ENVIRONMENTAL SUSTAINABILITY AS A PERFORMANCE MEASURE FOR ASSESSING PREVENTIVE MAINTENANCE POLICIES

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ABSTRACT

Although a significant number of environmental protection measures concerning industrial products and processes have emerged over the past few years, similar measures are 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 researches attempt to evaluate environmental impacts 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 of road pavements. In particular, preventive maintenance (PM) applied at the right time during the pavement service life has been proven to provide significant improvement of its performance and reduce the deterioration rate.

The present paper describes an innovative methodology to evaluate the environmental impacts of road preventive maintenance activities relating them to performance and costs during the service life of the pavement through a multi-attribute “life cycle cost, performance and environmental analysis.” The methodology provided could be a part of a decision support system useful to assist authorities and evaluate different alternatives related to road pavements.

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 an innovative multi-attribute approach. A full life cycle assessment (LCA) is therefore presented.

The approach adds performance and emissions in order to evaluate if the most cost effective alternative also corresponds to the most eco-friendly and/or the best-performing strategy. Several environmental certification approaches have been developed during the last decade to certificate companies, buildings and products [1]. New rating systems and tools are also becoming popular for assessing the eco-impact footprint of road pavement projects [2] [3]. 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 examples presented illustrate 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 used on 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 strategies should be selected not just considering costs and performance, but also the environmental impacts. Similar results in terms of cost and performance may be 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 three different PM strategies. In particular, the aim is to compare different maintenance strategies for a constant analysis period analyzing every choice according to three criteria: costs, performance and eco-effectiveness. An innovative procedure to include the three aspects in a single decision support tool was developed and hereafter described. The method is generally applicable to all the others PM treatments and/or road maintenance and rehabilitation activities.

2 INCLUDING ENVIRONMENT IMPACTS AS DECISION FACTORS

This section presents a methodology to incorporate 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.

Letting the pavement deteriorate until a major reconstruction is needed typically represent an ineffective strategy from cost, performance, and environmental standpoints. Many articles [4] [5] 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 [6], 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 [7].

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 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 thin overlay, microsurfacing, and slurry seal and 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 rehabilitation when the pavement reaches the minimum condition threshold. The method hereafter described points out the maintenance strategy that is more effective, minimizing costs and environmental impacts while maximizing the performance. However, the methodology adopted is general and it could be easily extended to other PM treatments and maintenance strategies.

2.1 Life-cycle Cost Assessment

Life cycle cost analysis already represents an established standpoint in evaluating different projects and strategies, and a great variety of technical literature is available on the topic.
In the paper, agency costs were evaluated over the life cycle of the specific maintenance plan accounting for different materials and maintenance treatments, following the VDOT standard price list for road materials and constructions [8]. The analysis period was set equal to 50 years. The remaining value of the asset at the end of the analysis period that can be 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.

After estimating the costs schedule over the analysis period, future costs were 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 back at 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. A discount rate of 4% was used for the calculations. The PWC and EUAC were estimated for a sample road unit of a square meter. Outcomes for the different maintenance plans are summarized in table 3.

2.2 Performance Assessment

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 [9] was carried out considering theoretical and empirical deterioration curves [10]. Performance curves were developed for predicting the Present Serviceability Index (PSI) over time. Moreover, different models [11] 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: (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 [12] available in literature for that specific treatment. For this investigation the performance improvement due to PM treatments was computed using the following formulas [11] that are a function of the before-treatment PSI:

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

$$PJ = 0.0853 \cdot PSI + 0.5552$$ Microsurfacing

$$PJ = \max\left[0.2\ ;\ 1.158 - 0.275 \cdot PSI\right]$$ Slurry seal

While pre-treatment curves were developed using the AASHTO deterioration curve [13] for all the alternatives provided in the analysis, post-treatment curves were extrapolated from previous experiences [11] 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) [14] 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:

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

That is, extending to all trapezoids:

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

The adopted pavement structure had at construction a structural number of 6.2 and it was built on a subgrade with a resilient modulus of 7,000 psi (48.26 MPa). The traffic was set equal to 2,500 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.

Three PM treatments were studied and two maintenance strategies were assumed for each one depending on how many times that specific treatment was applied in the pavement life cycle. Considering the microsurfacing, for instance, two different maintenance strategies were hypothesized: applying the treatment only at year 6 and applying it twice over the life cycle at years 6 and 13.

Deterioration trends, performance jumps and post-treatment curves are summarized in the following figure (Figure 1) and the areas under the curves for the different alternatives and maintenance strategies are summarized in Table 1.

As expected, the table shows that preventive maintenance results in the pavement having better conditions over the analysis period. This improved performance will reduce normal operating user costs (strictly related to the pavement conditions), improving user satisfaction.

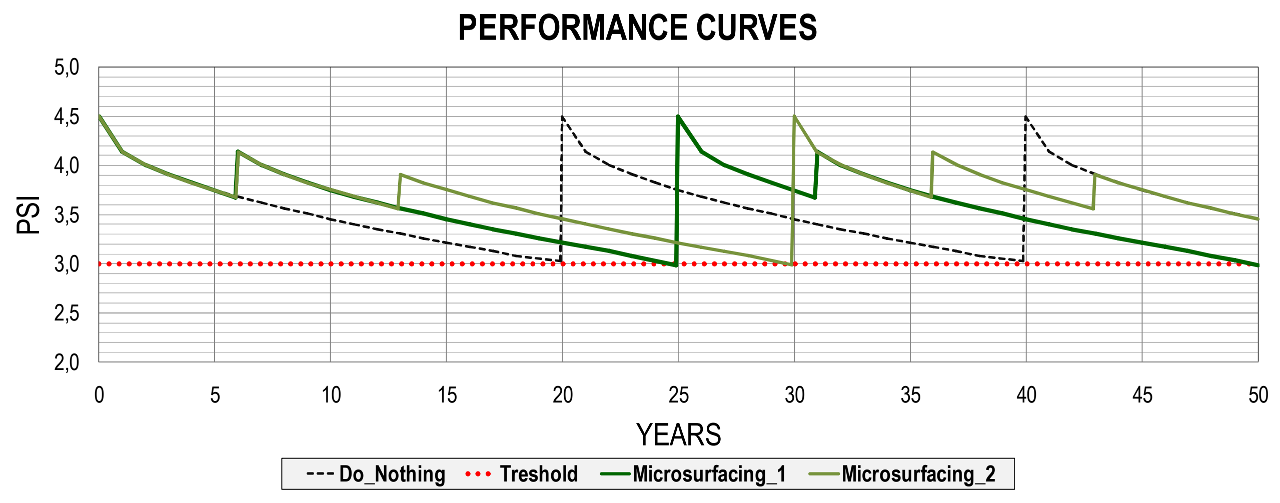


Figure 1 - Performance curves of microsurfacing-based strategies

Table 1 - Area Under Curve_AuC

Maintenance strategy	AuC *Area Under Curve*	Performance increase
DO_NOTHING	29.83	
OVERLAY (1)_*[@year 8]*	37.31	+ 25.08 %
OVERLAY (2) _*[@years 8 and 16]*	42.45	+ 43.65 %
MICROSURFACING (1) _*[@year 6]*	33.03	+ 10.73 %
MICROSURFACING (2) _*[@years 6 and 13]*	40.74	+ 36.57 %
SLURRY (1) _*[@year 5]*	32.91	+ 10.33 %
SLURRY (2) _*[@years 5 and 12]*	38.51	+ 29.10 %

2.3 Environmental Assessment

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 [15], 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.

2.3.1 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 2). 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 effective in terms of the three different criteria: cost, performance and environment. 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 2 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 2 - CO_2 emissions and energies (raw materials)

Material	**Emission – CO_2** [Kg/ton material]	**Embodied energy** [MJ/ton material]	**Literature source**
Bitumen	256.5	4603	[16],[17],[18],[19],[20]
Bitumen emulsion [60%]	221.0	3490	[16],[17]
Crushed aggregates	7.5	38.9	[17],[19],[20],[21],[22]
Pit-run aggregates	5.3	19.4	[17],[19],[21]
Cement	1079.6	5900	[17],[23],[26]
Quicklime	2500	9240	[17]
Water	0.29	10	[17]
Polymers – elastomers	3000	91440	[24],[25],[26]
Polymers – plastomers	1400	44667.3	[17],[25],[26]
Emulsifiers	600	63250	[17],[26]

2.3.2 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 [27] 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.

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

Where: *F* = fuel consumed; *BSFC* = basic 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.

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

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 [27] 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 [27], was adopted to compute energies involved in the process.

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

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

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

2.3.3 Construction 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, and 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.

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 2 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 paragraph 2.3.1. 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 [28]. 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).

The life-cycle costs, performance and eco-effectiveness for each strategy are summarized in the Table 3.

Table 3 - costs, performance and emissions/energies due to PM and Do_Nothing strategies

	PM_different strategies	**Costs**		**Performance**	**Environment**	
		PWC [$/m2]	*EUAC [$/m2]*	*AuC*	*energy [MJ]*	*CO$_2$e [g/m2]*
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

Do_Nothing	**Costs**		**Performance**	**Environment**	
	PWC [$/m2]	*EUAC [$/m2]*	*AuC*	*energy [MJ]*	*CO$_2$e [g/m2]*
	107.87	5.02	29.83	1154.84	86.21

3 MULTI-ATTRIBUTE APPROACH FOR LIFE CYCLE ASSESSMENT

Sustainability considerations are increasing being considered as part of long term plans for road pavement management worldwide. New tools to assess carbon footprints and embodied energies of road pavement, material, systems, and construction/maintenance processes are continuously released [27] [29] [30]. Road agencies at the national and municipal levels are providing guidelines to assess the relative sustainability of a road project [2] [3].

Unfortunately, the consideration of the environmental features of a road project is done independently or as something considered as an added value. Very little has been done to incorporate the environmental impacts as part of the pavement management systems and the decision support tools to choose between different strategies. In this way, giving a certificate or a medal [2] [3] to a road project could result in the belief that recognition corresponds to the best possible strategy. However, the most environmental friendly strategy may not be the one with the highest performance. That is, using materials that are “greener” 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 in more total emissions produced. Furthermore, 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 purposed.

3.1 Parameters Normalization

In order to bring the different quantities to a same scale, a normalization of the parameters between 0 and 1 was adopted.

COSTS: Since the “Do_Nothing” alternative is the most expensive, a value of 1 was assigned to it. All the other strategies were scaled to the base using a direct proportion:

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

Where: x_i = normalized value for the *i*-alternative; $PM\_strategy_{i\_cost}$ = cost related to the *i* PM_strategy; $Do\_Nothing_{cost}$ = cost related to the Do_Nothing strategy.

ENVIRONMENT: Since the Do_Nothing strategy is also the most polluting one, a value of 1 was assigned to it and the same procedure was adopted to compute the normalized values of the others strategies.

PERFORMANCE: Because of the Do_Nothing alternative had the lowest performance over the life cycle, some changes to the normalization procedure were needed in order to assign it the maximum value of 1. Supposing that a perfect ideal pavement has to show the same maximum performance over time (e.g. horizontal 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. Moreover, the Do_Nothing alternative, that presents the lower performance value, is now the most distant from the hypothetical perfect trend and therefore shows the maximum difference value. This value was taken as a reference and equal to 1. All the others PM_strategies were normalized in the same way adopted for costs and environmental features.

Table 4 summarizes the results of the normalization.

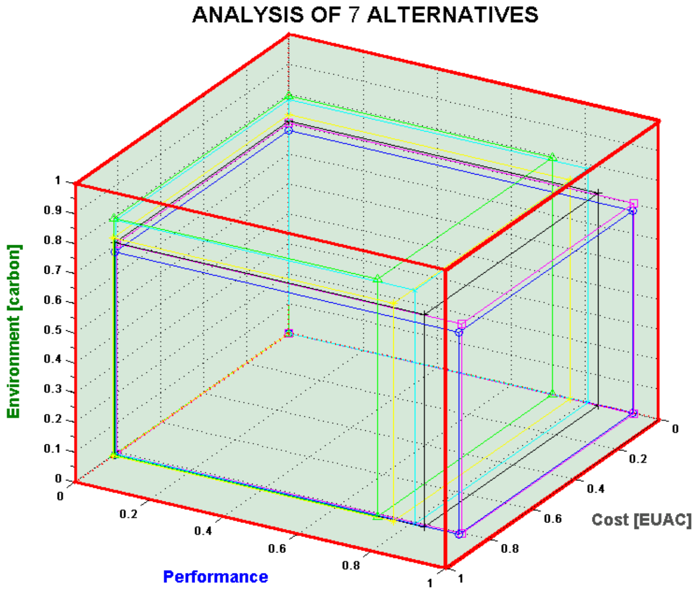
Table 4 - Normalized Quality Indicators for the Various Strategies

		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*	0.824	0.825	0.758	0.776	0.732
Thin overlay	*(1 intervention per cycle) – 8*	0.814	0.815	0.834	0.710	0.710
Thin overlay	*(2 interventions per cycle) - 8 & 16*	0.816	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

3.2 Parameters Representation

After being normalized, comparable quantities were then obtained. A three-dimensional representation can be done identifying the x-axis with life-cycle costs (PWC or EUAC values), the y-axis with performance, and the z-axis with environmental features (carbon footprints or embodied energies). 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 was done for all the PM alternatives creating a script in Matlab® that automatically showed the cubes related to the different alternatives and the associated volumes. Finally, the cube with the lowest volume represented the one with the highest "*score"* over the analysis period (e.g. the winning strategy) considering costs, performance, and environmental impacts. It resulted that doing microsurfacing twice over each life cycle lead to the maximization of performance while minimizing costs and environmental impacts.

Obviously, different weights and therefore different importance could be assigned to each parameter depending on policy maker preferences; national agencies and municipalities may give different priority to lowering costs, enhancing performance or choosing more eco-effective strategies. In addition, ranges of what is considered acceptable 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 2 - example of multi-attribute analysis

4 CONCLUSION

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 and lower life-cycle costs over the life cycle with respect to major rehabilitation. 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.

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

2. Anderson J., Weiland C., Muench S. (2011). Greenroads™ Manual v. 1.5. University of Washington. http://www.greenroads.us.
3. U.S. Department of Transportation. Federal Highway Administration (2010). Sustainable Highways Self-Evaluation Tool. http://www.sustainablehighways.org
4. 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.
5. U.S. Department of Transportation. Federal Highway Administration (1996). Preventive Maintenance Effectiveness: Preventive Maintenance Treatments. Report No. FHWA-SA-96-027.
6. 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.
7. Flintsch G. (2010). International Sustainable Pavements Workshop, Airie, VA (USA). Research Agenda for Sustainable Pavement. http://www.vtti.vt.edu/ISPW/ISPW-2010.html
8. Virginia Department of Transportation (2010). Statewide Average Costs from August 2008 to July 2010. www.virginiadot.org/business/resources/const/StatewideAverage.pdf
9. 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.
10. 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).
11. 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.
12. 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
13. American Association of State Highway and Transportation Officials - AASHTO (1993). AASHTO guide for design of pavement structures, Washington D.C. ISBN: 1560510552.
14. 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.
15. Akbari H., Menon S., Rosenfeld A. (2009). Global cooling: increasing world-wide urban albedos to offset CO_2. Climatic Change, Volume 94, Numbers 3-4, 275-286, DOI: 10.1007/s10584-008-9515-9.
16. Asphalt Institute and Eurobitume (2008). Bitumen Industry – A Global Perspective, Information Series No.230, IS-230, ISBN 978-1-934154-54-0.
17. Stripple H. (2001). Life Cycle Assessment of Road: a Pilot Study for Inventory Analysis. IVL Report B1210E, Swedish Environmental Research Institute, Gothenburg, Sweden.
18. Hammond G., Jones C. (2008). Inventory of Carbon & Energy (ICE). ICE V1.6a©, Energy Research Team (SERT), University of Bath, UK.
19. The ATHENA™ Sustainable Material Institute (1999). Life Cycle embodied energy and global warming emissions for concrete and asphalt roadways - Summary report. Canadian Portland Cement Association.
20. ATHENA™ Institute (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential. Cement Association of Canada.
21. Häkkinen T., Mäkelä K. (1996). Environmental impact of concrete and asphalt pavements, Technical Research Centre of Finland, VTT Tiedotteita, Meddelanden, Research Notes 1752.
22. 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.
23. 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.
24. Norton A. (2007). Ecoinvent, Materials: their manufacture, use & environmental impact. Greenspec®.
25. Association of Plastic Manufacturers in Europe - APME (2004).
26. Alcom A. (2003). Embodied Energy and CO2 coefficients for NZ Building Materials. Center for Building Performance Research, Virginia University of Wellington, New Zealand.
27. U.S. Environmental Protection Agency (2009). Office Carbon Footprint Tool - version 1.2. http://www.epa.gov/wastes/partnerships/wastewise/carboncalc.htm
28. Fugro (2004). Slurry Seal / Micro-Surface Mix Design Procedure, Phase I Report - Contract 65A0151 for California Department of Transportation (Caltrans), Materials/Infrastructure Section.
29. Horvath A. (2004). Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), Department of Civil and Environmental Engineering, University of California, Berkeley.
30. TRL Limited (2009). Asphalt Pavement Embodied Carbon Tool - asPECT, Version 2.0.