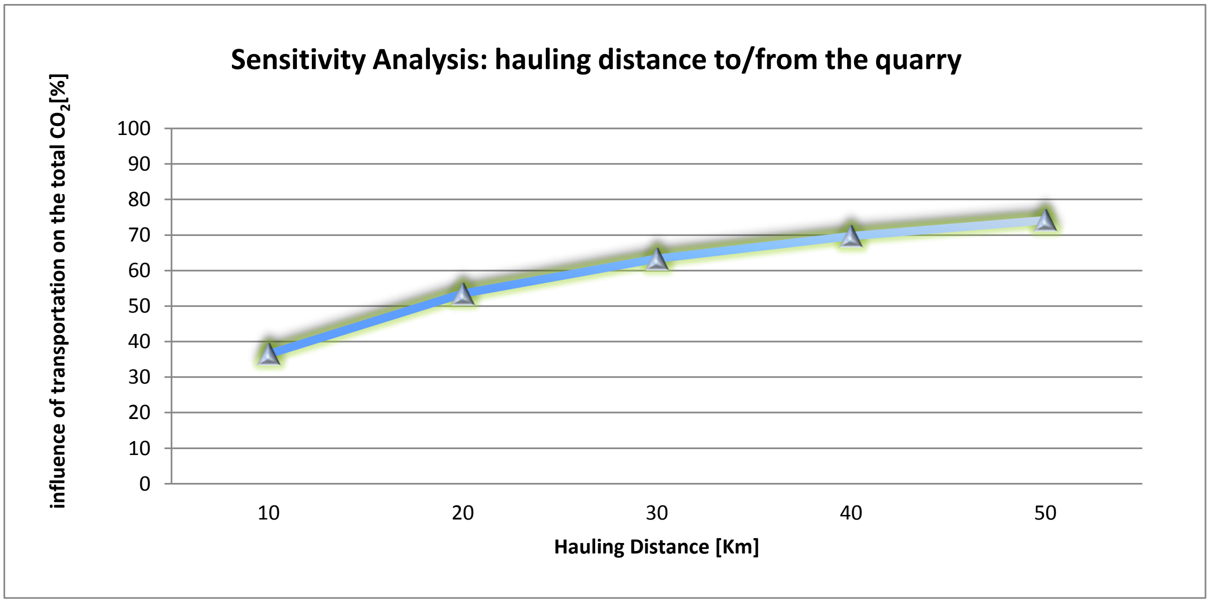


Figure 4.1: Influence of transportation on the total amount of emissions produced

4.6 Conclusions

This paper presented a carbon footprint assessment of two construction methods for road foundation/sub-base layers. In particular, stabilization of *in situ* soils represents an ideal opportunity for contractors and companies to reduce their environmental impacts when building foundation layers for road and airport pavements. This paper shows that the soil stabilization uses a smaller number of machines, has less material handle and supply, and consumes less virgin aggregates, thus providing a considerable eco-advantage in terms of emissions produced.

Although the proposed methodology is considered a step forward compared with current practice, the analysis could be improved by adding other variables and analysis processes. For instance, the use of recycled aggregates resulting from a nearby construction site could be investigated in order to evaluate the eco-saving of the total amount of emissions produced. Moreover, other techniques currently adopted in road construction practice should be analyzed and compared. The aim should be to define a low carbon pavement (maintaining the same performance of a standard pavement) to be used in current practice (i.e., a sustainable pavement).

4.7 REFERENCES

Alcom A. (2003). Embodied Energy and CO2 coefficients for NZ Building Materials. Center for Building Performance Research, Virginia University of Wellington, New Zealand.

Anderson J., Weiland C., Muench S. (2011). Greenroads™ Manual v. 1.5. University of Washington. http://www.greenroads.us.

Asphalt Institute and Eurobitume (2008). Bitumen Industry – A Global Perspective, Information Series No.230, IS-230, ISBN 978-1-934154-54-0.

ATHENA™ Sustainable Material Institute (1999). Life Cycle embodied energy and global warming emissions for concrete and asphalt roadways - Summary report. Canadian Portland Cement Association.

ATHENA™ Institute (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Cement Association of Canada.

Bahar, R. & al. (2004). “Performance of compacted cement-stabilized soil”, Cement and Concrete Composites, Volume 26, Issue 7, Pages 811-820.

Code of Federal Regulations (40 CFR 600.113). Fuel Economy Calculations. Title 40 - Protection of Environment. December 30, 2005.

Department Of The Army, The Navy and The Air Force. (1994). “Soil Stabilization For Pavements”, TM 5-822-14/AFJMAN 32-1019

Federal Highway Administration (FHWA) (2011). “Highway Statistics 2009”, Table SF 2 - State Disbursements For Highways.

Global Warming Potentials. Climate Change 1995, The Science of Climate Change: Summary for Policymakers. U.S. Energy Information Administration.

Häkkinen T., Mäkelä K. (1996). Environmental impact of concrete and asphalt pavements, Technical Research Centre of Finland, VTT Tiedotteita, Meddelanden, Research Notes 1752.

Hammond, G., Jones, C. "Inventory of carbon & energy (ICE)." Sustainable Energy Research Team (SERT) – University of Bath (UK), 2011. Version 2.0.

Intergovernmental Panel on Climate Change (2007). 4th Assessment Report, IPCC - (AR4). http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Marceau M., Nisbet M., VanGeem M. (2007). Life Cycle Inventory of Portland Cement Concrete, PCA R&D Serial No. 3011. Portland Cement Association, Skokie, Illinois, PCA, 121 pages.

Stripple H. (2001). Life Cycle Assessment of Road: a Pilot Study for Inventory Analysis. IVL Report B1210E, Swedish Environmental Research Institute, Gothenburg, Sweden.

U.S. Department of Transportation. Federal Highway Administration (2010). Sustainable Highways Self-Evaluation Tool. http://www.sustainablehighways.org

U.S. Environmental Protection Agency (2005). Office of Transportation and Air Quality (OTAQ). EPA420-F-05-001.Emission Facts. Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel. February. www.epa.gov/otaq/green housegases.htm

U.S. Environmental Protection Agency (2009). Carbon Footprint Tool - version 1.2. http://www.epa.gov/wastes/partnerships/wastewise/carboncalc.htm

U.S. Green Building Council (2009). Leed 2009 for new construction and major renovations. http://www.usgbc.org

Wang, M. (2007). "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8 b." Argonne National Laboratory.

Waste Resources Action Program - WRAP (2010). The CO2 emissions estimator tool for the use of aggregates in construction - User Guide v2.0. Project code: MRF-136.

Chapter 5. Recycling Practices for Achieving Environmental Sustainability in Road and Airport Pavements

F. Giustozzi[1], M. Crispino[2], G. Flintsch[3]

ABSTRACT: Both the design and the construction of airfield pavements have to be consistent with strict requirements and constraints and also higher safety standards due to their particular setting. In addition, maintenance and construction times must be minimized in order to avoid delays and limitations on airport capacity. Maintaining or constructing airfield pavements also entails working during all-weather conditions (e.g.; winter time and heavy cold conditions); materials adopted therefore play a major role in the success of the maintenance or construction activity.

Environmental management plans and eco-friendly policies and strategies are increasingly being adopted by airport directors. Noise reduction plans through improved air traffic management techniques, emissions control for aircraft engines and ground maneuvering vehicles, reuse of water for washing airfield pavements, use of renewable energies, and use of photocatalytic materials are only some of the numerous ways of achieving a sustainable airport.

The paper focuses on construction techniques and the development of innovative materials for the achievement of environmental sustainability on airfield pavements. In particular, the authors present how a long lasting and well performing airport pavement can be built if more than 85 % of the materials used are recycled materials. The environmental analysis of a case study on a major Italian airport shows that the release of almost 35 % of emissions could be avoided if recycling practices are taken into account. Furthermore, pavement performance is analyzed and

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

monitored as well in order to show that recycling does not necessarily result in lower performance.

Outcomes clearly suggest that the recycled airport pavement has a comparable performance and less of an environmental impact on standard airfield pavements. Moreover, results can be implemented into an Airport Pavement Management System to assess the best strategy, considering the environmental footprint in addition to the traditional performance analysis and cost effectiveness.

5.1 Introduction

The global aviation community is continuously studying and increasingly adopting sustainable practices into their airport management plans. Sustainability in aviation has been consistently enforced over recent decades through various practices: engine emissions reduction, curfew acts for low noise departing and landing procedures, recycling practices and waste management, renewable resources utilization, and electric vehicles for ground maneuvering, for instance.

Moreover, pavement structures represent a major asset in airport facilities. A massive amount of non-renewable resources is therefore consumed for maintenance and rehabilitation related projects in an attempt to cater to this asset. Despite this concern, very little has been done to achieve environmental sustainability while constructing and preserving these assets. In particular, airport pavement management systems (A-PMS) do not include environmental impacts as a decision factor among different alternatives. Lack of funding was mentioned as the first reason for not implementing sustainability practices into the A-PMS (Berry et al. 2008) although several references (i.e.; Giustozzi et al. 2012, Pittenger 2011, GTAA, 2010) demonstrate that applying the right treatment on the right pavement at the right time can significantly provide cost and environmental savings. Sustainable practices should therefore represent a way to develop more efficient solutions while planning both short and long-term strategies.

Airfield pavements in major airports usually have 24 hour operating periods in all-weather conditions; maintenance and rehabilitation activities must therefore respond to various needs: traffic (delays and airport capacity reduction), safety conditions (avoid F.O.D.), time of intervention (short re-opening to traffic), and effectiveness of materials used (performance and durability).

5.2 Objective

The paper presents a case study of a taxiway pavement construction on a major Italian airport adopting almost 85 % of recycled materials. The presented solution optimizes the eco-efficiency while preserving high performance.

The first section of the paper shows the methodology adopted and materials qualification while the second section provides the reader with an environmental assessment of the different stages that lead to the pavement construction. Results clearly show that high performance and durability, usually demanded by airport pavements, can be achieved with higher environmental benefits through the adoption of recycled aggregates and in-situ soils valorization.

5.3 Assessing sustainability on airports: a Case study

The paper presents the construction of a pavement in a major Italian airport. The work was carried out in three months during the fall and winter seasons. The aim was to improve the airport capacity to allow the new large aircrafts (NLAs) such as the Airbus 380 and the Boeing 777 to taxi on the new infrastructure. The area involved was approximately equal to 60,000 square meters. Considering that airport pavements usually have a standard thickness between 70 cm and 110 cm, the amount of material involved was therefore significant. Virgin aggregates and bitumen represented a significant quantity of non-renewable resources to be provided. Waste materials, mainly in-situ soil, substantially contributed to landfilling and dumping. Therefore, sustainability and environmental impacts had a main weight during the design stage; the final solution led towards the re-use and valorization of in-situ soils and the use of recycled aggregates as much as possible. In addition, since performance is a main feature of airport pavements, the following section investigates the mechanical characteristics of the pavement layers. A particular effort was made to test and characterize the recycled material used.

5.3.1 Performance assessment

Material mix-design and construction techniques were optimized to ensure a long lasting and well-performing pavement, in addition to the environmental benefits. The resulting pavement consisted of: an innovative surface layer made of open-graded asphalt filled with hyperfluid cement mortar (6 cm), a recycled cement bound layer as an intermediate layer (30 cm), and a cement stabilized soil adding recycled aggregates as a foundation layer (40 cm).

Materials adopted in the construction of the airport pavement were selected considering both the winter construction conditions and the environmental benefit with the main purpose of saving valuable non-renewable resources. The most notable feature, and also the most challenging aspect, was to build such an important structure composed of almost 85 % recycled resources. Material handling was in this way minimized, thus reducing greenhouse gasses emissions due to construction machineries and hauling, therefore lowering the pavement's embodied energy. Virgin aggregates and bitumen consumption was also minimized since they were used only on the surface layer of the pavement. Finally, hauling and its related environmental impact were significantly reduced since almost all of the construction material came from the airport area.

Materials selection and characterization were accomplished through laboratory, on-site, and full scale investigations.

The new taxiway was opened to air traffic after four months from the beginning of construction activities and seven days after the placement of the surface layer. The pavement classification number (PCN) was also computed according to the ICAO standards (ICAO 2004) through falling weight deflectometer testing. The average PCN was equal to 120.

5.3.1.1 Surface layer: open graded asphalt filled with hyperfluid cement mortar

The use of what can be still considered an innovative material on airfields was suggested for enhancing both the structural capacity and the resistance to particular surface actions (i.e.; chemical actions due to brake fluid loss from aircrafts landing gears).

Indeed, the bituminous surface layer consists of an open-graded asphalt mixture, modified bitumen, and high-quality aggregates filled with a specific hyperfluid cement mortar (Crispino et al. 2007a). The binder content and type had to be defined for assuring the best structural performance of the mixture when in-service. In the case study presented 50/70 penetration grade (EN12591:2009) polymer modified bitumen was chosen; the optimal amount was equal to 3.5 % by weight of dry aggregates.

The void content was equal to 25-30 % in order to allow a correct filling when pouring the cement mortar. Indeed, the mortar is hand-applied on the surface using scrapers to allow its full-depth penetration into the voids. The quick placement and hardening favor a swift re-opening to traffic and high compression resistance to heavy loads.

The main structural and functional characteristics of the surface layer can be summarized as follows (Table 5.1).

Table 5.1: Open graded asphalt filled with hyperfluid cement mortar

Index	Standard	Value
Density [g/cm^3]	ASTM 2726/88	2.32
Stiffness @5 °C [MPa]	EN 12697-26	12,326
Stiffness @20 °C [MPa]	EN 12697-26	7,560
Stiffness @40 °C [MPa]	EN 12697-26	4,324
ITS @20 °C [MPa]	EN 12697-23	1.53
BPN	EN 13036-4	65
Macrotexture depth [mm]	EN 13036-1	0.52

5.3.1.2 Intermediate layer: recycled cement bound layer

Since the thickness of the surface layer, although stiffer than usual bituminous mixtures, was consistently reduced when compared to standard airport pavement structures, a high bearing capacity and favorable durability characteristics were consequently demanded to the layers below.

An experimental investigation was therefore conducted to optimize the aggregate selection and the design and construction procedures of the recycled cement bound base layer (Crispino et al. 2007b).

Aggregates were recycled from the disposal of runway head concrete slabs inside the airport area; material handling and hauling were therefore strongly reduced in addition to the lower consumption of non-renewable resources.

The analysis was conducted according to laboratory and on-site tests. The laboratory investigation stage was aimed towards the water and cement content optimization of the recycled mixture. Mechanical properties and rheological behaviour during the compaction stage were also highlighted. The optimal water/cement ratio was finally established and the proper mixture was chosen. In addition, a full scale test section was performed within the airport area. The aim was the optimization of the laying and compaction methodology, and the monitoring of the bearing capacity evolution during the curing process.

According to the laboratory investigation (Crispino et al. 2007b) based on aggregate characterization (EN1097-2:2010), modified Proctor test (EN13286-2:2010), unconfined compression stress test, and indirect tensile test, the 4 % cement and 8 % water mixture was selected for the following on-site full scale investigation. A full scale test section (400 square meters) was used inside the airport area to optimize construction techniques and evaluate the curing process. The dynamic modulus (E_d) was measured using a light weight drop tester (Teil-B-8.3:2003) to assess the optimal number of passes during compaction. Six passes of a 15 tons single drum roller were identified as providing the optimal compaction (Crispino et al. 2007b).

5.3.1.3 Foundation layer: cement stabilized in-situ soil with recycled aggregates

The stabilization of in-situ soils was developed to reduce materials supplied and to limit handling throughout the construction site, a time consuming and massive activity when operating on a very large scale like airport areas. Re-use and valorization of existing soils, enhancing their properties through stabilization treatments, allows the reduction of virgin aggregate consumption and waste production (Bahar et al. 2004). Recycled aggregates from crushed concrete slabs were added to the existing in-situ soil to improve the mechanical performance of the layer and enhance the bearing capacity of the pavement. Recycled aggregates were initially cleaned from impurities (e.g.; pieces of steel wire fabric) and then sieved.

Besides technical and economic advantages (higher productivity during construction, lower cost of materials supplied, higher independence from climatic factors such as rain, etc.), a massive savings of non-renewable resources was achieved when compared to standard foundation layers.

The amount of hydraulic binder added to the mixture of soil and recycled aggregates to achieve the required performance was again established based on laboratory and on-site investigations (Toraldo 2007).

Recycled aggregates obtained from concrete slab disposal were selected and sieved through a plug mill. The maximum size was 70 mm, coarser than the aggregates used in the recycled intermediate layer previously described. According to the laboratory investigation (Toraldo 2007) based on aggregate characterization (EN1097-2:2010) and modified Proctor test (EN13286-2:2010), the optimal water content for providing the best compaction properties of the soil mixture was identified. A range between 6 % and 8 % of water content was therefore selected for the following on-site full scale investigation. A full scale test section (almost 12,000 square meters) was installed inside the airport area to optimize both the type and content of hydraulic binders for the in-situ stabilization process and construction techniques. Six different areas (almost 200 square meters each) were investigated adopting different contents and types of hydraulic binder, while keeping the optimum water content defined during laboratory tests constant. In particular, two different binders were used: Portland cement for enhancing strength and resilient properties, and lime for reducing plasticity and improving the mixing efficiency. Finally, the 3.5 % of cement and no lime was adopted as the final design mixture.

5.3.2 Environmental Assessment

The eco-effectiveness of the project has been evaluated through the analysis of the emissions released in the atmosphere due to the manufacture of materials, use of construction equipment, and processes (hauling of materials, recycling, etc.). The functional unit is therefore represented by the entire process of paving the airport taxiway; materials quantities, densities, and taxiway dimensions are provided in Table 5.2.

The boundary conditions adopted in the environmental assessment (ISO-EN14044:2006) make the analysis useful for comparison between similar construction projects. In particular, the manufacture of materials was computed within a cradle-to-gate approach; emissions were therefore computed from the manufacturing of raw materials to the point where the product was ready to use. Moreover, emissions from the fuel consumption of machines and processes included only the construction stage, omitting computations for the maintenance phase and the use phase over the life cycle. The time horizon of the analysis consequently ended with the start of the service life of the pavement.

The following sections provide a detailed investigation of the material consumption, the equipment used, and the processes involved. Finally, a comparison with a standard airport asphalt pavement, in terms of emissions produced was conducted.

5.3.2.1 Materials

Environmental analysis of materials was conducted through a comprehensive carbon footprinting assessment, the calculation of the total amount of greenhouse gasses emitted for a product. Processes, and their related emissions, involved for manufacturing the initial raw material up to the final product as ready-to-use, have been considered into the carbon footprint assessment. A single footprint refers to the six greenhouse gasses identified by the Kyoto Protocol (Oberthür and Ott 1999). It is common use to combine them into an equivalent unit of carbon dioxide (CO_2e). The conversion method is based on the global warming potential (GWP) of a certain gas over a specific time interval (Alley 2007). A time span of 100 years was adopted in the paper for evaluating the GWP of the different gasses. For instance, the GWP of nitrous oxide is established equal to 298 (Solomon 2007): one unit of nitrous oxide released in the atmosphere has the potential to trap the heat and warm up the planet equal to 298 units of carbon dioxide, whose GWP is standardized equal to 1.

The airport taxiway measured almost 2 km in length and 30 m width. Layers' mix-design was designed as follows:

- Open-graded asphalt with cement mortar: 66.5 % virgin aggregates, 30 % hyperfluid cement mortar, 3.5 % bitumen;
- Recycled Cement Bound Layer: 88 % recycled aggregates, 4 % cement, 8 % added water;
- Cement Stabilized In-situ Soil: 94.5 % soil and recycled aggregates mixture, 3.5 % cement, 2 % added water (the total amount of water added should also take into account the relative humidity of the in-situ soil when stabilization occurred).
- Asphalt emulsion was also used for ensuring a good bond between the intermediate layer and the surface layer.

Emissions related to materials production and manufacture were computed according to PaLATE database (Horvath 2004) (Table 5.2). Several literature sources are available on the topic but a global inconsistency between the data provided still represents a major issue in LCA for road/airport pavements and related materials (Giustozzi et al. 2012).

Table 5.2: Inventories of emissions related to materials

Material	**CO_2** [g/ton]	**CO** [g/ton]	**NO_2** [g/ton]	**SO_2** [g/ton]	**PM10** [g/ton]	**Hg** [g/ton]	**Pb** [g/ton]	**Water Use** [g/ton]
Sand and Gravel	10,922	14.4	22.0	10.7	156.5	4E-07	3E-03	21.5
Bitumen	1,121,978	4,736.4	6,239.0	5,653.1	1,057.5	4E-02	2E+00	8,292.2
Cement	715,000	1,131.9	3,185.9	3,158.2	596.7	3E-03	3E-01	1,870.5
Concrete Additives	2,302,229	11,804.5	9,373.6	6,929.6	3,370.8	7E-02	5E+00	35,885.3
Asphalt Emulsion	969,318	4,091.9	5,390.1	4,883.9	913.6	3E-02	1E+00	7,163.9
Water	0.497	0.002	0.003	0.003	0.001	4E-10	9E-07	0
	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
Electric services (utilities)	1,243.97	0.37	3.56	6.97	0.24	4.7E-08	1.9E-04	0.08

The following table provides data about the quantity of materials involved in the project. Those values were also useful for computing impacts related to transportation of materials.

Table 5.3: Carbon footprinting related to materials

Layer	Density [kg/m^3]	Width [m]	Length [m]	Thickness [m]	Volume [m^3]	Carbon Footprint [ton CO_2e]
Open Graded Asphalt with Cement Mortar – surface	2,320	30	2000	0.06	3,600	1,213.97
Recycled Cement Bound Layer – intermediate	2,300	30	2000	0.30	18,000	940.35
Cement Stabilized In-situ Soil with Recycled Aggregates - foundation	2,200	30	2000	0.40	24,000	850.90
			Total	**0.76**	**45,600**	**3,005.22**

5.3.2.2 Construction processes and equipment

This section presents, from an environmental standpoint (fuel consumption and related emissions), a detailed description of the processes involved for:

- the production of the recycled aggregates obtained from the disposal of concrete slabs;
- the construction of the foundation (in-situ stabilization), intermediate layer (cement bound layer), and surface layer (open graded asphalt filled with cement mortar) of the airport pavement previously described.

Emissions related to machines and on-site plants were computed to find the carbon footprint due to the construction process and equipment. In particular, recycled aggregates were produced by crushing concrete slabs into conveyable blocks, sorting out the steel of slab reinforcements, milling and sieving the blocks through a plug mill and a screening plant to come out with smaller particles having specific sizes.

Machines involved in the recycling process included:

- excavators with a rock-breaker bucket for crushing concrete slabs;
- loaders for loading up dumper trucks;
- trucks for transferring concrete blocks to the plug mill;
- loaders for supplying material unloaded from trucks into the plug mill;
- a screening movable plant for sieving particles into homogenous sizes and removing steel elements.

The cement stabilization of in-situ soil for building the foundation layer was performed using a grader for spreading recycled aggregates, a cement spreader, a soil stabilizer with a water tank to achieve the optimal soil humidity, and a single drum roller for the final compaction.

The recycled cement bound layer was made using the recycled aggregates and a mobile mixing plant installed inside the construction site; a standard paver was adopted for laying and a single drum roller was used for the final compaction. An asphalt spreader was used for applying the bonding coat between the intermediate and the surface layer.

The surface layer was then laid adopting the standard methodology for asphalt layers (paver and roller application); the hyperfluid cement mortar was finally hand-applied to fill the voids.

It should be noted that all the machines previously described used diesel except the plug mill, the mixing and the screening plant, which were all electric-power based. The analysis of fuel consumption for machines and movable plants was conducted by investigating the average fuel, mainly diesel, usually spent during their activity (i.e. loading 1 m^3 of soil, milling 3 cm of pavement, etc.). Technical specifications were used to ascertain, for standard working conditions, the maximum speed, the common operational speed, and their typical performance. Fuel consumption varies depending on the amount of power provided by the engine and on the working conditions of machines (temperature, altitude, etc.).

Several assessment methods for construction equipment fuel consumption are available (U.S. Environmental Protection Agency 2008, Wang 2007), however, coefficients from “Construction Equipment Ownership and Operating Expense Schedule” (U.S. Army Corps of Engineers 2009), unique for each type of equipment, were used in the calculations to obtain the fuel consumption.

The methodology adopted and results obtained are presented as follows:

1. The power-torque engine curve for every unit of equipment was analyzed and the value of the maximum power (brake horsepower - bhp) at a specific speed (revolutions per minute – RPM) was computed.
2. A fuel factor in gallons per brake horsepower-hour (gal/bhp*hr) was used (U.S. Army Corps of Engineers 2009). Diesel fuel factor (FF) is computed using the following formula:

$$FF\left[\frac{gal}{bhp\cdot hr}\right]=\frac{HPF*lbs\ Fuel\ per\ bhp\cdot hr}{lbs\ Fuel\ per\ gal} \qquad (5.1)$$

Where:

HPF is the horsepower factor and represents an average percent of full-rated horsepower being used by the engine, it is an estimate of the engine load under average working conditions. It is necessary to modify the rated horsepower as engines and motors in actual production do not work at their full-rated horsepower at all times. Periods spent idling, traveling in reverse, traveling empty, close maneuvering at part throttle, and operating downhill are examples of conditions that reduce the HPF.

Pounds (lbs) of fuel per bhp·hr is an average based on a variety of engine applications from manufacturer engine data.

Pounds (lbs) of fuel per gallon is the factor that determines the weight of the fuel consumed.

3. The fuel consumption (FC) for a specific unit of equipment was then obtained by multiplying the maximum power developed by the engine (from the power-torque engine curve), the fuel factor previously described, and a conversion factor for converting gallons into liters.

$$FC\left[\frac{l}{hr}\right] = \max Power[bhp] \cdot FF\left[\frac{gal}{bhp \cdot hr}\right] \cdot \gamma\left[\frac{l}{gal}\right] \tag{5.2}$$

4. Given the amount of material being handled and the productivity of a specific type of machine, the working time (WT) for carrying out a certain activity (i.e.; stabilizing 0.4 m of soil over 100 m^2) was computed using the formula that follows:

$$WT\ [hr] = \frac{\text{Volume of material } [m^3] \cdot \text{Density } [ton/m^3]}{\text{Productivity } [ton/hr]} \tag{5.3}$$

5. The final quantity of fuel for developing a certain activity with a specific unit of equipment was therefore computed as:

$$F\ [l] = FC\ \left[\frac{l}{hr}\right] \cdot WT\ [hr] \tag{5.4}$$

In addition, the Code of Federal Regulations (Code of Federal Regulations 2005) provides values for carbon content per gallon of diesel fuel: 2,778 g.

The Intergovernmental Panel on Climate Change guidelines (IPCC 2007) for calculating emissions inventories require that an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO_2. For all oil and oil products, the oxidation factor used is 0.99 (99 percent of the carbon in the fuel is eventually oxidized, while 1 percent remains un-oxidized (U.S. Environmental Protection Agency 2005). Moreover, to calculate the CO_2 emissions from a liter (or gallon) of fuel, the carbon emissions were multiplied by the ratio of the molecular weight of CO_2 (m.w. 44) to the molecular weight of carbon (m.w. 12): 44/12.

$$CO_2 \text{ from 1 gal diesel} = 2{,}778 \text{ g} \times 0.99 \times (44/12) \approx 10.1 \text{ kg/gal} = 2.6639 \text{ kg/l} \qquad (5.5)$$

Outcomes from the fuel consumption analysis related to equipment are summarized in the table 5.5.

5.3.2.3 Transportation

Transportation provides a variable contribution to the emission assessment depending on the distances involved. Whenever material handling requires long distances, emissions related to hauling become a main producer of pollutants; thus, minimizing transportation of material for a construction project can therefore produce a substantial environmental benefit.

In the case study hauling was largely reduced by recycling aggregates and using them as construction material. Only a small amount of resources (virgin aggregates, bitumen, and cement), mainly imputable to the surface layer, was transferred from outside the airport area.

In particular, transportation distances can be summarized as follows:

- virgin aggregates: 25 km (average distance from the nearby quarries)
- hot mix asphalt and asphalt emulsion: 30 km (average distance from the nearby asphalt plants)
- cement and cement mortar: 25 km (average distance from the nearby suppliers)
- recycled aggregates: 6 km (distance from the concrete slabs of the runway head to the new taxiway construction site); in particular, 1.5 km was the distance between the

runway head and the plug mill-screening plant while 4.5 km was the distance between the plug mill-screening plant and the construction site.

According to the U.S. Department of Energy (Davis et al. 2010) the average fuel efficiency for a truck in severe working conditions is 0.414 l/km (2.41 km consuming one liter of diesel). Furthermore, a capacity factor was added to the formulation to take into account the different amounts of fuel consumed depending on the loading conditions. A maximum loading capacity of 20 tons was assumed for trucks, almost 12-15 m^3 of sand-gravel materials. The formula adopted is expressed as follows.

$$CO_2[g] = \frac{Effective\ Load\ [ton]}{Capacity\ [ton]} \cdot Distance\ [km] \cdot Fuel\ Efficiency\left[\frac{l}{km}\right] \cdot CO_2\ per\ liter\ of\ diesel\left[\frac{g}{l}\right] \quad (5.6)$$

The amount of emissions related to hauling is summarized below. The following section presents an environmental comparison between the pavement presented in the case study and a common asphalt pavement for airport applications (no recycling practices adopted).

Table 5.4: Emissions related to hauling

Hauling	**CO_2** [kg]	**NO_x** [g]	**PM_{10}** [g]	**SO_2** [g]	**CO** [g]	**Hg** [g]	**Pb** [g]
Virgin aggregates	9,087	491,262	95,796	29,476	40,938	0.09	4.09
Bitumen	574	31,027	6,048	1,862	2,586	0.01	0.26
Cement	4,220	228,140	44,490	13,688	19,012	0.04	1.90
Cement mortar	3,058	165,304	32,222	9,918	13,775	0.03	1.38
Asphalt emulsion	161	8,691	1,694	521	724	0.00	0.07
Recycled aggregates	31,688	1,713,007	335,605	102,780	142,751	0.31	14.25
Total CO_2e [kg]				**49,594**			

5.3.2.4 *Recycled vs. Standard airport pavement: an environmental comparison*

An environmental assessment of a common asphalt airport pavement was conducted to compare its carbon footprint with the eco-benefits of the solution adopted in the case study. A standard pavement thickness and common materials were assumed according to the Airport practices (other pavements within the airport area have this structure): 30 cm of hot mix asphalt for surface, intermediate, and base layers altogether; 25 cm of cement bound layer as the sub-base; 35 cm of in-situ soil cement stabilization as the foundation layer. No recycled aggregates were to be used. It should be noted that if a granular layer was adopted as foundation then much more virgin aggregates had to be provided, increasing the total emissions coming from hauling and material handling.

Emissions were computed according to the methodologies previously described for materials production and manufacturing, the equipment used for construction, and hauling distances. The same transportation distances were assumed for both pavements. Results clearly suggested that recycled aggregates and low hauling distances provided massive environmental savings, especially when high quantities of materials are involved.

Table 5.5 summarize the findings.

Table 5.5: Comparisons – recycled vs. standard airport pavement

	Layer	**Material**	**Quantity [t]**	**Thickness [cm]**	**Emissions CO_2e [kg]**		
					Materials	**Hauling**	**Construction**
Recycled Airport Pavement	*Open Graded Asphalt with Cement Mortar*	Virgin aggregates	4,069.80	6	49,237	9,238	770
		Bitumen	214.20		269,017	583	
		Hyperfluid cement mortar	1,369.44		858,118	3,108	
		Asphalt emulsion	60.00		37,598	163	0.197
		Total Quantity - surface layer	**5,713.44**		**1,213,970**	**13,092**	**770.2**
	Recycled Cement Bound Layer	Recycled aggregates	28,512.00	30	141,276	15,532	28,022
		Cement	1,008.00		799,069	2,288	
		Water	1,440.00		0.802	negligible	
		Cement bound layer production	30,960.00		-		
		Total Quantity - intermediate layer	**30,960.00**		**940,346**	**17,820**	**28,022**
	Cement Stabilized In-situ Soil with Recycled Aggregates	Recycled aggregates	30,618.00	40	151,711	16,679	14,786
		Cement	882.00		699,185	2,002	
		Water	360.00		0.20	negligible	
		Total Quantity - foundation layer	**31,860.00**		**850,896**	**18,681**	**14,786**
	TOTAL EMISSIONS - RECYCLED AIRPORT PAVEMENT				**3,005,212**	**49,593**	**43,578.2**
Standard Airport Pavement	**Layer**	**Material**	**Quantity [t]**	**Thickness [cm]**	**Emissions CO_2e [kg]**		
					Materials	**Hauling**	**Construction**
	Hot Mix Asphalt layers	Virgin aggregates	27,740	30	355,324	73,357	5,150
		Bitumen	1,637		2,176,999	4,354	
		Asphalt emulsion	180		113,203	490	0.58
		Total Quantity - surface layer	**29,557**		**2,645,526**	**78,201**	**5,151**
	Cement Bound Layer	Virgin aggregates	23,760	25	287,447	53,930	4,281
		Cement	840		665,891	1,907	
		Water	1,200		0.67	negligible	
		Total Quantity - intermediate layer	**25,800**		**953,339**	**55,837**	**4,281**
	Cement Stabilized In-situ Soil	Virgin aggregates	25,515	35	308,679	57,914	12,214
		Cement	735		582,654	1,668	
		Water	300		0.16	negligible	
		Total Quantity - foundation layer	**26,550**		**891,333**	**59,582**	**12,214**
	TOTAL EMISSIONS - STANDARD AIRPORT PAVEMENT				**4,490,198**	**193,620**	**21,646**

Summing up the emissions related to the entire projects and dividing them by the total area of the new taxiway (almost 60,000 m^2) then a specific amount of equivalent CO_2e equal to 51.6 kg/m^2 and 78.4 kg/m^2 can be computed for the recycled and standard pavement, respectively. A comprehensive environmental saving of almost 35 % can therefore be estimated. Landfill saving, although not studied in the present paper, can also represent an effective eco-advantage to list.

Transportation of virgin aggregates represented a high-impact activity; emissions related to hauling in the standard airport pavement became in fact almost 3.5 times higher if compared with the recycled pavement. Construction equipment and related practices were almost similar in terms of pollution produced; this aspect was mainly due to the additional activities for processing and obtaining the recycled aggregates from concrete slabs (disposal, milling, screening, etc.).

5.4 Conclusions

The case study presented in the paper suggests a different way of designing and building airport pavements taking into account performance but also environmental impacts related to the materials used, the construction equipment and practices, and material handling.

A similar, and sometimes better, performance can be achieved by using recycling aggregates coming from demolition activities of obsolete infrastructures. However, laboratory and on-site preliminary investigations are strongly recommended since recycled material can vary greatly in its mechanical and structural behaviour.

In addition, significant environmental savings, in terms of lower emissions released in the atmosphere, can be provided. Limiting hauling can increase the productivity among the construction site and therefore shorten the working times, avoiding air traffic delays and airport safety issues.

Finally, costs can be significantly reduced by adopting recycled aggregates already available on site. Maintaining high performance while reducing costs and environmental impacts can represent a complementary way to achieve sustainability on airports. Comprehensive and multi-attribute approaches are therefore recommended for evaluating different design strategies.

5.5 References

Alley R. 2007. “Climate Change 2007: The Physical Science Basis - Summary for Policymakers”. *Intergovernamental Panel on Climate Change*.

Bahar R, Benazzoug M, Kenai S. 2004. “Performance of compacted cement-stabilised soil”. *Cement and concrete composites*. Volume 26, Issue 7 :811-20. ISSN: 0958-9465

Berry F, Gillhespy S, Rogers J., 2008. “Airport sustainability practices”. *Project 11-03*, Topic S02-02. ISBN: 0309098092

Code of Federal Regulations, 2005. “Fuel economy calculations.” *Title 40 - Protection of the Environment*, Part 600 - Fuel Economy of Motor Vehicles. Report n°40 CFR600.113-88

Crispino M, Toraldo E, Pozzi M., 2007a. “An innovative rehabilitation technique for airport concrete pavements.” *RILEM - International Conference on Advanced Characterization of Pavement and Soil Engineering Materials*. Athens, Greece.

Crispino M, Toraldo E, Pozzi M., 2007b. “The use of crushed concrete slabs in base layers of airport pavements.” *Proceedings of the Fifth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control*. Park City, Utah, USA.

Davis SC, Diegel SW, Boundy RG., 2010. “Transportation energy data book: Edition 28”. *Oak Ridge National Laboratory*. Center for Transportation Analysis, United States. Dept. of Energy. Office of Energy Efficiency.

EN1097-2, 2010. “Part 2: Methods for the determination of resistance to fragmentation Tests for mechanical and physical properties of aggregates.” *CEN/TC 154 - Aggregates: ICS 91.100.15 - Mineral materials and products*.

EN12591, 2009. “Specifications for paving grade bitumens.” *Bitumen and bituminous binders: BSI*. p. 36.

EN13286-2, 2010. “Part 2: Test methods for the determination of the laboratory reference density and water content - Proctor compaction.” *Unbound and hydraulically bound mixtures*: ICS 93.080.20 (Road construction materials). p.34.

Giustozzi F, Crispino M, Flintsch G., 2012. “Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability.” *The International Journal of Life Cycle Assessment*:1-11. DOI:10.1007/s11367-011-0375-6

GTAA Greater Toronto Airports Authority, 2010. “Outside, Inside, Upside: A Three-Dimensional Look at Corporate Social Responsibility.” http://www.torontopearson.com/en/gtaa/corporate-social-responsibility/#

Horvath A., 2004. “Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE).” *Recycled Materials Resource Center*, Department of Civil and Environmental Engineering, University of California, Berkeley.

ICAO, 2004. “Aerodromes: international standards and recommended practices: Annex 14 to the Convention on International Civil Aviation.” *International civil aviation organization*.

IPCC, 2007. “4th Assessment Report (AR4).” In: *Change IPoC*, editor. 2007. p. 104. http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

ISO-EN14044, 2006. “Life Cycle Assessment: Requirements and Guidelines.” *Environmental Management*. ICS: 13.020.60; 13.020.10. p. 46.

Oberthür S, Ott H., 1999. “The Kyoto Protocol: international climate policy for the 21st century.” *Springer Verlag*. ISBN: 354066470X

Pittenger DM., 2011. “Evaluating Sustainability of Selected Airport Pavement Treatments with Life-Cycle Cost, Raw Material Consumption, and Greenroads Standards.” *Transportation Research Record: Journal of the Transportation Research Board*, 2206:61-8.

Solomon S., 2007. “Climate change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.” *Cambridge University Press*. ISBN: 0521705967

Teil-B-8.3., 2003. “Dynamischer Plattendruckversuch mit Leichtem Fallgewichtsgerätes. Forschungsgesellschaft für Straßen und Verkehrswesen.” Technische Prüfvorschriften für Boden und Fels im Straßenbau: Arbeitsgruppe Erd und Grundbau.

Toraldo E., Mariani E., 2008. “Experimental Investigation On The Use Of Crushed Concrete Slabs For Subbase Layers In Airport Pavements.” *VARIREI International Conference*, Italy.

U.S. Environmental Protection Agency, 2005. “Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel.” *Office of Transportation and Air Quality (OTAQ)*.Report n° EPA420-F-05-001. www.epa.gov/otaq/greenhousegases.htm

U.S. Environmental Protection Agency, 2008. “NONROAD Model 2008a: nonroad engines, equipment, and vehicles.” http://www.epa.gov/otaq/nonrdmdl.htm

U.S. Army Corps of Engineers, 2009. “Construction Equipment Ownership and Operating Expense Schedule.” *EP 1110-1-8*. http://www.nww.usace.army.mil/html/offices/ed/c/ep_current.asp

Wang M., 2007. “Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model”, Version 1.8 b. *Argonne National Laboratory*.

Chapter 6. Environmental Analysis of Preventive Maintenance Treatments on Road Pavements

F. Giustozzi[1], G. Flintsch[2], M. Crispino[3]

ABSTRACT: Environmental protection measures to preserve natural resources while reducing the use of non-renewable energies and fossil fuels are nowadays becoming mandatory for a large variety of industrial products and processes. Climate change due to pollution and its effects are becoming a firm point for governments and policies. Road infrastructures, because of their expansionistic and strategic role, are spread in large amount over the globe surface and activities related to their construction, maintenance and disposal, consequently represent a main source of pollution and energy consumption.

Typical life-cycle analysis models emphasize life-cycle costs without taking into account important sustainability indicators such as energy consumption and emissions. The *Life-Cycle Environmental Impact Assessment* or *Life-Cycle Assessment* is being accepted and applied by road agencies and authorities to measure and compare the environmental impacts of asphalt products and related processes over the service life of the pavement. Therefore, more sustainable pavements have to be designed maximizing resources efficiency.

The paper focuses on preventive maintenance treatments applied on road pavements. The aim is to prove, through an environmental analysis over the service life of the pavement, the eco-effectiveness of preventive maintenance strategies in order to develop an environmental understanding of road preventive maintenance activities. Obviously, treatments performance is computed as well in the analysis. Finally, an *eco-saving factor* was estimated to quantify the eco-performances and related monetary costs. Results show that *"several"* PM treatments, each one with a small environmental impact, are most eco-efficient than *"few"* major rehabilitations, with a higher environmental impact. Obviously, the extension of the pavement service life due to PM

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

[3] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

treatments is a main factor to be considered in the analysis. The method is generally applicable to all the others PM treatments and/or road maintenance and rehabilitation activities.

6.1 Introduction

The paper shows a comprehensive methodology for assessing the effectiveness of a pavement strategy by enhancing the usual life-cycle cost analysis with a multi-attribute approach providing for materials performance and environmental features. A life-cycle assessment is therefore presented. The approach adds emissions in order to evaluate if a cost effective and best performing strategy also corresponds to the most eco-friendly alternative. Several environmental certification approaches have been developed during the last decade to certificate companies, products and building (U.S. Green Building Council 2009). New rating systems and tools are also becoming popular for assessing the eco-impact footprint of road pavement projects (FHWA 2010, Anderson 2011). A more comprehensive assessment would allow a more comprehensive evaluation of design and development of environmental management plans. Choosing between different alternatives could be no longer just a matter of traditional costs evaluation.

The paper focuses on the life-cycle assessment of road maintenance works to understand the environmental impact of M&R activities over the service life of the pavement. In particular, the assessment presented illustrates the eco-efficiency of preventive maintenance (PM) treatments on road pavements. Since millions of dollars and a huge amount of non-renewable resources are used every year for M&R activities, calculation of the emissions produced and the embodied energies involved over a certain preservation strategy is important. It could represent a step forward for selecting the right treatments and for preserving the environment. The optimal preservation strategy should be selected not just considering costs and performance, but also the environmental impacts. Similar results in terms of cost and performance may be achieved using more eco-efficient alternatives, which consume less energy and produce less pollution. The energy involved, from the extraction/production of raw materials up to their placement at the worksite, was computed in the analysis as well as emissions produced in each process, expressed as a quantity of equivalent CO_2. However, energy use and emissions should not represent a stand-alone evaluation of the project eco-efficiency but, more appropriately, they should be adopted as a relative comparison between different products and strategies. Also, besides energies and emissions, the assessment should be contextualized for the specific pavement structure and amount of traffic in order to highlight the role of the performance in the whole process.

The paper compares the environmental effectiveness of different PM treatments and related maintenance strategies based on a preservation approach. In particular, the aim is to compare the eco-effectiveness of two different maintenance strategies for a constant analysis period: with and without using a PM approach. Results show how applying preventive maintenance on road pavements leads towards a saving of emissions produced and energies spent.

6.2 Road Preventive Maintenance

Maintenance on road pavements still suffers from lack of technical specifications and mathematical models to plan interventions and therefore manage assets over a long term. Road agencies still continue to assign funds for pavements M&R on an “overall scheme” of budget plan: a fix amount is equally spread over the years of the maintenance contract. In this way a surplus or a lack of money for pavement maintenance treatments are expected and the budget allocation results to be often inadequate. Several researches (Hein 2010) showed that applying a preservation strategy can effectively provide a service life extension of pavements. The main idea is applying maintenance activities at the proper time before distresses appear to be evident so that pavements still have a high serviceability level. That’s because, once the pavement starts to deteriorate, the deterioration curve rapidly increases its slope and therefore a PM activity could no more be considered effective beyond that time. Several types of PM treatments are available to road agencies for extending the service life of flexible pavements.

Table 6.1: Preventive maintenance treatments

PM Treatment	Description	Extension of life provided
Crack sealing	*It's useful to avoid water infiltration on lower layers. Widely used and low cost treatment.*	2 ÷ 4 years
Thin overlay	*Below 1.5 inches (3.8 cm) of thickness, it is usually adopted when a consistent intervention is needed. It can be placed with or without milling the existing asphalt surface layer depending on the presence of segregation, raveling or block cracking, and rutting.*	7 ÷ 10 years
Chip seal	*It consists of a binder application followed by a specific amount of aggregates and a final compaction. It's useful to protect pavements from ultra-violet light degradation and moisture infiltration. It's useful to address raveling, bleeding, and minor cracking, but useless for rutting.*	4 ÷ 6 years
Microsurfacing	*It's a mixture of polymer-modified asphalt emulsion, aggregates, mineral filler, water and other additives, properly proportioned, mixed and spread on a paved surface (5). It is primarily used as a surface sealant to address rutting, loss of friction, damage from water and UV rays.*	4 ÷ 7 years
Fog seal	*It's an asphalt emulsion diluted with water that provides a waterproofing effect and prevents further stone loss fixing the aggregates in place. The emulsion is applied directly to the pavement surface without adding any aggregates. Fog seal can address raveling, oxidation, and low-severity fatigue cracking.*	1 ÷ 2 years
Slurry seal	*It is composed of a mixture of emulsified asphalt, aggregates, water, and additives. The mixture is therefore uniformly spread over the pavement. It is usually adopted to restore pavement texture providing a skid resistant surface while improving waterproofing properties and sealing.*	3 ÷ 5 years
Ultrathin friction course	*is a high quality layer where hot-mix asphalt with superior crushed aggregates is placed on the top of a polymer-modified asphalt emulsion tack coat. The total thickness ranges from 0.375 to 0.75 in (0.95 ÷ 1.9 cm). The treatment is adopted to seal the asphalt surface in order to avoid raveling and oxidation of the binder.*	3 ÷ 5 years

6.3 Environmental Effectiveness of Preventive Maintenance Treatments

The paper shows that a preservation strategy over the life cycle of the pavement could result in a more eco-effective plan avoiding energy waste and unsafe emissions. Being pavement maintenance one of the key-aspects to handle over the service life, a major attention should be dedicated to its planning, taking also into account environmental impacts of processes and activities. Letting the pavement deteriorate until a major reconstruction is needed typically represent an ineffective strategy from cost, performance, and environmental standpoints.

Many articles (Labi 2003, FHWA 1996) have already proved that intervening before the asset starts to seriously deteriorate, in a preventive way, results in a more cost-effective strategy that simply waiting until major rehabilitation or reconstruction is needed. Furthermore, maintaining the pavement at high levels of serviceability enhances the performance, minimizes user costs (Falls 1994), and provides a safer infrastructure. Environmental impacts of a PM strategy should be included in the analysis in order to set long term plans that combine the three aspects in a more general life cycle assessment that the still universally adopted, approach only based on costs. Nowadays, a minority of life cycle analysis on pavements develops performance features besides costs and almost nothing has still been written about how to combine and compare these three aspects together with a multi-attribute approach. However, an always stronger effort is placed on evaluating the eco-efficiency of roads and related features (Flintsch 2010).

Assuming that a PM approach provides a more cost-effective strategy, the paper focuses on evaluating environmental effects of preventive treatments over the whole life-cycle of a road pavement. Performance deterioration models were used to identify the time where preventive maintenance activities were needed based on pre-established thresholds. Two different maintenance strategies were analyzed. The first one adopted a preservation approach based on PM while the second used a standard M&R plan, including only major rehabilitations and reconstructions. Three PM alternatives were evaluated for the first strategy depending on the type of the PM interventions adopted: thin overlay, microsurfacing, and slurry seal. However, the methodology adopted is general and it could be easily extended to other PM treatments and maintenance strategies.

6.3.1 Performance Assessment of Preventive Maintenance Treatments

In order to assess the optimal timing over the life cycle to schedule PM activities and rehabilitations on road pavements, a life cycle performance analysis (Crispino 2010) was carried out considering theoretical and empirical deterioration curves (Hall 2002). Performance curves were developed for predicting the Present Serviceability Index (PSI) over time. Moreover, different models (Labi 2003b) were adopted to compute the performance improvement, or performance jump, due to the application of a certain treatment. The performance jump (PJ) concept allows the evaluation of incremental benefits, just-before and just-after, of the application of a specific treatment that is part of a long-term maintenance strategy. It provides a practical way to assess the effectiveness of a maintenance treatment in the short term. Unfortunately, the practice of measuring performance before and after maintenance activities is not common in road agencies and data availability is very limited. Performance jumps, for instance, can be assessed: - through real scale field measurements, which result in a more accurate estimate but limited to the proper conditions of the site (pavement structure and materials, traffic, weather conditions), or - deduced using data and models (Zheng 2010) available in literature for that specific treatment. For this investigation the performance improvement due to PM treatments was computed using the following formulas (Labi 2003b) that are a function of the before-treatment PSI:

$$PJ = \frac{71.63}{42.01+(10^{-5.11} \cdot 97.17^{PSI})} \qquad \text{Thin overlay} \tag{6.1}$$

$$PJ = 0.0853 \cdot PSI + 0.5552 \qquad \text{Microsurfacing} \tag{6.2}$$

$$PJ = \max[0.2\,;\ 1.158 - 0.275 \cdot PSI] \qquad \text{Slurry seal} \tag{6.3}$$

While pre-treatment curves were developed using the AASHTO deterioration curve (AASHTO 1993) for all the alternatives provided in the analysis, post-treatment curves were extrapolated from previous experiences (Labi 2003b) and taken as a reference to develop the final deterioration curve over the whole analysis period. Otherwise, when experimental data were not available, or not adaptable to the present analysis, the performance jump and after-treatment deterioration curves were obtained from the original untreated curve and life-extension. The after-treatment curve assumes that the pavement reaches the threshold value at the life extension and is parallel to the untreated curve. For instance, if a certain treatment is applied when the PSI of the pavement is equal to 3.5 (e.g. at year 10) and it provides an average extension of life equal to 4 years compared to the "do-nothing" curve, then, the new PSI value immediately after the treatment will be the one belonging to the "do-nothing" curve 4 years before (e.g. at year 6). In this way the "do-nothing" curve will just be moved depending on the extension of life provided by the specific PM treatment and therefore, the deterioration rate of the performance curve will remain the same before and after the maintenance activity. Finally, the "area under curve" (AuC) (Zimmermann 1992) was taken as a measure of the performance effectiveness for each alternative without considering the area below the threshold. Areas were estimated using the trapezoid method: the area under the performance curve was divided into 50 trapezoids, one for each year of the analysis period. The area of each trapezoid was therefore computed according to the following formula:

$$Area\ (trapezoid\ 1) = \frac{\left(PSI_{@year\ 0} + PSI_{@year\ 1}\right) \cdot 1year}{2} \tag{6.4}$$

That is, extending to all trapezoids:

$$Area\ Under\ Curve = \sum_{i=0}^{49} \frac{(PSI_i + PSI_{i+1}) \cdot 1year}{2} \tag{6.5}$$

The adopted pavement structure had at construction a structural number of 6.6 and it was built on a subgrade with a resilient modulus of 7,000 psi (48.26 MPa). The traffic was set equal to 3,500 ESAL per day with a growth factor of 2.5 % per year, constant over the analysis period. The analysis period was set equal to 50 years. The initial PSI value was 4.5 (new construction) and the threshold for major rehabilitations, considering an interstate road, was fixed at 3.0.

Deterioration trends, performance jumps and post-treatment curves are summarized in the following figure (Figure 6.1) and the areas under the curves for the different alternatives and maintenance strategies are summarized in Table 6.2. As expected, the table shows that preventive maintenance results in the pavement having better conditions over the analysis period. Averaging the areas under the curves, it results an average PSI over the analysis period of 3.75 for the “overlay-alternative” and equal to 3.68 and 3.65 for the “microsurfacing-alternative” and “slurry-alternative” respectively. Do_Nothing alternative provided an average PSI of 3.45 over the analysis period. The improved performance will reduce normal operating user costs (strictly related to the pavement conditions), improving user satisfaction.

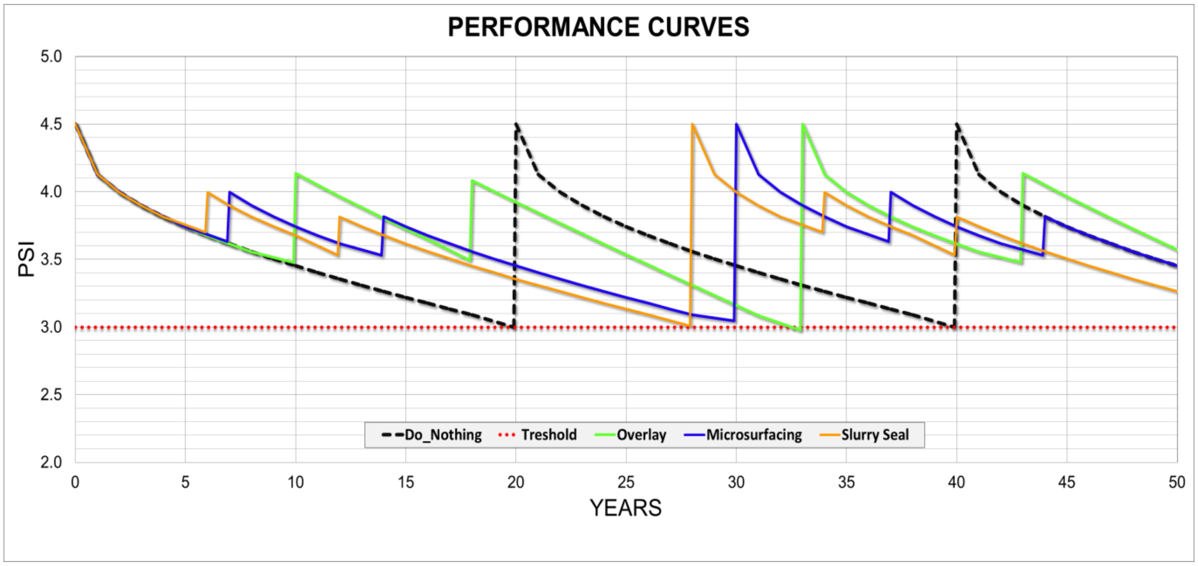


Figure 6.1: Performance curves for different maintenance alternatives.

Table 6.2: Area Under Curve

Alternative	AuC *Area Under Curve*	Performance increase
Do Nothing	29.53	
Overlay	37.32	+ 26.4 %
Microsurfacing	33.68	+ 14.0 %
Slurry Seal	32.48	+ 10.0 %

6.3.2 Environmental Assessment of Preventive Maintenance Treatments

A life-cycle eco-efficiency analysis was conducted in order to test whether preventive maintenance practices could also be more environmentally friendly than the traditional rehabilitation approach. Carbon emissions and embodied energies were both taken into account to develop an environmental assessment of PM strategies. Emissions coming from materials (from-cradle-to-grave analysis), processes, and construction procedures were converted into carbon equivalent emissions, to compute a carbon footprint for each alternative. The same guidelines were adopted to assess the total amount of energy involved. Energies are strictly related to the fuel consumption, whatever fuel type is adopted in the various processes as a motive-power, while carbon footprints are also referred to the specific manner a product is obtained, the particular material or machinery used. The investigation was developed taking into account different energies and emission sources coming from the different PM alternatives described in the previous paragraph, considering the different materials, equipment, and construction processes used.

6.3.2.1 Materials

Since the only way to correctly assess energies and emissions belonging to road raw materials is to exactly know every single phase of an extremely complex and articulate process (e.g. to compute emissions coming from bitumen, emissions coming from the oil extraction, transport to the plant, refining of crude oil into bitumen, transport and storage in depots, should then be calculated), several authoritative literature sources were analyzed and taken as a reference (Table 6.3). The different literature data available were then averaged computing a final reasonable value for emissions and energies due to the manufacture of raw materials. It should be noted that the main goal of the analysis was to compare different PM strategies against major rehabilitation/reconstruction policies in order to identify the most eco-efficient. Comparing different PM alternatives using a life cycle assessment approach can be done without assessing the exact value for a single material because the error made remains the same over the different comparisons and it could be therefore disregarded. Indeed, the aim of the investigation is to point out the differential between different strategies.

Table 6.3 summarizes the outcomes obtained from the literature review highlighting the different sources adopted. All entries listed in the table consider all the stages and processes to obtain the final product as ready-to-use.

Table 6.3: Emissions and energies – raw materials

Material	**Emission – CO_2e** [kg/ton material]	**Embodied energy** [MJ/ton material]	**Literature source**
Bitumen	256.5	4603	(Asphalt Institute and Eurobitume 2008, Stripple 2001, Hammond 2008, ATHENA™ Institute 2006)
Bitumen emulsion [60%]	221.0	3490	(Asphalt Institute and Eurobitume 2008, Stripple 2001)
Crushed aggregates	7.5	38.9	(Stripple 2001, ATHENA™ Institute 1999, ATHENA™ Institute 2006, Häkkinen 1996, WRAP 2010)
Pit-run aggregates	5.3	19.4	(Stripple 2001, ATHENA™ Institute 1999, Häkkinen 1996)
Cement	1079.6	5900	(Stripple 2001, Marceau 2007, Alcom 2003)
Quicklime	2500	9240	(Stripple 2001)
Water	0.29	10	(Stripple 2001)
Polymers – elastomers	3000	91440	(Norton 2007, APME 2004, Alcom 2003)
Polymers – plastomers	1400	44667.3	(Stripple 2001, APME 2004, Alcom 2003)
Emulsifiers	600	63250	(Stripple 2001, Alcom 2003)

6.3.2.2 Equipment

Several pieces of equipment, currently used in road construction sites, were analyzed and a final calculation of emissions produced and energies consumed was provided. Millers, pavers, rollers, and slurry machineries were examined identifying and quantifying emissions and energies embodied in road PM activities. The main factor computed is the total amount of motive-power necessary to carry out a specific type of maintenance work for a sample road unit (e.g. a square meter).

The primary source of emissions is due to the engine exhaust system, depending on the total amount of fuel consumed in each phase of the pavement maintenance process. However, the actual quantity of fuel consumed to do maintenance on a sample road unit while applying a certain treatment, is hard to estimate; indeed, a great variety of stochastic aspects could affect the assessed value (experience and behavior of the operator, inability to measure the instant fuel consumption, multiplicity of available engines and brands, etc.). The method adopted and the simplifications made in the analysis are hereafter explained.

Different recent machineries' engines belonging to major companies were analyzed identifying the fuel consumption to carry out a square meter of a specific action (milling, paving, rolling, etc.). A relation (U.S. Environmental Protection Agency 2009) to convert the fuel consumption into emissions produced and energy spent was applied. The total amount of equivalent CO_2 and energies consumed were assessed for each type of equipment and model. Technical specifications for the different engine types, obtained directly from equipment manufacturers, provided curves that allowed relating the BSFC (Basic Specific Fuel Consumption, expressed in g/KW·h of fuel) with the rotation speed of the engine, expressed in revolutions per minute (rpm). Torque and power curves determined the relation between the nominal power supplied by the engine, expressed in Kilowatt, and its rotation speed.

The amount of fuel consumed was calculated using the following formulas. Obviously, different amounts of fuel could be computed depending on the engine rotation speed and the nominal power supplied; thus, it was assumed that, during the execution of the work, the engine run at the rotation speed that provided the maximum torque.

$$F\ \left[\frac{l}{h}\right] = BSFC\left[\frac{g}{KW\cdot h}\right]\cdot P[KW]\cdot 1/\gamma\left[\frac{l}{g}\right] \tag{6.6}$$

Where: F = fuel consumed; $BSFC$ = brake specific fuel consumption; P = engine power when the rotation speed provides the maximum torque; γ = density of the fuel (diesel density = 0.832 kg/l).

The fuel consumption was then multiplied by the productivity of the machinery, given by manufacturers' technical specifications for specific thickness of intervention, in order to assess the amount of fuel needed to carry out the specific work on a square meter of pavement; the formula is quoted hereafter.

$$F_{sqm}\ \left[\frac{l}{m^2}\right] = \frac{F\left[\frac{l}{h}\right]}{prod.\left[\frac{m^2}{h}\right]} \tag{6.7}$$

Where: F_{sqm} = amount of fuel consumed to do a certain maintenance activity on a square meter of pavement; *prod.* = productivity of the machinery.

Finally, the amount of fuel consumed on a square meter of surface was multiplied by the specific amount of equivalent CO_2 emitted during the combustion of a liter of diesel (U.S. Environmental Protection Agency 2009) in order to find out the total quantity of emissions due to a certain type of equipment to carry out a specific maintenance treatment on a square meter of pavement. The same procedure, but using the specific amount of energy spent to burn a liter of diesel (U.S. Environmental Protection Agency 2009), was adopted to compute energies involved in the process.

$$CO_2\, emissions \left[\frac{g}{m^2}\right] = F_{sqm}\left[\frac{l}{m^2}\right] \cdot \alpha \left[\frac{g}{l}\right] \tag{6.8}$$

$$Energy \left[\frac{MJ}{m^2}\right] = F_{sqm}\left[\frac{l}{m^2}\right] \cdot \beta \left[\frac{MJ}{l}\right] \tag{6.9}$$

Where: α = specific amount of CO_2 emitted during the combustion of a liter of diesel = 2650 g/l;
β = specific amount of energy spent to burn a liter of diesel = 36 MJ/l.

Sample notes are provided on table 6.4 for an intervention thickness of 10 cm to summarize the outcomes obtained for various equipment analyzed. Only a small amount of machineries investigated is reported hereafter.

Table 6.4: Emissions and energies due to machineries*

<table>
<tr><th>Models</th><th>Prod. [m^2/h]</th><th colspan="2">P_engine [KW]</th><th>F [l/h]</th><th>$\mathbf{F_{sqm}}$ [l/m^2]</th><th>$\mathbf{CO_2e}$ [g/m^2]</th><th>Energy [MJ/m^2]</th><th>Company</th></tr>
<tr><td colspan="9">MILLERS</td></tr>
<tr><td>PL2000S</td><td>2448.98</td><td colspan="2">447</td><td>105</td><td>0.043</td><td>113.62</td><td>1.544</td><td>Dynapac</td></tr>
<tr><td>PL2100S</td><td>4320.00</td><td colspan="2">447</td><td>105</td><td>0.024</td><td>64.41</td><td>0.875</td><td>Dynapac</td></tr>
<tr><td>W120F</td><td>1020.41</td><td colspan="2">227</td><td>61</td><td>0.060</td><td>158.42</td><td>2.152</td><td>Wirtgen</td></tr>
<tr><td>W200</td><td>2040.82</td><td colspan="2">380</td><td>62</td><td>0.030</td><td>80.51</td><td>1.094</td><td>Wirtgen</td></tr>
<tr><td colspan="9">PAVERS</td></tr>
<tr><td>AP1000D</td><td>4082</td><td colspan="2">166</td><td>41.0</td><td>0.010</td><td>26.63</td><td>0.362</td><td>Caterpillar</td></tr>
<tr><td>AP600D</td><td>2449</td><td colspan="2">122</td><td>31.3</td><td>0.013</td><td>33.91</td><td>0.461</td><td>Caterpillar</td></tr>
<tr><td>DF145C</td><td>3673</td><td colspan="2">153</td><td>38.2</td><td>0.010</td><td>27.53</td><td>0.374</td><td>Dynapac</td></tr>
<tr><td>F121C</td><td>2449</td><td colspan="2">120</td><td>30.9</td><td>0.013</td><td>33.44</td><td>0.454</td><td>Dynapac</td></tr>
<tr><td>Super1603</td><td>2449</td><td colspan="2">100</td><td>26.5</td><td>0.011</td><td>28.68</td><td>0.390</td><td>Voegele</td></tr>
<tr><td>Super1803</td><td>2857</td><td colspan="2">130</td><td>33.1</td><td>0.012</td><td>30.70</td><td>0.417</td><td>Voegele</td></tr>
<tr><td colspan="2">SLURRY MACHINERIES</td><td>mixer engine [KW]</td><td>truck engine [KW]</td><td colspan="5"></td></tr>
<tr><td>M206</td><td>3600</td><td>74</td><td>186</td><td>41.7</td><td>0.0116</td><td>30.70</td><td>0.417</td><td>Bergkamp</td></tr>
<tr><td>M210</td><td>3600</td><td>74</td><td>224</td><td>42.4</td><td>0.0118</td><td>31.25</td><td>0.424</td><td>Bergkamp</td></tr>
</table>

** Rollers were investigated as well but they are not reported in the table because, to compact a same pavement thickness, emissions and energies also depend on the amount of passages and the compaction mode adopted (static or dynamic).*

6.3.2.3 Processes

The last step to assess emissions and energies embodied in PM activities for road pavements was to analyze the stages that led to the manufacture of the final maintenance treatment. After that emissions and energies due to materials and equipment are computed, processes involved to convert raw materials into the final PM treatment should then be investigated. Hot mix asphalt production, reclaimed asphalt pavement (RAP) processing, transportation from the plant to the working place, final disposal and recycling, represent only some of the different processes involved.

Depending on the mix design adopted and thickness chosen for the different PM treatments, various calculations result in diverse outcomes. A spreadsheet-tool was created to automate the analysis and take into account different possible strategies. Calculations were made for each PM treatment (thin overlay, microsurfacing, slurry seal) and major reconstruction/rehabilitation. The specifics of each case are discussed following.

Table 6.5 summarizes the outcomes showing the whole calculation only for the “thin overlay” strategy; a similar procedure was adopted to analyze the other maintenance strategies. Figure 6.2 shows emissions and energies over the analysis period. These results were obtained by simply summing the single emissions and energies related to interventions that took place in a specific maintenance strategy (Figure 6.1).

Thin Overlay A typical mix design for the hot mix asphalt was chosen in order to know the percentages of bitumen, aggregate type, and amount of filler used. The intervention thickness was fixed as well, so that the volume of materials involved could be computed for a square meter of treatment. Eventually, a pre-established amount of RAP could be used in the mixture.

Emissions and energies due to raw materials were simply estimated multiplying values cited in Table 6.3 by the tonnage of resources used. All emissions and energies involved to get the final hot mix asphalt from raw materials and RAP processing were computed with the same method described in the "Materials" paragraph. Then, the proper equipment was chosen to carry out each phase of the work. In particular, for a 3 cm (1.2 in) overlay, a tack coat sprayer, a paver, and a roller were selected. Energies and emissions were computed for a square meter of finished thin overlay. A hauling distance of 20 Km was assumed from the production site to the lay-down place.

The total amount of all energies spent and emissions produced were computed by summing the individual contributions of the various processes.

Microsurfacing and Slurry Seal A similar procedure was used to estimate energies and emissions to lay-down a square meter of microsurfacing and slurry seal. In this case the mix design changed depending on the type of microsurfacing (type II and type III) and slurry seal (type I, II, and III) chosen (Fugro 2004). The same transportation distance was adopted.

Major Reconstruction/Rehabilitation The major rehabilitation consisted of removing all the asphalt layers and replacing them to achieve a total structural number consistent with the traffic conditions at the time of rehabilitation (an increase in the structural number was provided after each major rehabilitation). The processes involved are similar to those used in the thin overlay intervention, except for the thickness (volume of materials), the previous milling of the old asphalt layers, and their disposal.

Transportation for waste removal was considered as well (5 Km from the working site).

Table 6.5: Emissions and energies due to PM activities

	Quantity [ton/m^2]	**Emission – CO$_2$e** [kg/ton material]	**Embodied energy** [MJ/ton material]	**Total CO$_2$e** [kg/m^2]	**Total Energy** [MJ/m^2]
THIN OVERLAY – 3 cm (20% RAP)					
<u>Materials</u>					
Bitumen	0.00294	256.5	4603	0.75	13.5
Tack coat emulsion	0.001	221.0	3490	0.22	3.49
Crushed Aggregates	0.037	7.5	38.9	0.28	1.44
Pit-run Aggregates	0.016	5.3	19.4	0.10	0.31
HMA production	0.0735	22	314.2	1.62	23.1
RAP processing	0.0147	8.7	42	0.13	0.62
<u>Equipment</u>					
	Fuel consumption [l/h]				
Tack coat sprayer	6			0.036	0.491
Paver	35.3			0.03	0.341
Roller	24.5			0.056	0.763
Hauling (20 Km)		0.06 / Km	0.9 / Km	0.088	1.32
			SUM	**3.30**	**45.39**
MICROSURFACING – type III (0.75 in – 2 cm)				**1.98**	**39.54**
SLURRY SEAL – type II (0.375 in – 0.95 cm)				**0.80**	**12.30**
MAJOR REHABILITATION 7 in. (17.8 cm) base + 2 in. (5.1 cm) intermediate + 1.5 in. (3.8 cm) surface				**26.41**	**352.43**

A saving factor (SF) could be provided for the different PM strategies if compared to the major rehabilitations approach (Table 6.6).

Table 6.6: Emissions and energy saving over the analysis period

SF	**Emission saving**	**Energy saving**
Thin overlay	31.3 %	30.7 %
Microsurfacing	35.0 %	27.6 %
Slurry seal	43.9 %	43.0 %

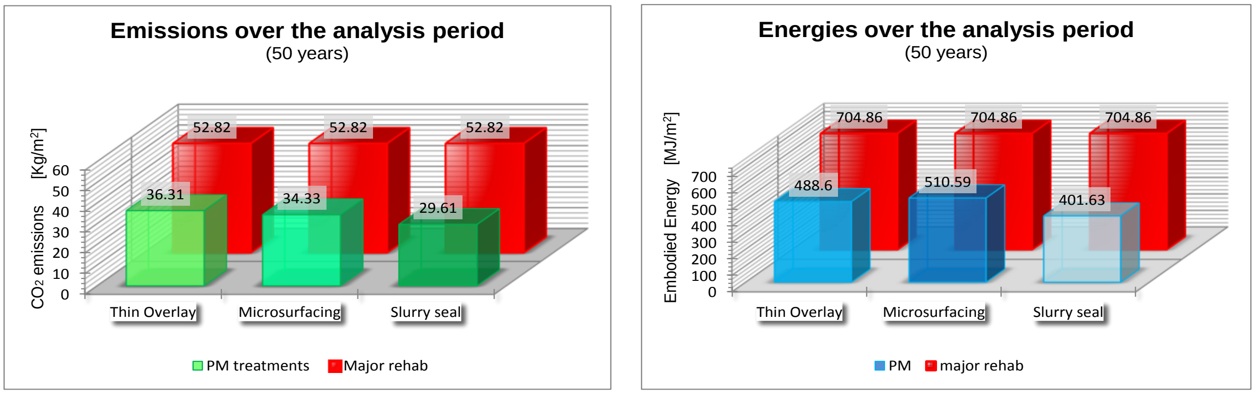


Figure 6.2: Emissions and embodied energies over the analysis period (50 years).

6.4 Conclusions

The paper proposes a new multi-attribute decision support methodology to compare pavement preservation and rehabilitation strategies. For the case study considered, pavement preventive maintenance strategies were shown to be eco-effective, in addition to providing enhanced average performance over the life cycle. Moreover, the paper shows how much eco-effective could be a PM strategy compared to a major rehabilitation and reconstruction approach (up to almost 44% of CO_2e emissions saved in 50 years). A large amount of emissions and energy could be saved by applying preventive maintenance plans on road pavements.

Although the proposed methodology is considered a step forward compared with current practice, the analysis could be improved by adding other variables and analysis processes. For example, a sensitivity analysis to the traffic over the analysis period could be done to determine whether for high levels of traffic, the PM treatments would be applied too often, thwarting the eco-advantages provided. Furthermore, other PM strategies could be created by combining various types of PM interventions in a single strategy and different pavements structures could then be analyzed.

Finally, a more general and comprehensive comparison that examines together costs effectiveness with performance and environmental impacts should be developed, as well as inclusive indexes to help road authorities and municipalities in the decision making process.

6.5 References

Alcom A. (2003). *Embodied Energy and CO2 coefficients for NZ Building Materials*. Center for Building Performance Research, Virginia University of Wellington, New Zealand.

American Association of State Highway and Transportation Officials - AASHTO (1993). *AASHTO guide for design of pavement structures*, Washington D.C. ISBN: 1560510552.

Anderson J., Weiland C., Muench S. (2011). *Greenroads™ Manual v. 1.5.* University of Washington. http://www.greenroads.us. Accessed March 15, 2011.

Asphalt Institute and Eurobitume (2008). *Bitumen Industry – A Global Perspective*, Information Series No.230, IS-230, ISBN 978-1-934154-54-0.

Association of Plastic Manufacturers in Europe - APME (2004).

ATHENA™ Sustainable Material Institute (1999). *Life Cycle embodied energy and global warming emissions for concrete and asphalt roadways - Summary report*. Canadian Portland Cement Association.

ATHENA™ Institute (2006). *A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential.* Cement Association of Canada.

Crispino M., Giustozzi F., Baracco G. (2010). *Evaluation of effectiveness of a preventive maintenance technology through a life cycle cost and performance analysis on road pavements.* Life-Cycle of Civil Engineering Systems. Taipei, 27-31/10/2010, ISBN/ISSN: 9789860249866.

Falls L. C., Khalil S., Hudson W. R., Haas R. (1994). *Long-Term Cost-Benefit Analysis of Pavement Management System Implementation.* Transportation Research Board. Volume 2, pp 133-138, ISSN: 1073-1652.

Flintsch G. (2010). *International Sustainable Pavements Workshop*, Airie, VA (USA). Research Agenda for Sustainable Pavement. http://www.vtti.vt.edu/ISPW/ISPW-2010.html

Fugro (2004). *Slurry Seal / Micro-Surface Mix Design Procedure*, Phase I Report - Contract 65A0151 for California Department of Transportation (Caltrans), Materials/Infrastructure Section.

Häkkinen T., Mäkelä K. (1996). *Environmental impact of concrete and asphalt pavements*, Technical Research Centre of Finland, VTT Tiedotteita, Meddelanden, Research Notes 1752.

Hall K., Correa C., Simpson A. (2002). *LTPP Data Analysis: Effectiveness of Maintenance and Rehabilitation Options*, National Cooperative Highway Research Program. NCHRP Project 20-50(03/04).

Hammond G., Jones C. (2008). *Inventory of Carbon & Energy (ICE)*. ICE V1.6a©, Energy Research Team (SERT), University of Bath, UK.

Hein, D., Rao, S. (2010). *Rational Procedures for Evaluating the Effectiveness of Pavement Preservation Treatments*. First International Conference on Pavement Preservation, Newport Beach, California, USA.

International Slurry Surfacing Association, (2010). *Recommended Performance Guideline For Micro Surfacing*. ISSA – Technical Bulletin A-143. http://www.slurry.org

Labi S., Sinha K. C. (2003). *Measures of Short-Term Effectiveness of Highway Pavement Maintenance.* Journal of Transportation Engineering. Volume 129, Issue 6, pp 673-683.

Labi S., Sinha K. (2003b). *The effectiveness of maintenance and its impact on capital expenditures.* Indiana Department of Transportation and Federal Highway Administration. Report No. FHWA/IN/JTRP-2002/27.

Marceau M., Nisbet M., VanGeem M. (2007). *Life Cycle Inventory of Portland Cement Concrete*, PCA R&D Serial No. 3011. Portland Cement Association, Skokie, Illinois, PCA, 121 pages.

Norton A. (2007). *Ecoinvent, Materials: their manufacture, use & environmental impact*. Greenspec®.

Stripple H. (2001). *Life Cycle Assessment of Road: a Pilot Study for Inventory Analysis*. IVL Report B1210E, Swedish Environmental Research Institute, Gothenburg, Sweden.

U.S. Department of Transportation. Federal Highway Administration (1996). *Preventive Maintenance Effectiveness: Preventive Maintenance Treatments*. Report No. FHWA-SA-96-027.

U.S. Department of Transportation. Federal Highway Administration (2010). *Sustainable Highways Self-Evaluation Tool.* http://www.sustainablehighways.org. Accessed March 13, 2011.

U.S. Environmental Protection Agency (2009). *Office Carbon Footprint Tool - version 1.2.* http://www.epa.gov/wastes/partnerships/wastewise/carboncalc.htm

U.S. Green Building Council. *Leed 2009 for new construction and major renovations*. http://www.usgbc.org. Accessed March 15, 2011.

Zheng W., Groeger J., Simpson A., Hicks G. (2010). *Performance Evaluation of Various Rehabilitation and Preservation Treatments.* U.S. Department of Transportation, Federal Highway Administration Report. www.fhwa.dot.gov/pavement/pub_details.cfm?id=666

Zimmermann K. (1992). *Pavement management methodologies to select projects and recommend preservation treatments*. National Cooperative Highway Research Program, NCHRP Synthesis 222, Project 20-5 FY. ISSN: 0547-5570.

Waste Resources Action Program - WRAP (2010). *The CO2 emissions estimator tool for the use of aggregates in construction* - User Guide v2.0. Project code: MRF-136.

Chapter 7. Multi-Approach Life Cycle Assessment of Road Pavements for Achieving Environmental Sustainability

F. Giustozzi[1], M. Crispino[2], G. Flintsch[3]

ABSTRACT:

Purpose. Although a significant number of environmental protection measures concerning industrial products and processes have emerged over the past few years, similar measures have only started to appear in road construction and related practices. There is a need for understanding what a “sustainable pavement” would entail in terms of greenhouse gas emissions and energy consumption. Since environmental impact assessment of major projects is becoming mandatory in many countries, various research projects attempt to evaluate the environmental impact of different pavement materials, technologies or processes over the road life cycle. To support these efforts, there is a need to measure and describe different aspects of sustainability related to road pavements. In particular, keeping road pavements at high service levels through a *preventive* maintenance approach during the pavement service life has been proven to provide significant improvement of their performance and reduce their deterioration rate.

Methodology. This paper describes an innovative methodology to evaluate the environmental impact of preventive maintenance activities. It relates these activities to performance and cost during the service life of the pavement through a multi-attribute “life cycle cost, performance, and environmental analysis”. Emissions and energy saved adopting several preventive maintenance strategies were computed, relating them to cost and performance. Equipment and materials usually involved in road maintenance practices were also analyzed in order to assess

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

[3] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

specific fuel consumption and energy spent. An ad-hoc index was ultimately created, adopting a script file to evaluate the best strategy through the multi-attribute approach.

Results and Conclusions. Results show how eco-effective it can be to improve pavement management practices on roads by implementing energy efficient treatments and strategies. Furthermore, eco-saving factors could represent a new and innovative feature to be added in the sustainability assessment process for pavements to evaluate different alternatives and assist authorities choosing between different investment solutions as a part of a decision support system.

7.1 Introduction

The paper shows a comprehensive methodology for assessing the effectiveness of a pavement maintenance strategy by enhancing the usual life cycle cost analysis (LCCA) with an innovative multi-attribute approach. A full life cycle analysis is therefore presented.

The approach adds performance and environmental features (emissions and embodied energy) to analytically evaluate whether or not the most cost effective alternative also corresponds to the best-performing strategy and/or the most eco-friendly. Several environmental certification approaches have been developed during the last decade to certify companies, buildings and products (U.S. Green Building Council 2009; U.S. Department of Energy 2010). New rating systems and tools are also becoming popular for assessing the eco-impact footprint of road pavement projects (Anderson et al. 2011; FHWA 2010). A more comprehensive assessment would allow a more comprehensive evaluation of road design projects, maintenance activities, and the development of environmental management plans. Choosing between different alternatives should not be just a matter of traditional cost evaluation.

The paper focuses on the life cycle assessment of road maintenance and rehabilitation (M&R) works to understand the environmental impact of those activities over the service life of the pavement. In particular, the examples presented illustrate the eco-efficiency of preventive maintenance (PM) treatments on road pavements. PM strategies apply specific maintenance treatments at the proper time, before distresses become evident so that pavements are still able to retain high serviceability levels.

Since millions of dollars and a huge amount of non-renewable resources are used every year for M&R activities, calculation of the emissions produced and the embodied energy used on a certain preservation strategy is highly recommended. It could represent a step forward for selecting the proper strategy while preserving the environment. The optimal strategy should be selected not just considering costs and performance, but also considering the environmental impacts. Similar results in terms of cost and performance may be achieved using more eco-efficient alternatives, which consume less energy and produce less pollution.

The energy involved, from the extraction and manufacturing of raw materials to their placement at the worksite, was computed in the analysis as well as emissions produced in each process, expressed as a quantity of equivalent carbon dioxide (CO_2e) released in the atmosphere. However, energy use and emissions should not represent a stand-alone evaluation of the project but, more appropriately, they should be adopted together with other parameters (costs, quality, etc.) as a relative comparison between different products and strategies. In addition to energy and emissions, the assessment should take the specific pavement structure and amount of traffic into account in order to highlight the role of performance in the whole process.

This paper compares the environmental effectiveness of three different preventive maintenance strategies. In particular, the aim is to compare different maintenance strategies for a constant analysis period by analyzing every choice according to three criteria: costs, performance and eco-efficiency. An innovative procedure to include the three aspects in a single decision support tool was developed and is described. The method is generally applicable to all other PM treatments or road maintenance and rehabilitation activities.

7.2 Life Cycle Analysis of Road Maintenance Activities

This section presents a methodology to include environmental aspects into the pavement management process in order to determine, using a multi-attribute approach, the best way to carry out maintenance activities on pavements. The approach aims to help develop more eco-effective maintenance plans over the life cycle of the pavement without ignoring costs and performance. *Sustainability* on road pavements needs to be properly defined.

Letting the pavement deteriorate until a major reconstruction is needed typically represents an ineffective strategy from cost, performance, and environmental standpoints: cost and emissions will be higher while performance decays. Many articles (Labi and Sinha 2003; FHWA 1996) have already proved that intervening before the asset starts to seriously deteriorate results in a more cost-effective strategy since the potential deterioration is prevented. Furthermore, maintaining the pavement at high levels of serviceability enhances the performance, minimizes user costs (Falls et al. 1994), and provides a safer infrastructure. Environmental impact should be included in the analysis in order to set long term plans that combine the three aspects in a more general life cycle assessment compared to the commonly adopted approach based only on costs. Presently, a small amount of life cycle analysis on pavements develops performance features besides cost and almost nothing has been written about how to combine these three aspects with a multi-attribute approach. However, strong emphasis is placed on defining what a "*sustainable pavement*" would entail and evaluating the eco-efficiency of roads and related features (Flintsch 2010).

The paper illustrates the proposed approach for a whole life cycle assessment of different road maintenance strategies by analyzing three PM treatments. The traffic volume and the pavement structure are assumed to be the same in the three cases. Performance deterioration models were used to identify the time where preventive maintenance activities were needed based on pre-established thresholds. Agency costs and environmental impacts were computed for each intervention and accumulated over a standard analysis period.

The three PM treatments considered were microsurfacing, slurry seal, and thin overlay; two maintenance strategies were set up for each. Consequently, six different maintenance strategies were analyzed comparing them with a standard M&R plan including only major rehabilitations when the pavement faces the minimum condition threshold.

Microsurfacing is a mixture of polymer-modified asphalt emulsion, aggregates, mineral filler, water and other additives, properly proportioned, mixed and spread on a paved surface (ISSA 2010, NCHRP 2010). It is primarily used as a surface sealant to address rutting, loss of friction, and damage from water and UV rays. *Slurry seal* is a mixture of emulsified asphalt, aggregates, water, and additives uniformly spread over the pavement. It is usually adopted to restore pavement texture providing a skid resistant surface while improving waterproofing properties and sealing. *Thin asphalt overlays*, below 1-1.25 inches ($\leq$ 3 cm) of thickness, are usually adopted when a more consistent method of intervention is needed. It can be placed with or without milling the existing asphalt surface layer depending on the presence of segregation, raveling or block cracking, and rutting.

The method described in the following section selects the most effective maintenance strategy, minimizing costs and environmental impacts while maximizing the performance over the analysis period. However, the methodology adopted is general and it can be easily extended to other PM treatments and maintenance strategies.

7.2.1 Cost Analysis

Life cycle cost analysis represents an established procedure in evaluating different projects and strategies, and a great variety of technical literature is available on the topic.

In the present paper, agency costs were evaluated over the life cycle for the specific maintenance plans and treatments accounting for different materials and construction procedures, following a standard price list for road materials and constructions (VDOT 2010). The remaining value of the asset at the end of the analysis period, represented as a negative cost (gain), was also included in the agency costs. It is estimated as the net value of the remaining useful life of a pavement at the end of the analysis period. User costs due to traffic delays occurring during construction and maintenance activities (*work zone road user costs*) or savings due to improved pavement conditions (*in-service road user costs*) were not evaluated since assessing their values and incorporating them into a LCCA still represents a challenging issue that is full of uncertainties (Papagiannakis and Delwar 2001; U.S. Department of Transportation 2002). When computed, user costs are often so large that they substantially exceed agency costs, particularly if high-traffic and congested areas are considered. Most Departments of Transportation have been averse to rely on user cost estimates for various reasons. The main concern is the difficulty in evaluating user delay time. Although several literature sources on the value of traveler time exist, much of this time does not have a traded market value. In the same way, uncertainties exist about the relationship between agency activities and accident rates or vehicle operating costs. In addition, user costs do not charge agency finances as do agency costs. This aspect, in combination with uncertainties related to actual values, may affect transportation decision makers in order to give less credibility to user costs than to their own agency cost figures, limiting the trade-offs between agency and user costs and restraining their capacity to find the lowest total cost solutions over the life cycle.

The analysis period was set to 50 years. The cost schedule was estimated over the analysis period and future costs were therefore discounted to a common base in time. Since money spent at different times have different present values, costs related to the single activities cannot simply be summed. They should be discounted to a common point in time. Several economic methods are available to convert future costs into present values, so that costs of different alternatives can be directly compared over the life cycle. The main methods considered in this paper are the Present Worth of Costs method (PWC) and the Equivalent Uniform Annual Cost method (EUAC). Both of them use a real discount rate to convert future costs into a common baseline. Though similar, both methods were considered in order to provide two different views of the same aspect: PWC offers an evaluation of an equivalent single cost assumed to occur at the beginning of the analysis period while EUAC combines all the costs into an equivalent annual cost over the analysis period.

A discount rate of 4% was used for the calculations (Walls and Smith 1998). The PWC and EUAC were estimated for a sample road unit (a square meter). Outcomes for the different maintenance plans are summarized in Table 7.4.

7.2.2 Performance Analysis

The optimal timing over the life cycle to schedule PM activities and major rehabilitation on road pavements needs to be assessed so a life cycle performance analysis (Crispino et al. 2010) was carried out considering theoretical and empirical pavement deterioration curves over time (Hall et al. 2002). Moreover, different models (Zheng et al. 2010) were adopted to compute and predict the Present Serviceability Index (PSI) over time and the performance improvement, or *performance jump*, due to the application of a certain treatment. Performance jumps allow the evaluation of incremental benefits, just-before and just-after, of the specific treatment application. It provides a practical way to assess the effectiveness of a maintenance treatment in the short term. Performance jumps, for instance, can be assessed: (1) through real scale field measurements, which result in a more accurate estimate but limited to the proper conditions of the site (pavement structure and materials, traffic, weather conditions), or (2) deduced using data and models available in literature for that specific treatment (Zheng et al. 2010).

In the paper, the performance jump due to PM treatments was computed as a function of the before-treatment PSI using experimental formulas available in literature (Labi and Sinha 2003).

While *pre-treatment* curves were developed using the standard American Association of State Highway and Transportation Officials deterioration curve (AASHTO 1993) for all the alternatives provided in the analysis, *post-treatment* curves were extrapolated from previous experiences (Labi and Sinha 2003) and taken as a reference to develop the final deterioration curve over the whole analysis period. Otherwise, when experimental data were not available or not adaptable to the present analysis, the performance jump and after-treatment deterioration curves were obtained from the original untreated curve and life-extension following the procedure hereafter described. The post-treatment curve assumes that the pavement reaches the threshold value at the life extension and is parallel to the untreated curve. For instance, if a certain treatment is applied when the PSI of the pavement is equal to 3.5 (e.g. at year 10) and it provides an average extension of life equal to 4 years compared to the "only-major-rehabilitations" curve, then, the new PSI value immediately after the treatment will be the one belonging to the "only-major-rehabilitations" curve 4 years before (e.g. at year 6). According to that, the "only-major- rehabilitations" curve will just be moved depending on the extension of life provided by the specific PM treatment and therefore, the deterioration rate of the performance curve (the slope of the curve) will remain the same before and after the maintenance activity.

Finally, the "*area under curve*" (AuC) (Zimmermann 1992) was taken as a measure of the performance effectiveness for each alternative. Areas were estimated using the trapezoid method: the area under the performance curve was divided into 50 trapezoids, one for each year of the analysis period. The area of each trapezoid was therefore computed according to a discrete model following the formula:

$$\mathrm{Area(trape\ zoid\_1)} = \frac{(\mathrm{PSI}_{@\mathrm{year0}} + \mathrm{PSI}_{@\mathrm{year1}}) \cdot 1\mathrm{year}}{2} \tag{7.1}$$

That is, extending to all trapezoids:

$$\mathrm{Area\_Under\_Curve} = \sum_{i=0}^{49} \frac{(\mathrm{PSI}_{i} + \mathrm{PSI}_{i+1}) \cdot 1\mathrm{year}}{2} \tag{7.2}$$

The adopted pavement structure had an initial structural number of 6.2 at construction and it was built on a subgrade soil with a resilient modulus of 7,000 psi (almost 48 MPa). The traffic was set equal to 2,500 Equivalent Single Axle Load (ESAL) per day with a growth factor of 2.5 %

per year, constant over the analysis period. The analysis period was set equal to 50 years. The initial PSI value was 4.5 (new construction) and the threshold for major rehabilitations was fixed at 3.0, which is the accepted threshold value for interstate roads. Three PM treatments were studied and two maintenance strategies were assumed for each, depending on the number of times that specific treatment was applied over the pavement life cycle. For instance, considering the microsurfacing, two different maintenance strategies were hypothesized: applying the treatment only at year 6 and applying it twice at years 6 and 13. Deterioration trends, performance jumps and post-treatment curves are summarized in Figure 7.1 and the areas under the curves for the different alternatives and maintenance strategies are provided in Table 7.1.

Preventive maintenance strategies, as expected, result in the pavement having better conditions over the analysis period. Improving pavement performance will reduce in-service user costs (strictly related to the pavement condition) while increasing user satisfaction.

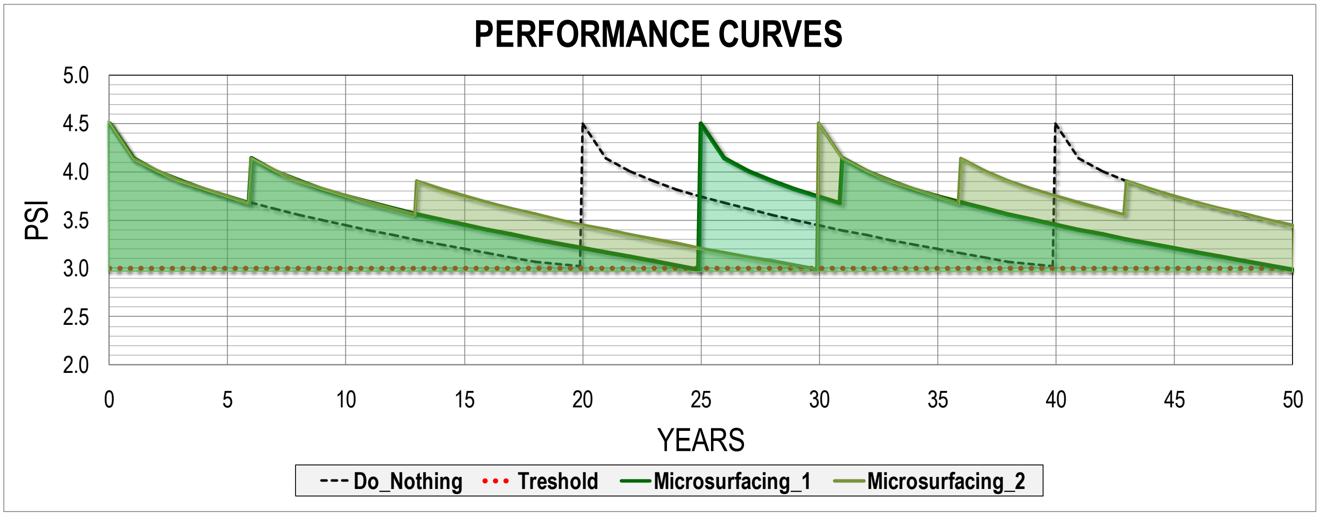


Figure 7.1: Performance curves of microsurfacing-based strategies

Table 7.1: Area Under Curve-AuC

Maintenance strategy	**AuC** ***Area Under Curve***	**Performance increase**
ONLY_MAJOR_REHABILITATION	29.8	
OVERLAY (1)_ *[@year 8]*	37.3	+ 25.1 %
OVERLAY (2) _ *[@years 8 and 16]*	42.5	+ 43.6 %
MICROSURFACING (1) _ *[@year 6]*	33.0	+ 10.7 %
MICROSURFACING (2) _ *[@years 6 and 13]*	40.7	+ 36.6 %
SLURRY (1) _ *[@year 5]*	32.9	+ 10.3 %
SLURRY (2) _ *[@years 5 and 12]*	38.5	+ 29.1 %

7.2.3 Environmental Assessment

Including environmental assessments in the standard cost and performance analysis characterizes the innovative approach proposed by this paper. A life cycle assessment was therefore conducted in order to test whether or not preventive maintenance practices could also be more environmentally friendly than the traditional rehabilitation approach. Carbon emissions and embodied energy were both taken into account to develop an environmental assessment of PM strategies. Emissions coming from materials (from-cradle-to-grave analysis), processes, and construction procedures were converted into carbon equivalent emissions (U.S. Energy Information Administration 1995), to compute a carbon footprint for each alternative. The same guidelines were adopted to assess the total amount of energy involved. Energy is strictly related to the fuel consumption in the various processes, while carbon footprints refer to the specific manner in which a product is obtained and the particular material or machinery used. The investigation was developed taking into account different energy and emission sources coming from the PM alternatives described in the previous paragraph, considering the different materials, equipment, and construction processes used.

7.2.3.1 Embodied energy and emissions due to raw materials

Since the only way to correctly assess energy and emissions belonging to raw materials in road maintenance activities is to exactly know every single quantity of energy involved and emission produced in every single phase of an extremely complex and articulate process (e.g. to compute emissions coming from bitumen, emissions coming from the oil extraction, transport to the plant, refining of crude oil into bitumen, transport and storage in depots, should then be calculated), several authoritative literature sources were analyzed and taken as a reference as shown in Table 7.2. The different literature data available were then averaged in order to compute a final reasonable value for emissions and energy due to the manufacture of raw materials. It should be noted that the main goal of the analysis was to compare different PM strategies against major rehabilitation/reconstruction policies in order to identify the most effective in terms of the three different criteria: cost, performance and environment. Comparing different PM alternatives adopting a life cycle assessment approach can be done without assessing the exact values for a specific material involved. That is because the error made remains the same over the different comparisons and it could be therefore disregarded. The aim of the investigation is to identify the difference between different strategies, not an absolute value. However, a sensitivity analysis or a probabilistic approach is recommended when dealing with emissions and energy related to road materials since quantities involved are usually different among strategies.

Table 7.2 summarizes the outcomes obtained from the literature review. The spread of the data is quite large, as can be inferred from the standard deviation analysis; where no standard deviation is provided it is because just one data source was available. All entries listed in the table consider all the stages and processes to obtain the final product as ready-to-use.

Table 7.2: CO_2e emissions and energy (raw materials)

Material	**Emission – CO_2e** [kg/ton material]	**Standard Dev.**	**Embodied energy** [MJ/ton material]	**Standard Dev.**
Bitumen	256.5	118.2	4603	2226.0
Bitumen emulsion [60%]	221.0	21.9	3490	428.8
Crushed aggregates	7.5	9.9	38.9	2.7
Pit-run aggregates	5.3	2.2	19.4	11.4
Cement	1079.6	311.5	5900	847.1
Quicklime	2500	-	9240	-
Water	0.29	-	10	-
Polymers – elastomers	3000	543.4	91440	36753.5
Polymers – plastomers	1400	424.3	44667.3	51087.7
Emulsifiers	600	52.4	63250	6010.4

7.2.3.2 Embodied energy and emissions due to equipment

Several pieces of equipment currently adopted in road construction sites were analyzed to provide a calculation of emissions and energy spent. Millers, pavers, rollers, slurry machineries, and trucks were investigated for identifying and quantifying emissions and energy embodied in road PM activities and specific treatments.

The total amount of motive-power to carry out a certain maintenance work on a sample road unit (e.g. a square meter) was estimated. The primary source of emissions, in fact, is due to the engine exhaust system, depending on the total amount of fuel consumed in each phase of the pavement maintenance process. However, the true quantity of fuel consumed while applying maintenance treatments on a sample road unit is hard to estimate; indeed, a great variety of stochastic aspects could affect the assessed value: work experience and behavior of the operator, inability to measure the instantaneous fuel consumption, and multiplicity of available engines and brands, etc. The method adopted and the simplifications made in the analysis are explained in the following section.

Different engines related to major companies' machines were analyzed identifying the fuel consumption to carry out a square meter of a specific action (milling, paving, rolling, etc.). A relationship (U.S. Environmental Protection Agency 2009) to convert the calculated fuel consumption into emissions produced and energy spent was therefore applied. Finally, the total amount of equivalent CO_2 and energy consumed were computed for each equipment model.

Technical specifications of the different engine types, obtained directly from equipment manufacturers, provided curves for relating the BSFC (Brake Specific Fuel Consumption) expressed in g/KW·h of fuel, with the engine rotation speed, expressed in revolutions per minute (rpm). Torque and power curves determined the relationship between the nominal power supplied by the engine, expressed in Kilowatts, and its rotation speed. The amount of fuel consumed was calculated using the following formulas. Different amounts of fuel could be computed depending on the engine rotation speed and the nominal power supplied. Thus, it was assumed that the engine was run at the rotation speed that provided the maximum torque while conducting the work. This circumstance is desirable from an environmental standpoint; in fact, the BSFC of an endothermic engine is next to the minimum value at the maximum torque because it is more efficient at that running speed.

$$F\ \left[\frac{l}{h}\right] = BSFC\left[\frac{g}{KW\cdot h}\right]\cdot P[KW]\cdot 1/\gamma\left[\frac{l}{g}\right] \tag{7.3}$$

Where: F = fuel consumed, $BSFC$ = brake specific fuel consumption, P = engine power when the rotation speed provides the maximum torque, and γ = density of the fuel (diesel density = 0.832 kg/l).

The fuel consumption was then divided by the productivity of the equipment, given by manufacturers' technical specifications for specific intervention thicknesses, in order to assess the amount of fuel needed to carry out that specific maintenance activity on a square meter of pavement; the formula is quoted as follows.

$$F_{sqm}\ \left[\frac{l}{m^2}\right] = \frac{F\left[\frac{l}{h}\right]}{prod.\left[\frac{m^2}{h}\right]} \tag{7.4}$$

Where: F_{sqm} = amount of fuel consumed to apply a specific maintenance treatment on a square meter of pavement; *prod.* = productivity of the machine.

Finally, F_{sqm} was multiplied by the specific amount of equivalent CO_2 produced in the combustion of a liter of diesel (U.S. Environmental Protection Agency 2009) in order to find out the total quantity of emissions due to a certain type of equipment for applying a specific maintenance treatment on a square meter of pavement. A similar procedure was adopted to compute energy involved in the process.

$$CO_2\, emissions\ \left[\frac{g}{m^2}\right] = F_{sqm}\left[\frac{l}{m^2}\right]\cdot \alpha\ \left[\frac{g}{l}\right] \tag{7.5}$$

$$Energy\ \left[\frac{MJ}{m^2}\right] = F_{sqm}\left[\frac{l}{m^2}\right]\cdot \beta\ \left[\frac{MJ}{l}\right] \tag{7.6}$$

Where: α = specific amount of CO_2 emitted during the combustion of a liter of diesel ≈ 2650 g/l; β = heating value of a liter of diesel ≈ 36 MJ/l.

Outcomes obtained for equipment analyzed are provided in Table 7.3. The intervention treatment thickness considered in the table was set equal to 10 cm for millers and pavers (i.e.; milling 10 cm of asphalt, placing 10 cm of asphalt). Only a small amount of investigated machinery is reported in the table.

Table 7.3: Emissions and energy due to machinery*

<table>
<tr><th>Models</th><th>Prod. [m^2/h]</th><th colspan="2">P_engine [KW]</th><th>F [l/h]</th><th>F_{sqm} [l/m^2]</th><th>CO_2e [g/m^2]</th><th>Energy [MJ/m^2]</th><th>Company</th></tr>
<tr><td colspan="9">MILLERS</td></tr>
<tr><td>PL2000S</td><td>2448.98</td><td colspan="2">447</td><td>105</td><td>0.043</td><td>113.62</td><td>1.544</td><td>Dynapac</td></tr>
<tr><td>PL2100S</td><td>4320.00</td><td colspan="2">447</td><td>105</td><td>0.024</td><td>64.41</td><td>0.875</td><td>Dynapac</td></tr>
<tr><td>W120F</td><td>1020.41</td><td colspan="2">227</td><td>61</td><td>0.060</td><td>158.42</td><td>2.152</td><td>Wirtgen</td></tr>
<tr><td>W200</td><td>2040.82</td><td colspan="2">380</td><td>62</td><td>0.030</td><td>80.51</td><td>1.094</td><td>Wirtgen</td></tr>
<tr><td colspan="9">PAVERS</td></tr>
<tr><td>AP1000D</td><td>4082</td><td colspan="2">166</td><td>41.0</td><td>0.010</td><td>26.63</td><td>0.362</td><td>Caterpillar</td></tr>
<tr><td>AP600D</td><td>2449</td><td colspan="2">122</td><td>31.3</td><td>0.013</td><td>33.91</td><td>0.461</td><td>Caterpillar</td></tr>
<tr><td>DF145C</td><td>3673</td><td colspan="2">153</td><td>38.2</td><td>0.010</td><td>27.53</td><td>0.374</td><td>Dynapac</td></tr>
<tr><td>F121C</td><td>2449</td><td colspan="2">120</td><td>30.9</td><td>0.013</td><td>33.44</td><td>0.454</td><td>Dynapac</td></tr>
<tr><td>Super1603</td><td>2449</td><td colspan="2">100</td><td>26.5</td><td>0.011</td><td>28.68</td><td>0.390</td><td>Voegele</td></tr>
<tr><td>Super1803</td><td>2857</td><td colspan="2">130</td><td>33.1</td><td>0.012</td><td>30.70</td><td>0.417</td><td>Voegele</td></tr>
<tr><td colspan="2">SLURRY MACHINERIES</td><td>mixer engine [KW]</td><td>truck engine [KW]</td><td colspan="5"></td></tr>
<tr><td>M206</td><td>3600</td><td>74</td><td>186</td><td>41.7</td><td>0.0116</td><td>30.70</td><td>0.417</td><td>Bergkamp</td></tr>
<tr><td>M210</td><td>3600</td><td>74</td><td>224</td><td>42.4</td><td>0.0118</td><td>31.25</td><td>0.424</td><td>Bergkamp</td></tr>
</table>

** Rollers and trucks were also investigated. Nevertheless, they are not reported in Table 3 because emissions and energy also depend on the total amount of passages to compact, the compaction mode adopted (static or dynamic), hauling distance, load, etc.*

7.2.3.3 Embodied energy and emissions due to construction processes

After computing emissions and energy due to materials and equipment, processes involved to convert raw materials into the final PM treatment should then be investigated. Hot mix asphalt production, reclaimed asphalt pavement (RAP) processing, transportation from the plant to the construction site, and final disposal and recycling represent only some of the several processes involved. Different outcomes are also expected depending on the mix design adopted for the asphalt mixtures and the thickness chosen for the application of different PM treatments. Calculations were made for each PM treatment (thin overlay, microsurfacing, and slurry seal) and major reconstruction or rehabilitation.

Thin Overlay. A typical mix design was chosen for the hot mix asphalt to know the percentage of bitumen, aggregate type, and amount of filler used. The intervention thickness was fixed as well, so that the total volume of materials involved could be computed per square meter of treatment. Eventually, a pre-established amount of RAP could be used in the mixture. Emissions and energy due to raw materials were estimated by multiplying values cited in Table 7.2 by the tonnage of resources used. All emissions and energy involved in getting the final hot mix asphalt from raw materials and RAP processing were computed with the same method already mentioned in paragraph 7.2.3.1.

After that procedure, the proper equipment type for carrying out each phase of the work was chosen. In particular, for a 3 cm (1.2 in) overlay, a tack coat sprayer, a paver, and a roller were selected. Energy and emissions were computed for a square meter of finished thin overlay. A hauling distance of 20 km was assumed from the asphalt plant to the construction site. The total amount of all the energy spent and emissions produced were computed by summing the individual contributions of the various processes.

Microsurfacing and Slurry Seal. A similar procedure was used to estimate energy and emissions for applying the microsurfacing and the slurry seal on a square meter of road pavement. Eventually, the mix design could be changed depending on the type of microsurfacing (type II and type III) and slurry seal (type I, II, and III) chosen (ASTM 2010; Caltrans 2004). The same distance was adopted for hauling.

Major Reconstructions or Rehabilitations. Major rehabilitations consisted of milling all the existing asphalt layers and replacing them in order to achieve a pavement structural number consistent with the traffic conditions at the time of rehabilitation. Processes involved are similar to those used for the thin overlay, except for the thickness (and therefore volume of materials), the previous milling of the old asphalt layers, and their disposal. Transportation for waste removal was considered equal to 5 km from the construction site.

The life-cycle costs, performance and eco-efficiency of each strategy are summarized in Table 7.4.

Table 7.4: Costs, performance and Environmental Features due to PM and Do-Nothing strategies

	PM strategies	**Costs**		**Performance**	**Environment**	
		PWC [\$/m^2]	*EUAC [\$/m^2]*	*AuC*	*energy [MJ/m^2]*	*CO$_2$e [g/m^2]*
Microsurfacing	*(1 intervention per cycle) – yr. 6*	87.90	4.09	33.03	808.78	58.45
Microsurfacing	*(2 interventions per cycle) – yrs.6 &13*	88.89	4.14	40.74	896.45	63.07
Thin overlay	*(1 intervention per cycle) - yr. 8*	87.80	4.09	37.31	820.42	61.17
Thin overlay	*(2 interventions per cycle) - yrs.8 & 16*	88.05	4.10	42.85	918.95	68.45
Slurry seal	*(1 intervention per cycle) - yr. 5*	87.10	4.05	32.91	764.35	60.64
Slurry seal	*(2 interventions per cycle) - yrs. 5 &12*	87.44	4.07	38.51	807.95	67.48
	Only_Major_Rehabilitations Or Do-Nothing	**Costs**		**Performance**	**Environment**	
		PWC [\$/m^2]	*EUAC [\$/m^2]*	*AuC*	*energy [MJ]*	*CO$_2$e [g/m^2]*
		107.87	5.02	29.83	1154.84	86.21

7.3 Multi-Attribute Approach For Life Cycle Assessment

Sustainability is increasingly becoming a main theme of long term plans for road pavement management worldwide. New tools to assess carbon footprints and embodied energy of road pavement, material, systems, and construction/maintenance processes are continuously being released (U.S. Environmental Protection Agency 2009; Horvath 2004; TRL Limited 2009). Road agencies at the national and municipal levels are currently providing guidelines to assess the relative sustainability of road projects (Anderson et al. 2011; U.S. Department of Transportation 2010). Unfortunately, environmental features of a road project are still considered as a stand-alone evaluation, an added value. A multi-attribute approach for life cycle assessment is needed to evaluate the implications of incorporating the environment into the decision making process, in addition to costs and performance. Very little has been done to incorporate the environmental impact as a part of the pavement management systems and the decision support tools to choose between different strategies. In this way, being awarded with a “green” certificate (Anderson et al. 2011; FHWA 2010) or a medal through a checklist approach for a specific road project could result in the belief that recognition would correspond to the best possible strategy. Moreover, a single road project awarded with a “green” rating does not mean that the project results “green” on a network level. Indeed, the most environmental friendly strategy may not be the one with the highest performance. That is, using “greener” materials than others or performing recycle-related practices may lead to a lower performance over the life cycle and therefore to an increase in the amount of maintenance treatments needed, which could in turn result into higher total emissions produced and network congestion due to work zones.

On the other hand, it is not easy to combine different quantities (costs, performance, and environmental impacts) with different unit measures to compute an effective comprehensive index that summarizes the three different points of view. An ad-hoc methodology to set a multi-attribute approach system is proposed.

7.3.1 Parameters Rescaling

In order to handle variables having different unit measures, a rescaling was chosen to make their values fall between the range of 0 to 1. This rescaling would allow a direct comparison between quantities for developing indexes that incorporate the three aspects fully explained before. Developing indicators to assess sustainability constitutes the base for creating sustainability rating systems. A standard procedure was adopted for rescaling.

COSTS: Since the "Do-Nothing" alternative is the most expensive, a maximum value of 1 was assigned to it. All the other strategies were scaled using the following direct proportion:

$$x_i = \frac{(PM\_strategy_{i\_cost} \cdot 1)}{Do\_Nothing_{cost}} \tag{7.7}$$

Where: x_i = rescaled value for the *i*-alternative; $PM\_strategy_{i\_cost}$ = cost related to the *i*-PM_strategy; $Do\text{-}Nothing_{cost}$ = cost related to the Do-Nothing strategy.

ENVIRONMENT: Since the Do-Nothing strategy has been proved to be the most polluting one, a maximum value of 1 was assigned to it and the same procedure was adopted for rescaling the values of the others strategies.

PERFORMANCE: In this particular case, because the Do-Nothing alternative had the lowest performance over the life cycle, some adaptations to the above mentioned rescaling procedure were needed in order to assign it the maximum value of 1. Supposing that an ideal pavement keeps performing with the same maximum performance over time (e.g. no-deterioration trend in the performance curve), new areas under curve were calculated as the difference between the hypothetical horizontal deterioration trend and the real ones discussed in paragraph 7.2.2. The Do-Nothing alternative, that presents the lowest performance value, is now the most distant from the hypothetical ideal trend and therefore it shows the maximum gap from the ideal condition.

This value was taken as a reference and equal to 1. All the others PM_strategies were rescaled in the same way already adopted for costs and environmental features.

Table 7.5 summarizes the results for the rescaling.

Table 7.5: Quality indicators rescaled for the various strategies

		Costs		**Performance**	**Environment**	
		PWC	*EUAC*	*AuC*	*Energy*	*Carbon*
Microsurfacing	*(1 intervention per cycle) - 6*	0.815	0.815	0.929	0.700	0.678
Microsurfacing	*(2 interventions per cycle) - 6 & 13*	0.825	0.825	0.758	0.776	0.732
Thin overlay	*(1 intervention per cycle) – 8*	0.815	0.815	0.834	0.710	0.710
Thin overlay	*(2 interventions per cycle) - 8 & 16*	0.817	0.817	0.712	0.796	0.794
Slurry seal	*(1 intervention per cycle) – 5*	0.807	0.807	0.932	0.662	0.703
Slurry seal	*(2 interventions per cycle) - 5 & 12*	0.811	0.811	0.808	0.700	0.783
Do-Nothing		1	1	1	1	1

Handling quantities with the same scale is the first step for creating a multi-approach index and comparing different strategies and alternatives. National agencies and municipalities may give different priority to lowering costs, enhancing performance or choosing more eco-effective strategies. Moreover, authorities can set up their own decision indexes assessing criteria and weights for each variable depending on their short-term needs as well as budget scenarios. In this case, a *"greener plan"* can result in a higher weight for the environmental variable when compared to the cost (or performance) variable. Or, a cost-effective strategy will ascribe the main decision value to the savings over the life cycle that will result in the biggest weight for that variable. For instance:

$$Multi\_Attribute\_Index = w_1 \cdot X + w_2 \cdot Y + w_3 \cdot Z + ... + w_n \cdot N \qquad (7.8)$$

Where: w_i = *i*-weight for that particular variable; $X, Y, Z, ..., N$ = dependent variable.

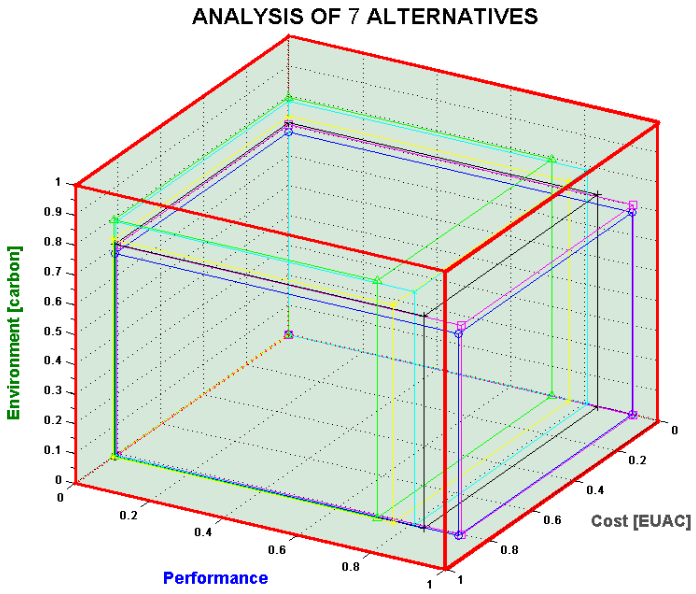
Unfortunately, values for weighting factors are not straightforward to assess. Depending on the actual condition of the pavement with respect to the predicted conditions, they can also change over the analysis period. Therefore, an iterative change of weights can be made to obtain different solutions for achieving particular requirements (e.g., budget limitation, increase in road user perception of comfort, demand for reducing accident rates, etc.). An *a priori* decision process could therefore be turned into an *a posteriori* solution in the analysis period. In addition, including user costs in the analysis will result in establishing weighting factors for user safety, improvement of quality of life as measured by accessibility, and a lot of other variables related to the social impact of road investments that are not so easy to set. The environmental variable should consequently take into account other factors that, again, are not straightforward to assess and weight: pollution from vehicle emissions, traffic noise, and possibly water and ground contamination due to traffic and road works.

The interaction between so many factors makes multi-attribute utility theories essential for the decision making process but extremely complex to develop: the contrast between economic criteria, environmental features, and engineering standard is still an open and on-going research (COST 2008).

7.3.2 Parameters Representation

After rescaling, comparable quantities were then obtained and a three-dimensional representation can be done, identifying the x-axis with the life-cycle costs (PWC or EUAC values), the y-axis with the performance, and the z-axis with environmental features (carbon footprints or embodied energy). According to this schematization, the point denoting the Do_Nothing strategy is expressed through its coordinates (1, 1, 1) on the particular three-dimensional space created. Considering that point as a vertex and projecting it on the three axes, a cube with a volume equal to one could be drawn. The same procedure was done automatically for all the PM alternatives creating a script in Matlab® that showed the cubes related to the different alternatives and the associated volumes. In this way, the cube with the lowest volume represents the strategy with the highest "*score*" over the analysis period (e.g. the winning strategy) considering costs, performance, and environmental impacts. In particular, outcomes showed how applying microsurfacing twice over each life cycle leads to the maximization of performance while minimizing costs and environmental impacts. It should be noted that the same weight was adopted for the three parameters.

Different weights, and therefore different importance, could be assigned to each parameter depending on policy maker preferences. In addition, boundary conditions of what is considered an acceptable value for the three parameters could be established (e.g. a PM strategy could be considered suitable if its carbon footprint over the life cycle is lower than 65 g of CO_2 emitted per square meter or otherwise discarded), automatically rejecting the alternatives that do not lie within that specific range.



		Volume (EUAC * AuC * Carbon)
Microsurfacing	*(1 intervention every cycle) - 6*	0,513
Microsurfacing	*(2 intervention every cycle) - 6 e 13*	0,458
Thin overlay	*(1 intervention every cycle) - 8*	0,482
Thin overlay	*(2 intervention every cycle) - 8 e 16*	0,462
Slurry seal	*(1 intervention every cycle) - 5*	0,529
Slurry seal	*(2 intervention every cycle) - 5 e 12*	0,513
Do_Nothing		1

Figure 7.2: Multi-attribute analysis, an example

7.4 Conclusions

The paper assesses the functionality of adopting a preventive maintenance strategy taking into account costs, performance, and environmental features. For the case study considered, pavement preventive maintenance strategies were shown to be more eco-effective, well-performing and cost effective over the life cycle than major rehabilitations. A large amount of emissions and energy could be saved by adopting preventive maintenance plans on road pavements.

Although the proposed methodology is considered a step forward when compared to current practice, the analysis may be improved by adding other variables and analysis processes. For instance, a sensitivity analysis to the traffic over the analysis period can be carried out in order to determine whether or not, for high levels of traffic, PM treatments are still effective or if the eco-advantage provided is thwarted in this way. Furthermore, other PM strategies could be created by combining various types of PM interventions and different pavement structures could then be analyzed as well.

The methodology provided is useful to compare strategies and alternatives considering multiple decision variables. The proposed approach provides road authorities and municipalities with a more general and comprehensive comparison without taking away the possibility of customizing their policies by changing the relative weights assigned to the different parameters considered.

7.5 References

Alcom A. (2003). Embodied Energy and CO2 coefficients for NZ Building Materials. Center for Building Performance Research, Virginia University of Wellington, New Zealand.

American Association of State Highway and Transportation Officials - AASHTO (1993). AASHTO guide for design of pavement structures, Washington D.C. ISBN: 1560510552.

Anderson J., Weiland C., Muench S. (2011). Greenroads™ Manual v. 1.5. University of Washington. http://www.greenroads.us.

Asphalt Institute and Eurobitume (2008). Bitumen Industry – A Global Perspective, Information Series No.230, IS-230, ISBN 978-1-934154-54-0.

Association of Plastic Manufacturers in Europe - APME (2004). http://www.plasticseurope.org/plastics-sustainability/eco-profiles/browse-by-family.aspx

American Standard Testing Method (2010). ASTM D6372-05 Standard Practice for Design, Testing, and Construction of Micro-Surfacing. DOI: 10.1520/D6372-05R10

ATHENA™ Sustainable Material Institute (1999). Life Cycle embodied energy and global warming emissions for concrete and asphalt roadways - Summary report. Canadian Portland Cement Association.

ATHENA™ Institute (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Cement Association of Canada.

CALTRANS, Fugro (2004). Slurry Seal / Micro-Surface Mix Design Procedure, Phase I Report - Contract 65A0151 for California Department of Transportation (Caltrans), Materials/Infrastructure Section.

COST Action 354, Litzka et al. (2008). Performance Indicators for Road Pavements – Final Report. European cooperation in the field of scientific and technical research.

Crispino M., Giustozzi F., Baracco G. (2010). Evaluation of effectiveness of a preventive maintenance technology through a life cycle cost and performance analysis on road pavements. Life-Cycle of Civil Engineering Systems. Taipei, 27-31/10/2010, ISBN/ISSN: 9789860249866.

Falls L. C., Khalil S., Hudson W. R., Haas R. (1994). Long-Term Cost-Benefit Analysis of Pavement Management System Implementation. Transportation Research Board. Volume 2, pp 133-138, ISSN: 1073-1652.

Flintsch G. (2010). International Sustainable Pavements Workshop, Airie, VA (USA). Research Agenda for Sustainable Pavement. http://www.vtti.vt.edu/ISPW/ISPW-2010.html

Häkkinen T., Mäkelä K. (1996). Environmental impact of concrete and asphalt pavements, Technical Research Centre of Finland, VTT Tiedotteita, Meddelanden, Research Notes 1752.

Hall K., Correa C., Simpson A. (2002). LTPP Data Analysis: Effectiveness of Maintenance and Rehabilitation Options, National Cooperative Highway Research Program. NCHRP Project 20-50(03/04).

Hammond G., Jones C. (2008). Inventory of Carbon & Energy (ICE). ICE V1.6a©, Energy Research Team (SERT), University of Bath, UK.

Horvath A. (2004). Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), Department of Civil and Environmental Engineering, University of California, Berkeley.

International Slurry Surfacing Association (2010). Recommended Performance Guideline For Micro Surfacing. Project A143, revised February 2010. http://www.slurry.org/downloads/A143.pdf

Labi S., Sinha K. (2003). Measures of Short-Term Effectiveness of Highway Pavement Maintenance. J TRANSP ENG-ASCE. Volume 129, Issue 6, pp 673-683.

Labi S., Sinha K. (2003). The effectiveness of maintenance and its impact on capital expenditures. Indiana Department of Transportation and Federal Highway Administration. Report No. FHWA/IN/JTRP-2002/27.

Marceau M., Nisbet M., VanGeem M. (2007). Life Cycle Inventory of Portland Cement Concrete, PCA R&D Serial No. 3011. Portland Cement Association, Skokie, Illinois, PCA, 121 pages.

National Cooperative Highway Research Program (2010). Microsurfacing: a synthesis of highway practice. D. Gransberg. NCHRP Synthesis 411, Project 20-05, Topic 41-12, ISSN 0547-5570, ISBN 978-0-309-14319-6.

Norton A. (2007). Ecoinvent, Materials: their manufacture, use & environmental impact. Greenspec®.

Papagiannakis A., Delwar M. (2001). Incorporating User Costs into Pavement Management Decisions. 5th International Conference on Managing Pavements, Seattle, Washington 2001.

Stripple H. (2001). Life Cycle Assessment of Road: a Pilot Study for Inventory Analysis. IVL Report B1210E, Swedish Environmental Research Institute, Gothenburg, Sweden.

TRL Limited (2009). Asphalt Pavement Embodied Carbon Tool - asPECT, Version 2.0.

U.S. Department of Transportation. Federal Highway Administration (1996). Preventive Maintenance Effectiveness: Preventive Maintenance Treatments. Report No. FHWA-SA-96-027.

U.S. Department of Transportation. Federal Highway Administration (2010). Sustainable Highways Self-Evaluation Tool. http://www.sustainablehighways.org

U.S. Environmental Protection Agency (2009). Office Carbon Footprint Tool - version 1.2. http://www.epa.gov/wastes/partnerships/wastewise/carboncalc.htm

U.S. Department of Energy and U.S. Environmental Protection Agency (2010). ENERGY STAR® and Other Climate Protection Partnerships, 2009 Annual Report. http://www.energystar.gov/ia/partners/publications/pubdocs/2009%20CPPD%20Annual%20Report.pdf

U.S. Department of Transportation (2002). Life Cycle Cost Analysis Primer. Federal Highway Administration Office of Asset Management, FHWA IF-02-047

U.S. Energy Information Administration (1995). Global Warming Potentials. Climate Change 1995, The Science of Climate Change: Summary for Policymakers and Technical Summary of the Working Group I Report, page 22.

U.S. Green Building Council (2009). Leed 2009 for new construction and major renovations. http://www.usgbc.org

Virginia Department of Transportation (2010). Statewide Average Costs from August 2008 to July 2010. www.virginiadot.org/business/resources/const/StatewideAverage.pdf

Zheng W., Groeger J., Simpson A., Hicks G. (2010). Performance Evaluation of Various Rehabilitation and Preservation Treatments. U.S. Department of Transportation, Federal Highway Administration Report. http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=666

Zimmermann K. (1992). Pavement management methodologies to select projects and recommend preservation treatments. National Cooperative Highway Research Program, NCHRP Synthesis 222, Project 20-5 FY. ISSN: 0547-5570.

Walls, J. and M. R. Smith (1998). Life-cycle cost analysis in pavement design-Interim technical bulletin. Report No. FHWA-SA-98-079. FHWA, Washington, DC. Page 6.

Waste Resources Action Program - WRAP (2010). The CO2 emissions estimator tool for the use of aggregates in construction - User Guide v2.0. Project code: MRF-136.

Chapter 8. Multi-Approach Life Cycle Assessment Optimization to Incorporate Environmental Impacts into PMS

F. Giustozzi[1], G. Flintsch[2], M. Crispino[3]

ABSTRACT: Asset management is increasingly focusing on sustainable practices for constructing and maintaining roadway systems; sustainability is therefore becoming a significant part of strategic asset management worldwide. Road agencies at the national and municipal levels are developing guidelines to assess the relative sustainability of road projects. Unfortunately, environmental features are still considered separate from the main factors: costs and performance. A multi-attribute approach including life cycle impacts assessment is needed to evaluate the implications of incorporating the environment into the decision making process, in addition to costs and performance.

To seek more sustainable decision, the three factors, cost, performance, and environmental impacts, should be considered together in the pavement management process. However, it is not easy to combine different quantities (costs, performance, and environmental impacts) with different measurement units to compute an effective comprehensive index that summarizes the three different points of view. The paper proposes an optimization procedure for including environmental impacts into a Pavement Management System. A methodology to set a multi-attribute approach system, computing costs, performance, and eco-efficiency, is proposed. The method can be useful for road authorities and municipalities for enhancing their decision support systems and choose between several asset management alternatives.

---

[1] Dual PhD candidate, Civil and Environmental Engineering, Politecnico di Milano, Milan, 20133, Italy, and Virginia Tech, Blacksburg, VA 24061. Email: filippo@vt.edu

[2] Director, Center for Sustainable Transportation Infrastructure, Virginia Tech Transportation Institute and Professor, The Charles Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061. Email: flintsch@vt.edu

[3] Director, DIIAR – Transportation Infrastructure section, Politecnico di Milano, and Professor, Civil Engineering, Politecnico di Milano, Milan, 20133, Italy. Email:maurizio.crispino@polimi.it

8.1 Introduction

The optimization of available, and generally very limited, resources to preserve high system performance is currently one of the most significant problems affecting the management of road infrastructure networks. Providing road pavements at a high level of performance entails an effective maintenance and rehabilitation (M&R) plan over the service life. Despite the common belief to the contrary, maintenance, if conducted pro-actively at the proper time and adopting the right treatments, can significantly decrease the overall costs while preserving the asset at high levels of performance over the long-term. One of the most common approach to achieve these goals is preventive maintenance (PM): act now pro-actively for extending the pavement service life, later minimizing overall maintenance costs. PM consists of applying specific treatments on pavements when performance are still high to slow down the deterioration and lower the need for routine maintenance and major rehabilitations over the service life.

Beside performance and cost considerations several environmental certification approaches have been developed during the last decade for companies, buildings, and products (Energy star©, 2011; US Green Building Council, 2009). Various rating systems and tools are also becoming popular for assessing the eco-impact of road pavement projects (Anderson et al., 2011; FHWA, 2010).

Since a considerable amount of non-renewable resources (i.e.; virgin aggregates, bitumen, etc.) are used daily for constructing and maintaining pavement assets, a calculation of emissions produced and a comparison between design/maintenance strategies is thus significant. Emissions analysis represents a step forward for selecting the right design and maintenance alternative to be applied while preserving the environment. Similar results in terms of cost and performance might be achieved using more eco-efficient alternatives, consuming a lower amount of energy and producing less greenhouse gasses.

Multi-attribute decision processes therefore represent a major requirement. A more comprehensive assessment including the environmental perspective, in addition to costs and performance, would allow a broader evaluation of road projects and maintenance strategies. Choosing among different construction and maintenance alternatives over the service life of a pavement should not be just a matter of traditional costs evaluation.

8.2 Multi-Attribute Evaluation of M&R Alternatives

An ideal pavement management system (PMS) for a road network should preserve all pavement sections at a high level of service, with adequate structural conditions, and requiring a reasonable low budget. In addition, environmental impacts due to material consumption (especially non-renewable resources such as virgin aggregates or bitumen), construction equipment, hauling (to/from and within the construction site), use-phase (users delays, rolling resistance and related fuel consumption, etc.), and final disposal or recycling, should be minimized. Therefore, the optimal maintenance and rehabilitation strategy to be implemented into a PMS would be the one that maximize performance over time, minimizing costs (both agency and user costs), and lowering the impacts on the environment over the life cycle of the pavement.

Unfortunately, many of these goals are usually in conflict; e.g., more frequent maintenance interventions will provide higher traffic delays and congestion for users, increasing their costs for instance. Often rehabilitations will result in higher material consumption, use of equipment, and traffic disruptions, therefore providing higher environmental impacts. Several studies (Cuelho and Freeman, 2004; Geoffroy, 1996; Labi and Sinha, 2003; Labi and Sinha, 2005; Hass et al., 1994) have identified preventive maintenance approaches, for instance, as significant contributors for saving money while enhancing the performance of the pavement over the service life. Giustozzi et al. (2012b) showed that this practice typically also show significant environmental benefits.

Decision processes in programming of pavement maintenance alternatives should involve multi-objective considerations in order to address conflicting goals. However, the current practice in pavement management is based on single-objective optimization, usually considering costs the only criterion for choosing among alternatives. Other parameters involved into the decision process are imposed as constraints in the analysis (i.e.; minimum level of service required, maximum amount of resources to be used, etc.). Outcomes obtained by subjectively setting limits and boundaries are therefore sub-optimal if compared to the results obtained using multi-objective optimization methods (Fwa et al. 2000). The luck of use of multi-objective approaches in road pavements, such as the one presented in the next section, is mainly due to the perceived the higher level of complexity in the formulation.

8.2.1 Costs, performance, and environmental impacts of maintenance strategies

8.2.1.1 Life cycle cost analysis

Life cycle cost analysis (LCCA) represents a well-known procedure in evaluating different projects and strategies, and a great variety of technical literature is available on the topic.

In the present paper, agency costs were evaluated over the life cycle for several M&R plans and maintenance treatments. The remaining value of the asset at the end of the analysis period, represented as a negative cost (gain), was also included in the evaluation. User costs due to traffic delays occurring during construction and maintenance activities (work zone road user costs) or savings due to improved pavement conditions (in-service road user costs) were not evaluated since assessing their values and incorporating them into a LCCA still represents a challenging issue and involves a lot of uncertainties (Papagiannakis and Delwar 2001; U.S. DOT 2002).

8.2.1.2 Life cycle performance

The timing of cash flows was estimated over the analysis period and future costs were then discounted to a common time base. Since money spent at different times have different present values, costs related to the single activities cannot simply be summed. They should be discounted to a common point in time. Several economic methods are available for converting future costs into present values; costs of different alternatives can thus be directly compared over the life cycle. The main method considered in this paper is the Equivalent Uniform Annual Cost method (EUAC) that combines all the costs into an equivalent annual cost over the analysis period.

A discount rate of 4% was used for all the calculations (Walls and Smith 1998) over an analysis period of 50 years.

Pavement performance was assessed considering the effectiveness of M&R treatments according to deterioration trends obtained from an experimental long-term analysis of pavement sections (Giustozzi et al. 2012b). The Composite Condition Index (CCI) was adopted as a measure of pavement performance during the analysis period. Finally, the area-under-curve (AuC) (Zimmermann 1992) was taken as a measure of the performance effectiveness for each alternative. The higher the area under the performance curve over the life cycle the greater the benefits of that particular M&R strategy. Generally, improving pavement performance will reduce in-service user costs (strictly related to the pavement condition) while increasing user satisfaction. Several mathematical methods are available in literature to compute AuC; in the present paper areas were estimated using the trapezoid method (Abaza 2004).

More than six hundred M&R strategies were generated for a constant level of traffic (i.e.; 2000 ESAL/day) varying the number of treatment applications per life cycle (1, 2, or 3 applications per life cycle), the type of treatment applied (microsurfacing, slurry seal, and ultra-thin asphalt overlay), and the timing of maintenance application (year of applications). Related costs were accordingly generated for each strategy. Non-feasible strategies (i.e.; strategies with resulting performance below the minimum acceptable threshold) were disregarded from the analysis.

8.2.1.3 Life cycle environmental assessment

Including environmental impacts in the standard cost and performance analysis characterized the innovative approach proposed by this paper. A life cycle assessment was conducted in order to test the eco-efficiency of the several maintenance strategies generated. Environmental impacts are usually measured through the computation of the greenhouse-gasses (GHG) emitted in the atmosphere during the whole process, known as the carbon footprint (Wintergreen, 2004;Wiedmann, 2007). The lower the amount of emissions produced, the more sustainable the material or process. Emissions from the manufacture of raw materials, transportation of materials, equipment utilized during the construction stage, maintenance practices, and rehabilitation/reconstruction procedures, were then converted into carbon equivalent emissions to compute their carbon footprints. The methodology adopted for estimating environmental impacts of maintenance and rehabilitation strategies can be found in Giustozzi et al. (2012).

8.2.1.4 Rescaling and Normalization

EUACs, AuC, and environmental impacts were consequently assessed for each strategy. Those strategies were then represented as a cloud of points into a cost-performance-environment 3D-space (Figure 8.1). Each point represented a specific M&R strategy. The methodology described in the following sections has been implemented writing a Matlab© code provided in Appendix A.

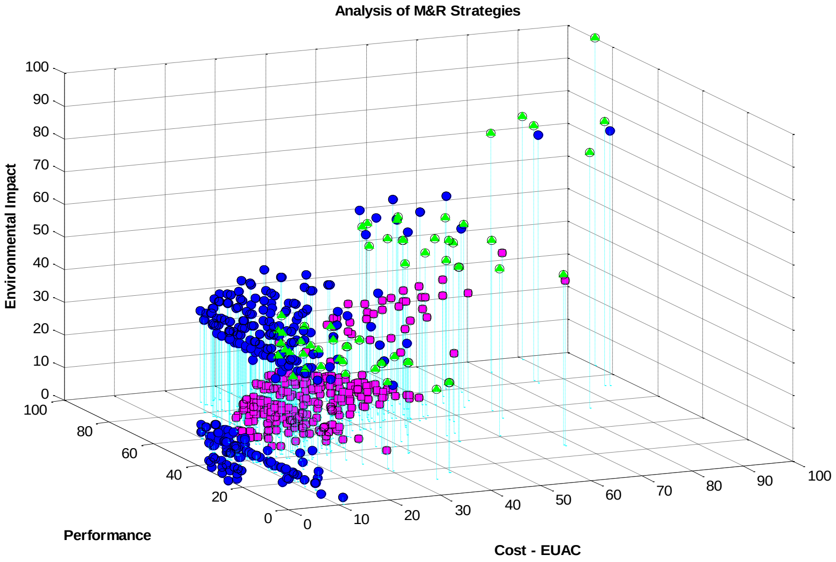


Figure 8.1: M&R strategies - costs, performance, and environmental impacts over the life cycle

In order to easily handle parameters having different unit measures a rescaling procedure was adopted to make their values fall in the range of 0 to 100. The following transformation rule was adopted:

$$Xn = \left(\frac{X - Xmin}{Xmax - Xmin}\right) \cdot 100 \qquad (8.1)$$

where: X_n = normalized parameter value; X = actual value of the parameter; X_{max}, X_{min} = the maximum and the minimum parameter value, respectively.

For the particular problem analyzed: C_{min} = 3168 [\$/(lane*km)]; C_{max} = 17294 [\$/(lane*km)]; P_{min} = 3970 [CCI*year]; P_{max} = 4329 [CCI*year]; E_{min} = 139583 [kg of CO_2e/(lane*km)]; E_{max} = 526040 [kg of CO_2e/(lane*km)]. C, P, and E represent equivalent uniform annual costs, Area-under-Curve (performance), and environmental impacts (carbon footprint) of M&R strategies over the life-cycle.

Although not strictly necessary for developing the multi-attribute approach proposed in the paper, points were also interpolated using Delaunay triangulation (Delaunay 1934). The resulting surface is presented in Figure 8.2.

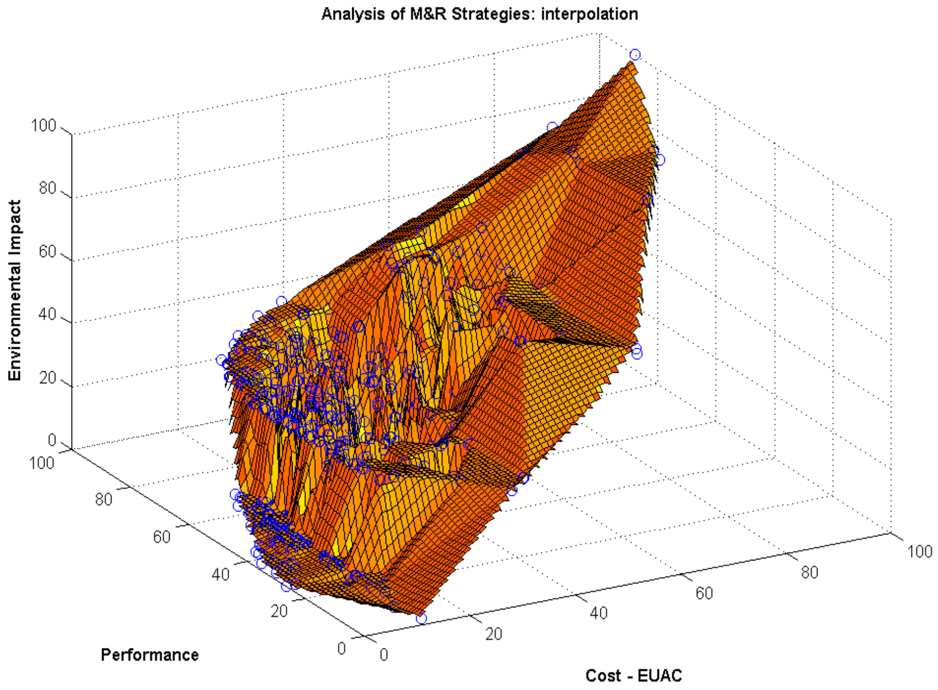


Figure 8.2: M&R strategies – an interpolation

The resulting surface allowed making some practical observations:

1. It can be inferred that if the three parameters have the same importance in the decision making process (i.e.; the same weight), increasing costs is not always correlated with an increase of performance; generally, spending more money does not mean having a better pavement. This aspect seemed to confirm the principles behind a preventive maintenance approach identifying it as cost-effective and finally resulting in a higher performance.
2. Applying maintenance when the pavement still retains good condition can save money while enhancing the pavement performance.
3. Performance and environmental impacts do not seem to be strictly correlated; various strategies having different performance can produce the same impact on the environment depending on the type of maintenance treatment adopted and the timing of application.
4. Costs and environmental impacts seemed to be related since spending more money generally ended up having higher environmental impacts. Indeed, one of the variable that highly affects costs of strategies, making them rapidly increase, is the amount of major rehabilitations over the analysis period. Major rehabilitations are more expensive than

preventive maintenance treatments, are also more polluting since a greater quantity of non-renewable material and equipment is usually involved during operations. However, adding the usage-phase and therefore evaluating environmental impacts related to users fuel consumption while driving on roadways having different conditions may modify the outcomes of the analysis

8.2.1.5 Parameters weighting

National road agencies and municipalities may give different priorities to reducing the costs, enhancing performance, or choosing more eco-effective strategies. Additionally, road authorities should be able to set up their own decision processes assessing criteria and weights for each parameter depending on their needs (i.e.; budget scenarios, political agreements on pollution, fulfillment of public expectations, etc.). For instance, a "green" policy can result in a higher weight for the environmental parameter when compared to the cost (or performance) parameter. Or, a cost-effective strategy will ascribe the main decision value to the savings over the life cycle that will therefore result in the biggest weight for that variable. Therefore, the three parameters may also be weighted generating a set feasible weighted solutions (points) in the 3D-space as illustrated in Figure 8.3.

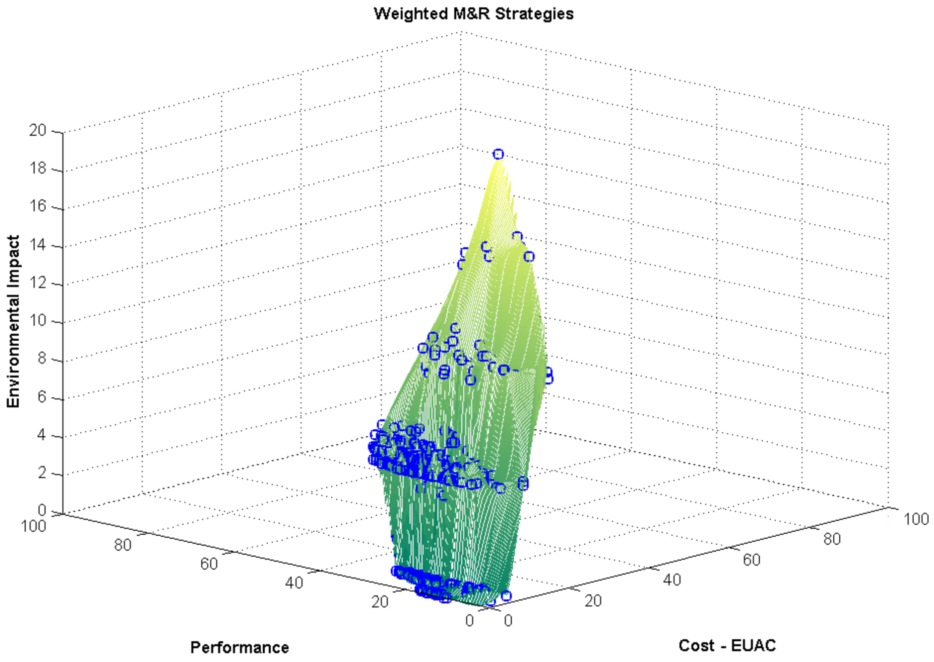


Figure 8.3: M&R strategies – application of weighting factors (C=40%, P=40%, E=20%)

Unfortunately, values for the weighting factors are not simple to define. Depending on the actual conditions of the pavement with respect to the predicted conditions, for instance, the weights can also change over the analysis period. In addition, adding user costs to the analysis will result in establishing weighting factors for user safety, quality of life, accessibility, and other variables related to the social impact of road investments. Moreover, the environmental parameter should consequently account for pollution from vehicle emissions, noise generated by traffic, water and ground contamination due to traffic and road works, etc. All those variables are not straightforward to assess and weight. A sensitivity analysis was therefore conducted for identifying the optimum M&R strategy varying weights for the three parameters involved: costs, performance, and environmental impacts.

8.2.1.6 Selection of the optimal M&R strategy

The optimization of M&R strategies requires that costs and environmental impacts are minimized while performance is maximized. Therefore, the point within the cloud (Figure 8.2) that represents the optimal strategy in the particular 3D-space is O = [C, P, E] = [0, 100, 0]. Obviously, after the weighting procedure is conducted the theoretical optimal strategy will be represented by the point O = [C, P, E] = [0, 100*w_p, 0], where w_p is the weight established by the analyst for the performance.

However, since the theoretical best solution results to be unfeasible (no strategy can have a cost equal to zero, for instance) the selection procedure for the optimal strategy is to identify the solution having the smallest weighted distance from the point O. The following formula can be adopted:

$$d = \sqrt{(C_i - (0 * w_c))^2 + (P_i - (100 * w_p))^2 + (E_i - (0 * w_e))^2} \tag{8.2}$$

Where: d = Euclidean distance to be minimized; C_i = cost of the i-strategy; P_i = performance of the i-strategy; E_i = environmental impact of the i-strategy. The variable "d" can therefore be represented by a array having dimensions 633x1.

The optimal strategy has the minimum distance from the optimal point O. However, since a multitude of other variables are involved in the decision-making process, it would be reasonable to identify a range of "sub-optimal" strategies, closed to the optimum, instead of dealing with a single optimal solution. Although they do not mathematically represent the optimum, can still be considered reasonable according to other perspectives (i.e.; political reasons, easiness of implementation, previous availability of materials, workmen's skills, etc.).

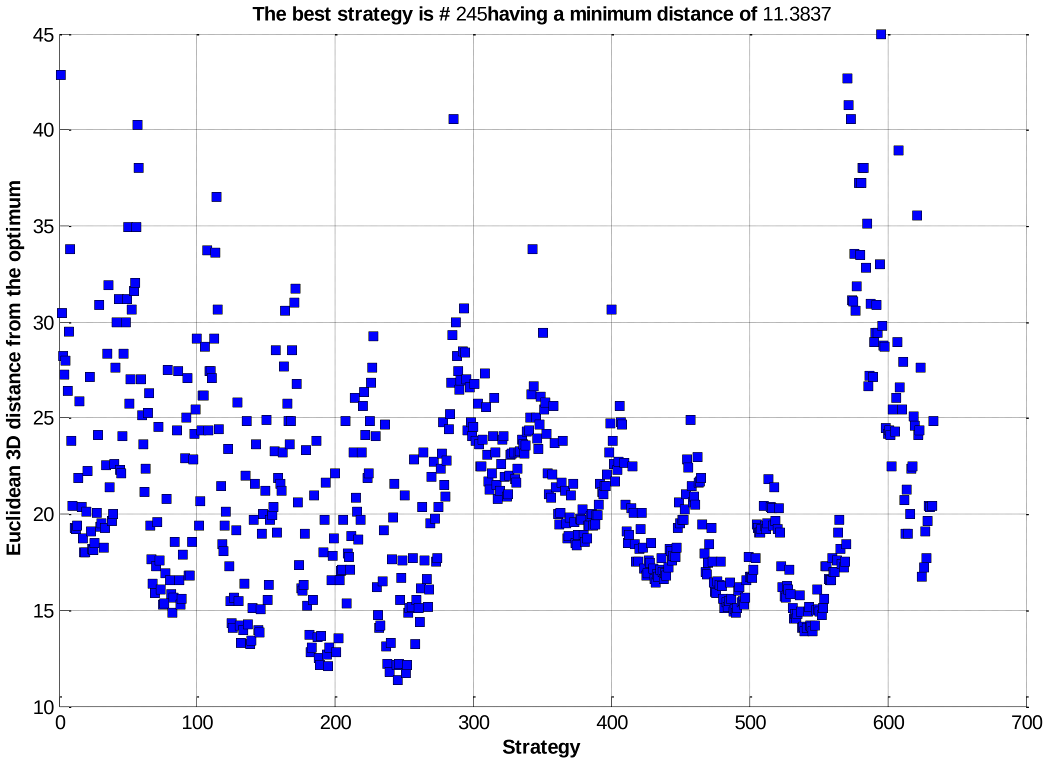


Figure 8.4: M&R strategies – distance from the optimum

8.2.2 Sensitivity Analysis

Since road authorities and municipalities have to consider different objectives depending on several factors, such as actual pavement conditions, budget availability, or short and long-term goals, decision-makers might want to emphasize specific goals by setting their own weights. This section shows the results of several iterative runs of the program, which provide a general idea on the influence of weights in the assessment of the optimal M&R strategy. Table 8.1 reports the results from several analysis varying the weighting factor for the cost (Wc), performance (Wp), and environmental impacts (We). Obviously, the sum of the three weighting factors must be equal to 1.

Table 8.1: sensitivity analysis to weighting factors

Run #	***Wc, Wp, We***	***Minimum distance from theoretical optimum***	***Optimal strategy #***	***Treatment type***	***Timing of treatment applications [year]***
1	0.99, 0.005, 0.005	0.37	285	Microsurfacing	7, 16, 25
2	0.005, 0.99, 0.005	0.26	408	Ultra-thin overlay	5, 9, 14
3	0.005, 0.005, 0.99	0.27	270*	Microsurfacing	7, 14, 22
4	0.8, 0.15, 0.05	8.95	271	Microsurfacing	7, 14, 23
5	0.6, 0.2, 0.2	9.78	268	Microsurfacing	7, 14, 20
6	0.4, 0.4, 0.2	11.38	245	Microsurfacing	7, 11, 15
7	0.2, 0.6, 0.2	8.85	524	Ultra-thin overlay	7, 11, 17
8	0.2, 0.4, 0.4	9.11	537	Ultra-thin overlay	7, 13, 18
9	0.2, 0.2, 0.6	7.29	261*	Microsurfacing	7, 13, 19
10	0.33, 0.33, 0.34	11.51	540	Ultra-thin overlay	7, 13, 21

** the optimal strategy, in this case, was very close to other sub-optimal strategies*

Table 8.1 shows how changing weighting factors can lead to different optimal strategies. In particular, several observations can be drawn:

- Optimal strategies always entail three maintenance treatments per life cycle even if weighting factors are modified. A 3-treatment approach, in fact, is able to postpone major rehabilitations to future times resulting in more cost-performance-environmental efficient M&R strategies. Indeed, as already pointed out in previous sections, major rehabilitations account for higher costs and massive consumption of materials.
- If cost is the major parameter to consider (i.e.; run #1) then application of microsurfacing is recommended; if performance is the main variable to take into account (i.e.; run #2) then application of ultra-thin overlay is preferred; if an eco-efficient strategy is favored (i.e.; run #3) then microsurfacing results again the optimal treatment to be applied although with a very small difference with the ultra-thin overlay strategies is observed.
- Usually, whenever performance is preponderant in the decision-making process and budget limitations do not represent a main constraint, ultra-thin overlays are preferred. On the other hand, if budget is more important then microsurfacing strategies should be applied. On the environmental side, both microsurfacing and ultra-thin overlay strategies show high values of eco-efficiency.

- Slurry seal does not represent a convenient strategy for the type of road analyzed even if the weights change. The main reason is that slurry seals have poorer performance compared to the other treatments (microsurfacing, ultra-thin overlay) and major rehabilitations occur more often during the analysis period. These additional rehabilitations imply more costs and more environmental impacts.

8.3 Conclusions

The paper proposes a methodology for evaluating maintenance strategies taking into account costs, performance, and environmental features and user preference in terms of ranking of these factors. Incorporating environmental impacts into pavement management systems represents a step forward for providing more sustainable road pavements. The application of the methodology for comparing three pavement preservation strategies, slurry seal, microsurfacing, and ultra-thin overlays, illustrated the practicality of the process and allowed to assess the impact of varying the importance given to each of the three criteria. The proposed approach might provide road authorities and municipalities with a more general and comprehensive comparison between M&R alternatives without that can be customized to their policies by changing the relative weights assigned to the different parameters considered.

Although the methodology provided is useful to compare strategies and alternatives considering multiple decision variables, it can be improved by adding other variables and analysis processes. More maintenance treatments, different levels of traffic and their consequent changes in deterioration curves, different discount rates, evaluation of the usage phase environmental impacts over the life cycle, would allow to comprehensively identifying the optimal solution.

8.4 References

Abaza K. A. (2004). *Deterministic Performance Prediction Model for Rehabilitation and Management of Flexible Pavement*, International Journal of Pavement Engineering, 5:2, 111-121.

Anderson J., Weiland C., Muench S. (2011). *Greenroads*™ Manual v. 1.5. University of Washington. http://www.greenroads.us.

Cuelho E., Freeman R.B. (2004). *Cost-effectiveness of crack sealing materials and techniques for asphalt pavements.* Montana Department of Transportation, Research Section, USA

Delaunay B. (1934). *Sur la sphère vide,* Izvestia Akademii Nauk SSSR, Otdelenie Matematicheskikh i Estestvennykh Nauk, 7:793–800.

Energy star© (2011). National Association of State Energy Officials. 1414 Prince Street, Suite 200, Alexandria, VA 22314. www.naseo.org

Fwa T., Chan W., and Hoque K. (2000). *Multi-objective optimization for pavement maintenance programming*. Journal of Transportation Engineering

Geoffroy, D.N, (1996). *NCHRP Synthesis of Highway Practice 223: Cost-Effective Preventive Pavement Maintenance*. Transportation Research Board, National Research Council, Washington D.C.

Giustozzi F, Crispino M, Flintsch G., 2012. *Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability*. The International Journal of Life Cycle Assessment:1-11. DOI:10.1007/s11367-011-0375-6

Giustozzi F., Crispino M., Flintsch G. (2012b). *Effectiveness of Preventive Maintenance Treatments on Road Pavements*. Submitted to Mairepav7 conference, New Zealand, August 2012.

Haas R, Hudson WR, Zaniewski JP. (1994). *Modern pavement management*. Krieger Publishing Company. ISBN: 0894645889

Labi, S. and Sinha K.C. (2003). *The effectiveness of maintenance and its impact on capital expenditures*. Publication FHWA/IN/JTRP-2002/27. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2003. DOI: 10.5703/1288284313331

Labi, S. and K.C. Sinha (2005). *Life-cycle evaluation of flexible pavement preventive maintenance*. Journal of Transportation Engineering. 131: p. 744.

Papagiannakis A., Delwar M. (2001). *Incorporating User Costs into Pavement Management Decisions*. 5th International Conference on Managing Pavements, Seattle, Washington 2001.

Smith, M. and J. Walls (1998). *Life-Cycle Cost Analysis in Pavement Design*. Report No. FHWA-SA-98-079. FHWA, Washington, DC.

U.S. Department of Transportation (2002). *Life Cycle Cost Analysis Primer*. Federal Highway Administration Office of Asset Management, FHWA IF-02-047.

U.S. Department of Transportation. Federal Highway Administration (2010). *Sustainable Highways Self-Evaluation Tool*. http://www.sustainablehighways.org

U.S. Green Building Council (2009). *Leed 2009 for new construction and major renovations*. http://www.usgbc.org

Zimmermann K. (1992). *Pavement management methodologies to select projects and recommend preservation treatments*. National Cooperative Highway Research Program, NCHRP Synthesis 222, Project 20-5 FY. ISSN: 0547-5570.

Wiedmann, T. and Minx J., (2007). *A definition of 'Carbon Footprint'*. ISA UK Research Report, 7(01).

Wintergreen, J. and Delaney T., (2004). *ISO 14064, International Standard for GHG Emissions Inventories and Verification*, U.S. Environmental Protection Agency.

Chapter 9. Conclusions and Recommendations

9.1 Summary

The dissertation explored different decision aspects of planning maintenance interventions on road pavements. Since rehabilitating and reconstructing the whole pavement system cannot be sustained anymore because of budget constraints, new methodologies and proper maintenance activities should be defined and applied to preserve the current pavement assets. A sustainable pavement management approach is not only related to the economic impact assessment; environmental considerations on how our decisions affect the planet has to be included into the analysis. Therefore, besides costs other perspectives must be added into the analysis; long-term performance of maintenance activities has to be monitored over time to identify the best performing treatment and its proper application time. Wasting the already limited resources because of wrong strategies only planned based on experience instead of relying on real data must thus be avoided. Moreover, an increasing attention to environmental aspects and climate change have been promoted by media and researchers recently. Since roadways are spread in large extension all over the planet they represent a massive amount of non-renewable resources that is used every day for constructing new infrastructures or just maintaining and rehabilitating them.

The dissertation analytically showed the advantages of maintaining pavements acting proactively to extend the road service life. The assessment was developed according to three main perspectives: costs, performance, and environmental impacts.

9.2 Findings

The major findings of the research include the following:

- Life cycle cost analysis results showed that applying specific types of maintenance (i.e.; preventive maintenance) on road pavements has the potential to increase the monetary savings over the service life of the pavements returning several dollars for each dollar invested in maintenance.
- Pavement deterioration is a main issue in life cycle analyses of roads. Designers usually select a service life of 20 years or more to be achieved by their pavements, but the actual

performance turns to be lower, making major rehabilitations and reconstructions more frequent. Performance assessment consequently plays a main role in the life cycle analysis of maintenance strategies. The present research developed performance models and pavement deterioration curves according to experimental data gathered over years by the Virginia Department of Transportation. Performance data were related to the traffic levels (Equivalent Standard Axle Loads - ESAL) and the pavement structure. Results showed the effect of specific types of maintenance activities on the pavement service life and estimates the extension of life provided by these maintenance treatments.

- A life cycle assessment methodology was developed for identifying environmental impacts during the pavement service life caused by initial construction, maintenance, and rehabilitation/reconstruction activities. Application in two case studies helps evaluating the impacts of construction and maintenance practices on road pavements and fostered the understanding of the relationships between pavements and the environment. A large amount of emissions could be eliminated by adopting ad-hoc maintenance plans. In particular, emissions coming from raw materials extraction and manufacturing, transportation to the construction site, and maintenance treatment placement, were evaluated.
- Finally, since costs, performance, and environmental impacts cannot be addressed as stand-alone evaluations of projects they have been linked into a multi-attribute approach for defining the optimal maintenance strategy according to specific boundary conditions (i.e.; level of traffic, type of road, etc.). A multi-attribute optimization methodology was developed in order to set different weighting factors for the three parameters involved in the decision process (cost, performance, and environment) and identify the optimal maintenance strategy. The methodology was again illustrated through a case study that identified the optimal maintenance and rehabilitation strategies over an analysis period of 50 years choosing between more than six hundreds competing strategies.

9.3 Conclusions

This dissertation proposed a framework to evaluate maintenance and rehabilitation strategies for road pavements according to three different perspectives: costs, performance, and environmental impacts.

The main scientific contributions were represented by the evaluation of pavement deterioration trends and maintenance effectiveness, and by the development of a methodology to include environmental impacts in the common cost evaluation of road-related strategies. Indeed, very few data, and mainly very site-specific data, are available in literature to predict pavement performance during the pavement life cycle. The dissertation analyzed real data from current pavement sections differentiating deterioration trends according to commonly used parameters such as the equivalent single axle load (ESAL). Pavement structure was also considered in the analysis distinguishing between main arterials (i.e.; highways) and primary roads. Furthermore, the proposed methodology addressed the challenging issue of including environmental impacts into the pavement management process.

From an engineering contribution perspective, a more comprehensive decision support process is proposed, which provides transportation agencies with an innovative methodology to evaluate the impacts of the choices they make on the environment. Constructing, maintaining, and expanding our road infrastructure system to meet future transportation demands in a sustainable way is a challenge that must be accomplished. Currently, our knowledge about the way our road-related decisions impact the environment is far to be even sufficient. Understanding the complex relationship between road pavements and the environment is therefore an actual and significantly important task.

Although representing a step forward in the decision making process and a useful tool for practitioners, the methodology developed has to be still enhanced adding several other parameters into the analysis. However, as a result, road agencies and municipalities will be able to make better use of non-renewable resources and available funds, while users will benefit from better maintained and safer infrastructures.

9.4 Recommendations for Future Research

Although the proposed methodology is considered a step forward when compared to current practice, the analysis may be improved by adding other variables and processes. For instance, climate effects on pavement performance and maintenance effectiveness should be evaluated and implemented into the model besides traffic impacts. Weather-related parameters such as relative humidity, temperature, or rainfall, in fact, have been proven to highly affect pavement performance over time.

The inclusion of time considerations in life cycle environmental assessment is also needed. Activities that occur at different time will have, in fact, different environmental impacts because of changes in inputs, such as plants and equipment efficiency, for instance. However, current practice simply sums all impacts related to current and future activities. Therefore, a more accurate method would consider a sort of discount rate, such as the one used in economic assessments, that incorporates the expected future changes.

Another main area to be further investigated is the usage-phase during the pavement service life; a computation of the environmental benefits, in terms of fuel consumption and pollution, produced by road users driving on pavements with higher performance conditions is a key topic to be addressed. Lower values of roughness and rolling resistance (i.e.; pavement-tire interaction) may lead to a saving in terms of fuel consumption for road users avoiding a massive amount of emissions in the atmosphere especially on high volume roads.

In addition, environmental impacts should also be computed for the end-of-life phase; materials are always more being recycled at the end of their service lives but the environmental savings related to recycle-practices are still far to be rigorously defined.

Finally, since pavement construction and maintenance consumes a significant amount of non-renewable resources and energy, design solutions that decrease the consumption of virgin material resources, use recycled materials, or improve durability and service life, have to be preferred and further analyzed. The size of the energy and material annual investment recommends that enhancing the environmental understanding of using virgin versus recycled materials may lead to a more sustainable road construction sector.

The multi-attribute approach should therefore take into account all the previous aspects for a more comprehensive assessment of maintenance strategies for road pavements. Road authorities and municipalities will greatly benefit from having a rigorous and powerful tool for deciding among alternatives without relying on subjective judgments and personal experience. In addition, users will benefit from having roads in better condition, consuming less fuel, and producing less environmental impacts.

Appendix A: Matlab© script

```
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
%$$$   Multi-Attribute Evaluation of M&R Strategies   $$$
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
%$ Read Cost-Performance-Environmental impacts from an  $
%$ excel file and find out the optimal strategy         $
%$ according to specific weights set by the user        $
%$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

function [treDplot,distance,opt,opt_strategy,opt_range] =
Draw3DPoint03

%Step 1: read the excel file and plot scattered points
highlighting with different colors the different materials used
in M&R strategies
[treDplot] = xlsread('3Dnormalized');
%[x,y,z] = size(treDplot);
x=treDplot(1:633,1);
y=treDplot(1:633,2);
z=treDplot(1:633,3);
figure(1);
hold on
grid on
xlabel('{\bfCost - EUAC}','color','k');
ylabel('{\bfPerformance}', 'color', 'k');
zlabel('{\bfEnvironmental Impact}','color', 'k');
Title = ['{\bfAnalysis of}',' {\bfM&R Strategies}'];
view(-24,20);
title(Title, 'color','k');
scatter3(x(1:285),y(1:285),z(1:285),'o','b','filled');
scatter3(x(286:570),y(286:570),z(286:570),'s','m','filled');
scatter3(x(571:633),y(571:633),z(571:633),'^','g','filled');
stem3(x,y,z,'LineStyle',':','Color','cyan');

%Step 2: plot a figure where points are interpolated. The same
weight is assumed for each parameter (i.e.; 33.3% C, 33.3% P,
33.3% E)
figure(2);
hold on
grid on
xlabel('{\bfCost - EUAC}','color','k');
ylabel('{\bfPerformance}', 'color', 'k');
zlabel('{\bfEnvironmental Impact}','color', 'k');
Title = ['{\bfAnalysis of}',' {\bfM&R Strategies:
interpolation}'];
```

```
view(-29,34);
title(Title, 'color','k');
% another way instead of using the function ‘griddata’… F =
TriScatteredInterp(x,y,z,'natural');
ti = 0:1:100;
[qx,qy] = meshgrid(ti,ti);
%qz = F(qx,qy);
qz=griddata(x,y,z,qx,qy,'linear');
surfl(qx,qy,qz)
colormap autumn;
hold on;
plot3(x,y,z,'o');
axis([0 100 0 100 0 100]);

%Step 3: points are weighted according to the decision maker'
wishes and a new figure is plotted
figure(3);
hold on
grid on
xlabel('{\bfCost - EUAC}','color','k');
ylabel('{\bfPerformance}', 'color', 'k');
zlabel('{\bfEnvironmental Impact}','color', 'k');
Title = ['{\bfWeighted}',' {\bfM&R Strategies}'];
view(-41,40);
title(Title, 'color','k');
Wc=input('Please select your weight for COSTS (i.e.; input 0.5
for a 50% weight)');
Wp=input('Please select your weight for PERFORMANCE (i.e.; input
0.3 for a 30% weight)');
We=input('Please select your weight for ENVIRONMENTAL IMPACTS
(i.e.; input 0.2 for a 20% weight)');
if 0.99<=Wc+Wp+We<=1.01
    Xw=x.*Wc;
    Yw=y.*Wp;
    Zw=z.*We;
    scatter3(Xw,Yw,Zw,'s','b');
    tii = 0:0.25:100;
    [px,py] = meshgrid(tii,tii);
    %pz = F(px,py);
    pz=griddata(Xw,Yw,Zw,px,py,'cubic');
    meshz(px,py,pz);
    hold on;
    view(-41,40);
    plot3(Xw,Yw,Zw,'o');
    colormap summer;
    %axis([0 100*Wc 0 100*Wp 0 100*We]);
```

```
else error('Sorry, the sum of the three weights must be equal to
1')
end

%Step 4: find out the strategy with the minimum distance from
the optimal "weighted" point Opt=(C,P,E)=(0,100*Wp,0)
distance=diag(zeros(633));
for i = 1 : 633
    distance(i)=sqrt((Xw(i)-0)^2+(Yw(i)-(100*Wp))^2+(Zw(i)-
0)^2);
end
opt=min(distance);
opt_strategy=find(distance==opt);
opt_range=find(distance<=(opt+1.5));

figure(4);
hold on
grid on
xlabel('{\bfDistance from the optimum}','color','k');
ylabel('{\bfnum of strategies}', 'color', 'k');
Title = ['{\bfSpread of M&R strategies around the optimum}'];
title(Title, 'color','k');
hist(distance,50);

for i = 1: 633
    Point(i) = i;
end
figure(5)
hold on
grid on
xlabel('{\bfStrategy}','color','k');
ylabel('{\bfEuclidean 3D distance from the optimum}', 'color',
'k');
Title = ['{\bfThe best strategy is #
}',int2str(opt_strategy),'{\bfhaving a minimum distance of
}',num2str(opt)];
title(Title, 'color','k');
plot(Point,distance,'s');


end
```