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Multi-Attribute Life Cycle Assessment of Preventive Maintenance Treatments on Road Pavements for Achieving Environmental Sustainability

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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 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.

Keywords: sustainable road pavements, LCA, multi-attribute approach, preventive maintenance, carbon footprints, embodied energy

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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_2 e) 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.

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 (≤ 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.

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 4.

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:

$$\text{Area}(\text{trapezoid}\_1) = \frac{(\text{PSI}_{@\text{year}0} + \text{PSI}_{@\text{year}1}) \cdot 1\text{year}}{2}$$

That is, extending to all trapezoids:

$$\text{Area}\_\text{Under}\_\text{Curve} = \sum_{i=0}^{49} \frac{(\text{PSI}_i + \text{PSI}_{i+1}) \cdot 1\text{year}}{2}$$

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 1 and the areas under the curves for the different alternatives and maintenance strategies are provided in Table 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.

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.

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 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 2 summarizes the outcomes obtained from the literature review highlighting the different sources adopted. 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.

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.

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

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.

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

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.

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

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

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 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.

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 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 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 4.

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.

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:

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

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 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 5 summarizes the results for the rescaling.
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:

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

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).

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.

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.

REFERENCES

1. Alcom A. (2003). Embodied Energy and CO2 coefficients for NZ Building Materials. Center for Building Performance Research, Virginia University of Wellington, New Zealand.
2. American Association of State Highway and Transportation Officials - AASHTO (1993). AASHTO guide for design of pavement structures, Washington D.C. ISBN: 1560510552.
3. Anderson J., Weiland C., Muench S. (2011). Greenroads™ Manual v. 1.5. University of Washington. http://www.greenroads.us.
4. Asphalt Institute and Eurobitume (2008). Bitumen Industry – A Global Perspective, Information Series No.230, IS-230, ISBN 978-1-934154-54-0.
5. Association of Plastic Manufacturers in Europe - APME (2004). http://www.plasticseurope.org/plastics-sustainability/eco-profiles/browse-by-family.aspx
6. American Standard Testing Method (2010). ASTM D6372-05 Standard Practice for Design, Testing, and Construction of Micro-Surfacing. DOI: 10.1520/D6372-05R10
7. ATHENA™ Sustainable Material Institute (1999). Life Cycle embodied energy and global warming emissions for concrete and asphalt roadways - Summary report. Canadian Portland Cement Association.
8. ATHENA™ Institute (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Cement Association of Canada.
9. CALTRANS, Fugro (2004). Slurry Seal / Micro-Surface Mix Design Procedure, Phase I Report - Contract 65A0151 for California Department of Transportation (Caltrans), Materials/Infrastructure Section.
10. COST Action 354, Litzka et al. (2008). Performance Indicators for Road Pavements – Final Report. European cooperation in the field of scientific and technical research.
11. 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.
12. 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.
13. Flintsch G. (2010). International Sustainable Pavements Workshop, Airie, VA (USA). Research Agenda for Sustainable Pavement. http://www.vtti.vt.edu/ISPW/ISPW-2010.html
14. Häkkinen T., Mäkelä K. (1996). Environmental impact of concrete and asphalt pavements, Technical Research Centre of Finland, VTT Tiedotteita, Meddelanden, Research Notes 1752.
15. 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).
16. Hammond G., Jones C. (2008). Inventory of Carbon & Energy (ICE). ICE V1.6a©, Energy Research Team (SERT), University of Bath, UK.
17. Horvath A. (2004). Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), Department of Civil and Environmental Engineering, University of California, Berkeley.
18. International Slurry Surfacing Association (2010). Recommended Performance Guideline For Micro Surfacing. Project A143, revised February 2010. http://www.slurry.org/downloads/A143.pdf

19. 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.

20. 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.

21. 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.

22. 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.

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

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

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

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

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

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

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

30. 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

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

32. 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.

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

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

35. 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

36. 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.

37. 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.

38. 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.

FIGURES

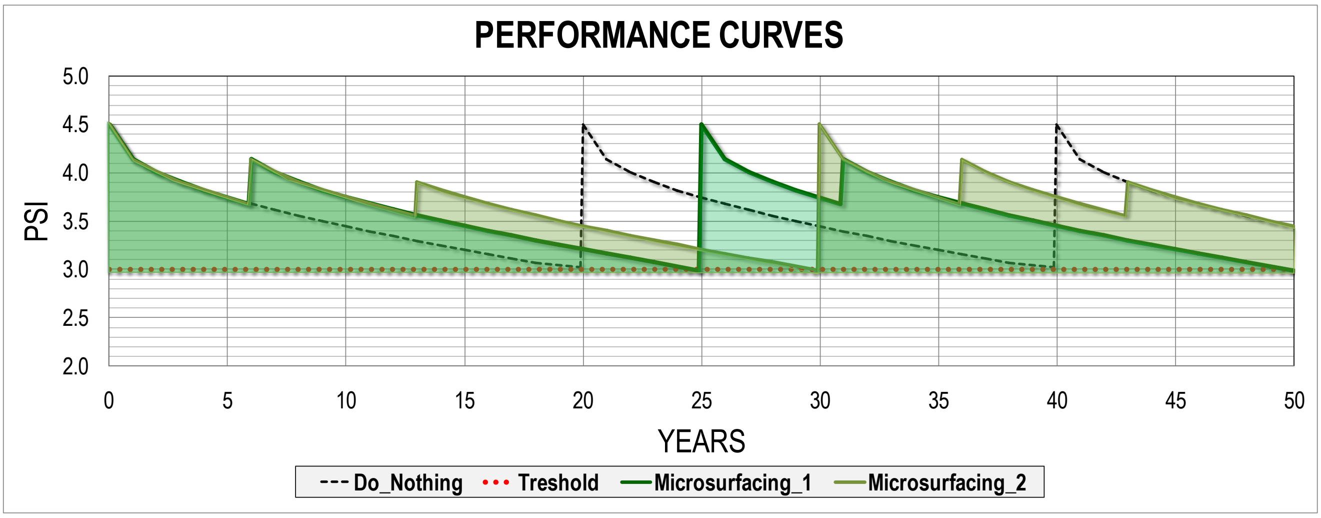
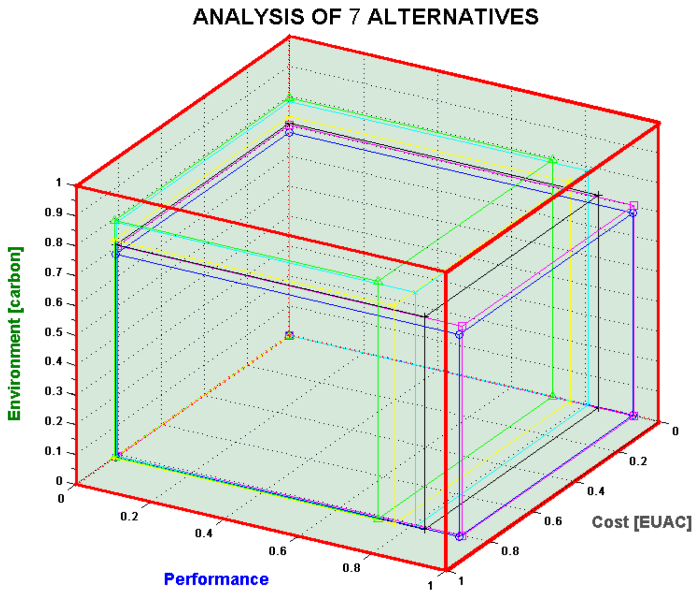


Fig. 1 Performance curves of microsurfacing-based strategies



		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

Fig. 2 Multi-attribute analysis, an example

TABLES

Table 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 %

Table 2 CO_2e emissions and energy (raw materials)

Material	Emission – CO_2e [kg/ton material]	Standard Dev.	Embodied energy [MJ/ton material]	Standard Dev.	Literature sources
Bitumen	256.5	118.2	4603	2226.0	[4],[25],[16],[7],[8]
Bitumen emulsion [60%]	221.0	21.9	3490	428.8	[4],[25]
Crushed aggregates	7.5	9.9	38.9	2.7	[25],[7],[8],[14],[38]
Pit-run aggregates	5.3	2.2	19.4	11.4	[25],[7],[14]
Cement	1079.6	311.5	5900	847.1	[25],[21],[26]
Quicklime	2500	-	9240	-	[25]
Water	0.29	-	10	-	[25]
Polymers – elastomers	3000	543.4	91440	36753.5	[23],[5],[1]
Polymers – plastomers	1400	424.3	44667.3	51087.7	[25],[5],[1]
Emulsifiers	600	52.4	63250	6010.4	[25],[1]

Table 3 Emissions and Energy Due to Machinery*

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

** 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.*

Table 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_2e [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_2e [g/m^2]*
		107.87	5.02	29.83	1154.84	86.21

Table 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