PREVENTIVE MAINTENANCE ON ROAD PAVEMENTS: PERFORMANCE AND ENVIRONMENTAL ASSESSMENT OF STRATEGIES

Authors:
Giustozzi F., Ph.D, P.E. (corresponding author)
Research Associate – Politecnico di Milano/Virginia Tech – filippog@vt.edu
P.zza Leonardo Da Vinci 32, 20133, Milan, Italy
Office:+39-02-23996605
and
3500 Transportation Research Plaza, 24060, Blacksburg, Virginia, USA
Mobile: +1-(540)505-6861

Crispino M., Ph.D, P.E.
Professor – Politecnico di Milano – maurizio.crispino@polimi.it
Director, Infrastructure Section – DIIAR

Flintsch G., Ph.D, P.E.
Professor – Virginia Tech – gflintsch@vt.edu
Director, Center for Sustainable Transportation Infrastructure - CSTI

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ABSTRACT

Pavement preservation can be achieved through a wide range of maintenance treatments. Some of these treatments are more effective than other for specific level of condition and traffic. Thus, assessing the actual performance of preventive maintenance treatments is very important for assessing the long-term effectiveness of pavement preservation. Furthermore, besides costs and performance, environmental impacts are becoming important aspects to be evaluated over the pavement service life. Different maintenance plans and strategies entail a different amount of emissions produced and energies spent. Thus, there is a need for improving and set maintenance best practices in order to limit greenhouse gasses towards the development of sustainable road pavement management strategies.

The present paper analyzes short and long-term performance of four preventive maintenance treatments: microsurfacing, slurry seal, chip seals, and ultra-thin overlay. Although infrequent in Italy, they represent a common practice for road authorities in several countries around the world, especially in the United States. A significant amount of pavement sections in the state of Virginia (USA) were analyzed over time identifying the treatments effectiveness according to different traffic levels. Deterioration curves were developed and adopted for further life-cycle analyses.

Finally, emissions related to these preventive maintenance strategies were computed and compared to routine maintenance alternatives in order to highlight environmental benefits and savings over the life-cycle of the pavement. Preventive maintenance revealed to be well-performing, providing higher performance over the analysis period, and eco-effective.

Keywords: preventive maintenance, life cycle assessment, carbon footprinting.

INTRODUCTION

The optimization of available resources, which are generally very limited, to preserve high system performance is currently one of the most significant problems affecting the management of our road infrastructure systems. Keeping road pavements at a high level of performance entails an effective maintenance plan over the service life. Maintenance, if conducted 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. An effective pavement database within a more comprehensive pavement management system that continuously tracks the current road conditions is therefore desirable for predicting future deterioration trends, properly schedule maintenance activities, and correctly allocate funds.

Unfortunately, the majority of road authorities and municipalities do not gather the pavement data required to assess maintenance effectiveness. A general lack of monitoring and therefore a substantial unawareness of long-term pavement behavior usually results in allocating funds on an experience-based approach, which is frequently ineffective. Indeed, road agencies usually allocate funds for maintenance and rehabilitation according to an overall budget scheme: a constant amount of funds is equally spread over the years of the maintenance contract. This typically results in allocations that are lower than those needed for applying effective maintenance strategies. Pavement assets are usually ignored until safety is affected since no money has been correctly allocated. As a result, pavement performance is often low and a run-to-failure approach has becoming a common practice in order to postpone outflow costs. Corrective and emergency maintenance seems to be the general rule instead of the exception: deteriorate first, react later.

Pavement assets are consequently deteriorating faster than planned and the lack of adequate and previously allocated funding does not allow proper reactions. However, rehabilitating the entire infrastructure system is too onerous and road authorities cannot afford it.

Thus, techniques oriented towards the preservation of existing pavement assets are needed; a pro-active approach has to be preferred to re-active. 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) assessed 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. 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 is represented by the preventive maintenance (PM) approach: act now proactively for extending the pavement service life later minimizing costs. PM consists of applying specific treatments when the pavement still retains high performance to slow down the deterioration and lower the need for routine maintenance and major rehabilitations over the service life. Several studies have shown that PM strategies are cost effective and provide high performance (Cuelho & Freeman, 2004) (Geoffroy, 1996) (Labi & Sinha, 2003) (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, microsurfacing, thin and ultra-thin overlay. Several descriptions of PM treatments can be found elsewhere in the literature (i.e.; Peshkin et al., 2004; Cuelho et al., 2006; Peshkin et al., 2011; NAPA, 2009).

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). New rating systems and tools are also becoming popular for assessing the eco-impact of road pavement projects (Anderson et al., 2011; FHWA, 2010). A more comprehensive assessment including the environmental perspective, in addition to costs and performance, would allow a complete 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.

Since a massive amount of non-renewable resources are used daily for constructing and maintaining road assets, a calculation of emissions produced by applying a certain design/maintenance strategy is considerably significant. Emissions analysis could therefore represent a step forward for selecting the right design and maintenance material to be applied while preserving the environment. Indeed, similar results in terms of cost and performance might be achieved using more eco-efficient alternatives, consuming a lower amount of energy while producing less greenhouse gasses.

OBJECTIVE

The present paper evaluates the effectiveness of preventive maintenance on roads in terms of (1) pavement performance over the life cycle defining post-treatment deterioration trends and (2) environmental impacts related to preventive maintenance strategies according to emissions from materials and equipment adopted for PM applications. Performance assessment was conducted analyzing results from several pavement sections over a 10-year time span in Virginia (USA).

PERFORMANCE ANALYSIS OF PREVENTIVE MAINTENANCE EFFECTIVENESS

Although frequently associated with higher performance over the service life, preventive maintenance approach relies on very few experimental data on its effectiveness. However, deterioration models after a certain maintenance treatment is applied (post-treatment deterioration curves) are mostly unknown and commonly based on the service life extension concept according to literature (Wood et al., 2009). The presumed extra-time to the pavement service life by a specific maintenance treatment is therefore figured out according to literature records instead of evaluating the real deterioration trend over time. For instance, microsurfacing applications have been acknowledged to provide an extension of pavement service life within a range of 3 – 6 years, slurry seal from 2 to 5 years, etc.

The development of maintenance strategies according to wide ranges of effectiveness entails multiple uncertainties that may in turn heavily affect the reliability of predictions, especially in the long-term. Allocating funds to be spent at a specific year and having the pavement deteriorates faster cannot be acceptable since it entails significant weaknesses in the whole budget allocation process. Furthermore, the ability to forecast future pavement conditions has potential economic benefits when implemented into a pavement management system.

The following sections present post-treatment deterioration models obtained by analyzing the effectiveness of several PM treatments over a 10-year time span.

DATA COLLECTION

Data on post-treatment effectiveness was gathered by the Virginia Department of Transportation (VDOT) over a time span of ten years. More than 1,400 pavement sections located throughout the State of Virginia (USA) were analyzed. Only PM treatments for flexible pavements were considered.

Data for each pavement section surveyed included the following list of information (non-exhaustive list):

- location of the site (district, route name, direction, lane mile, road category, section ID);
- traffic data (average daily traffic, daily truck number, traffic categories);
- pavement data (year of construction, year of inspection, surface layer materials);
- PM treatment (year of treatment application, treatment type, pavement condition after a specific time span from application).

In particular, pavement conditions after PM treatment applications were described over time according to several performance indices: International Roughness Index (IRI), rutting depth, Load-related Distress Rating (LDR), Non-load-related Distress Rating (NDR), and Combined Condition Index (CCI). For the sake of the present paper two main indices were used and then grouped into one comprehensive performance index. Individual performance data was aggregated into the LDR and NDR indices. LDR evaluates pavement condition taking into account distresses that occur as a result of vehicle load related damages (e.g. fatigue cracking, rutting, etc.) while NDR evaluates distresses considered to be primarily non-load related - i.e., caused by weathering of pavement surface, materials and/or construction deficiencies (e.g. thermal cracking, longitudinal joint separation, bleeding, etc.). Both indices, based on deduct values (different quantities are deducted to the maximum according to the severity and extent of the distresses), are on a scale of 0 to 100, with 100 representing a pavement with no visible distresses.

LDR and NDR are the grouped into the Combined Condition Index (CCI), calculated as the lowest between them. CCI therefore can be expressed using the same scale between 0 and 100 and it is adopted in the present paper as the main reference index to evaluate the actual condition of the pavement. Commonly, pavement sections having a CCI value below 60 are considered ‘deficient’ and therefore proposed as ideal candidates for major rehabilitations or reconstructions. Furthermore, CCI can be easily associated to more well-known and adopted indices such as the Pavement Condition Index (PCI). Indeed, both are based on a deduct-value theory and expressed over a 0-100 scale.

ASSUMPTIONS

Main assumptions made in the analysis are presented below.

- The application of preventive maintenance treatment was assumed to completely restore the pavement condition (i.e.; CCI = 100). It was thus assumed that preventive maintenance was performed at a time when the pavement still retains high performance conditions (i.e.; CCI $\geq$ 80).
- Effectiveness of PM treatments was evaluated over time analyzing trends for performance indices in a time span ranging from 0 to 10 years; year-0 is the time when the treatment was applied, year-1 denotes the first year after the treatment application, etc. It was decided not to use older data because of the poor reliability and the difficulty to relate them with traffic.
- Road sections considered in the analysis belonged to both the interstate and primary systems. Data was therefore divided according to that in order to investigate the relevance of the pavement structure on the effectiveness of PM treatments.
- Since the influence of traffic on the effectiveness of PM treatments still remains an *a posteriori* consideration, traffic was grouped into 1000-ESAL intervals and data on effectiveness was investigated according to traffic levels. Interstates sustained a maximum traffic of 6000 ESALs while primary roads did not exceed 2000 ESALs per day.
- Some treatments (i.e.; slurry seal) were not applied under specific traffic conditions and/or type of roadway; therefore, available data referred only to particular situations as identified in table 1. Slurry seal type II, for instance, was not applied on high-volume roads since it proved not to be effective.

A graphical representation of the available data for primary roads is shown in Figure 1.

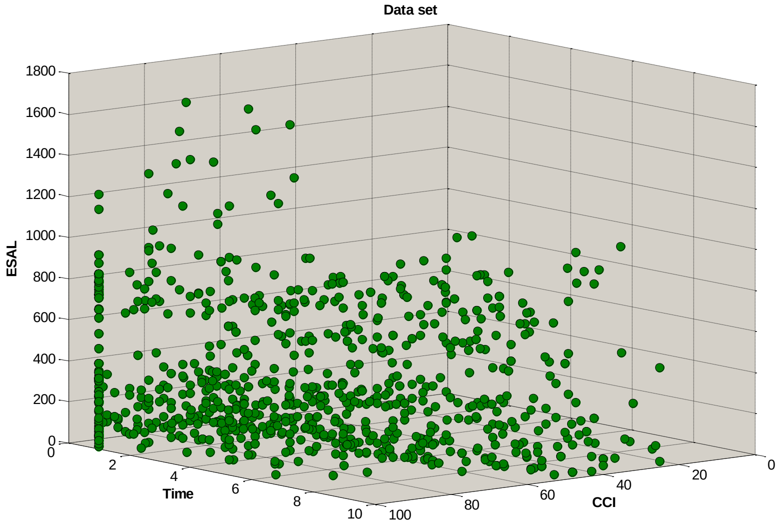
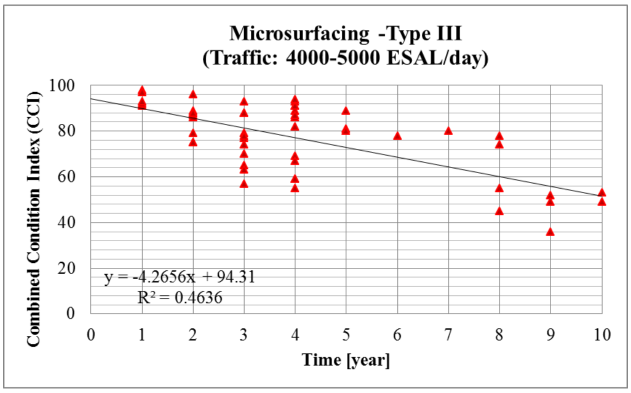
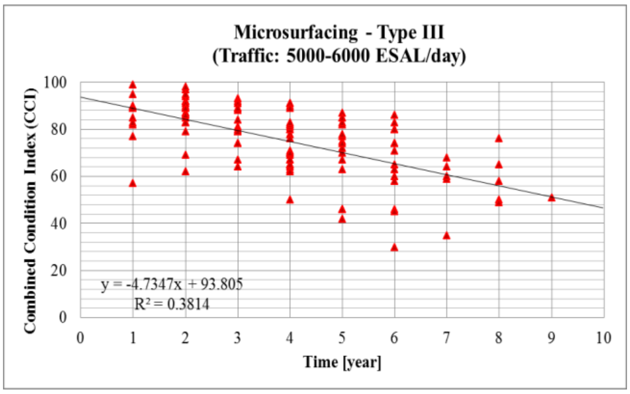


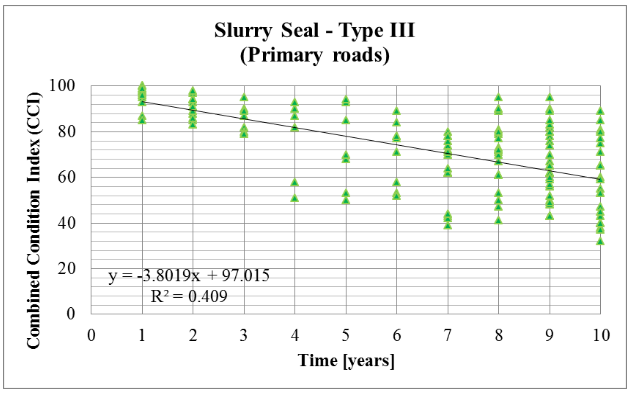
Figure 1 Available data, primary roads

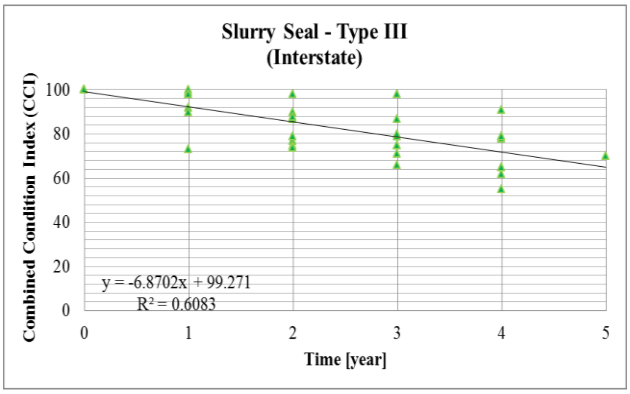
TREATMENTS EFFECTIVENESS

The present section illustrates results of the regression analyses conducted. Types of preventive maintenance treatments investigated can be listed as follows: microsurfacing type II and type III (ISSA 2010), slurry seal type II and type III (Caltrans, 2007), ultra-thin overlay (Russel, 2008), and chip seal (Gransberg, 2005). A latex-modified asphalt emulsion is used for the Type III microsurfacing. Examples of the resulting models for microsurfacing and slurry seal are presented in Figure 2.









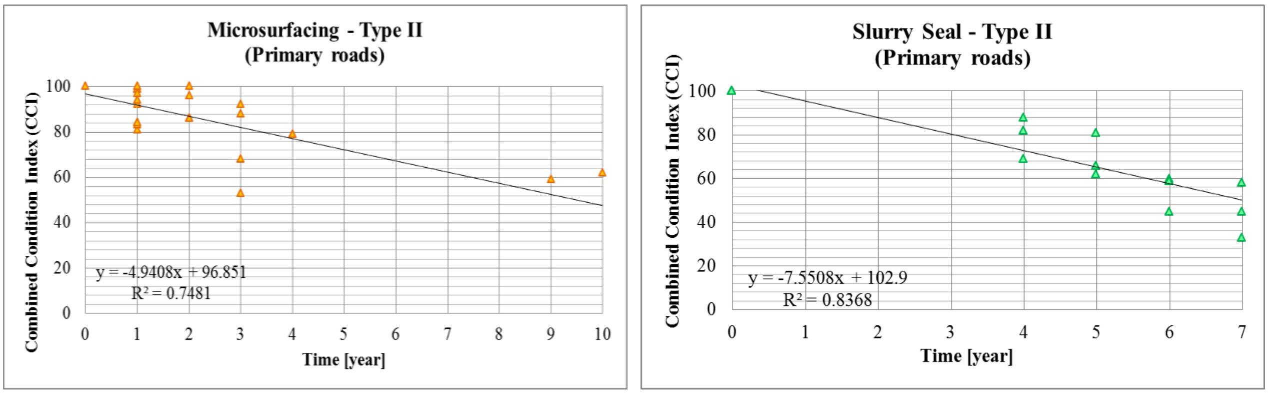


Figure 2 Effectiveness of PM treatments vs. time, some examples

Several non-linear models were tested but no significant changes in the model prediction capabilities from the linear trend were obtained; a linear trend was therefore adopted. It should also be noted that not all the best-fit deterioration equations had an intercept equal to 100. However, this feature is strongly dependent on the available data; in addition, the main outcome is represented by the slope variance since road agencies and municipalities aim to predict the future conditions of the pavement. As expected, slope is always negative in all models. The results for all the PM treatments and road types evaluated are summarized in the Table 1.

Table 1 PM effectiveness, summary of findings

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			
Averaging traffic	$CCI = - 4.2824 x + 96.386$	0.57			
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
Ultra-thin overlay (interstate)			**Chip seal (primary)**		
ESAL	Post-Treatment deterioration models	R^2	ESAL	Post-Treatment deterioration models	R^2
-	$CCI = - 2.4727 x + 100$	0.57	< 500	$CCI = - 9.60 x + 100$	0.87

Table 1 shows how the pavement deteriorates after preventive maintenance is applied. As it can be inferred, increasing traffic also entails a faster deterioration of the pavement over time (higher slope in the linear model); preventive maintenance is consequently less effective when the traffic grows. A similar deduction can be made if the same treatment is applied to different type of roadways; indeed, the same material applied to primary roads having a lower volume of traffic results in a pavement deteriorating generally slower.

Moreover, microsurfacing type II, as well as slurry seal type II, provided a lower performance than the respective type III if the same roads and the same traffic are considered. Slurry seals and chip seal were also found to perform generally worse than microsurfacing for a similar traffic, as largely stated by the literature.

Finally, ultra-thin overlays were shown to be the most effective treatment providing the lowest slope although fewer sections were surveyed to evaluate the treatment.

The following section investigates the environmental burden related to preventive maintenance strategies. The aim is to evaluate if a well-performing maintenance type (i.e.; preventive maintenance) can also represent an eco-efficient strategy.

ENVIRONMENTAL ASSESSMENT OF PREVENTIVE MAINTENANCE TREATMENTS

Although computing emissions due to road-related practices is a step in the right direction, the environmental assessment cannot represent a stand-alone evaluation of a road project. Performance and costs of the infrastructure over the life cycle should always be associated to the environmental analysis. 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.

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.

Carbon footprinting analyses are not easy to develop mainly because specific 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. A carbon footprint is a measure of the impact a specific activity has on the environment, and in particular, climate change. 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 into the atmosphere (Carbon Trust, 2010).

Emissions from the manufacture of raw materials, equipment utilized during the construction stage, maintenance practices, and rehabilitation/reconstruction procedures, are then converted into carbon equivalent emissions to compute their carbon footprints. Indeed, in order to simplify the calculations, the six gasses are combined together into the equivalent carbon dioxide (CO_2e). The conversion from a certain greenhouse gas into a unit of equivalent carbon dioxide is conducted by 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).

A comprehensive pavement life cycle assessment should be able to include several components; however, some of them are usually disregarded in the current environmental analyses. In order to correctly assess the impact of a specific maintenance strategy, for instance, life cycle assessment should include: the design phase, processes related to extraction and manufacturing of pavement materials, transportation of materials to the construction site and within it, construction phase, usage phase, maintenance phase, end-of-life and recycling phase.

The following sections analyze environmental impacts associated to pavements providing the reader with some phase-related analytical computation.

MATERIALS EXTRACTION AND PRODUCTION

Materials extraction and production involves the processes needed to convert raw materials (i.e.; aggregate, petroleum, etc.) into pavement materials (i.e.; asphalt, etc.). Unfortunately, knowing exactly every single emission produced in every phase of an extremely complex and articulate process is not straightforward.

Different literature data available were therefore averaged to compute a reasonable value of emissions due to the manufacture of raw materials. However, comparing different alternatives adopting a life cycle analysis approach can be done without assessing the exact emission value for a specific material involved under specific conditions; if material quantities are the same then the same error will be made throughout different strategies. Table 2 summarizes the outcomes from the literature review. The variability for some of the parameters is rather high, as shown by the standard deviation. All entries listed in the table consider all the stages and processes to obtain the final product as ready-to-use.

Table 2 Emission due to material manufacturing and extraction

Material	**Emission – CO_2e** [kg/ton material]	**Standard Dev.**
Bitumen	256.5	118.2
Bitumen emulsion [60%]	221.0	21.9
Crushed aggregates	7.5	9.9
Pit-run aggregates	5.3	2.2
Cement	1079.6	311.5
Quicklime	2500	-
Water	0.29	-
Polymers – elastomers	3000	543.4
Polymers – plastomers	1400	424.3
Emulsifiers	600	52.4

TRANSPORTATION

The transportation phase consists of the handling of materials between extraction points, production facilities, and the construction site. 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 significant part in the environmental impacts assessment; thus, minimizing transportation of material for a construction project can therefore produce a substantial environmental benefit (i.e.; reusing in situ materials and/or recycling).

Environmental impacts associated with transportation are mainly influenced by three factors: mode of transportation (road, railway, water), distance of transportation, and overall mass of materials being transported. According to the U.S. Department of Energy (Davis, 2010) the average fuel efficiency for a truck in severe working conditions is 0.414 l/km (2.41 km while consuming one liter of diesel). Moreover, 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.

$$CO_2[g] = \frac{Effective\ Load\ [ton]}{Capacity\ [ton]} \cdot Distance\ [km] \cdot Fuel\ Efficiency \left[\frac{l}{km}\right] \cdot CO_2\ per\ liter\ of\ diesel \left[\frac{g}{l}\right] \qquad (1)$$

The amount of equivalent carbon dioxide emitted per one liter of diesel combusted is better explained in the following section.

MAINTENANCE TREATMENT APPLICATION EQUIPMENT

This phase accounts for the emissions related to construction and maintenance activities carried out by units of equipment. Several approaches and tools can be adopted to compute them. For the sake of the paper, several units of equipment, currently used in road construction sites, were analyzed to calculate the emissions produced for conducting a specific activity. Millers, pavers, rollers, slurry/microsurfacing machineries, graders, and trucks, were investigated for identifying and quantifying emissions in road preventive maintenance activities.

The total fuel consumption for carrying out a specific maintenance work using a specific equipment on a sample road unit (i.e.; a lane-kilometer) was estimated. A significant source of pollution in a construction site, in fact, is related to the engine exhaust system of the equipment. First, the analysis aimed to identify the number and the type of machines utilized to carry out the work. Then, the time each piece of equipment is going to be used on the sample road unit (lane-kilometer) was estimated; i.e., considering the productivity data reported in the technical specifications of the machines.

Different engines related to major companies' machines were analyzed identifying the fuel consumption based on the Power-Torque-BSFC (Brake Specific Fuel Consumption) curves. A relationship (U.S. EPA, 2005) to convert the calculated fuel consumption into emissions produced and energy spent was therefore applied. Finally, the total amount of equivalent CO_2 were computed for each equipment model.

$$F\ [l] = BSFC \left[\frac{g}{kW \cdot h}\right] \cdot P[kW] \cdot T[h] \cdot 1/\gamma \left[\frac{l}{g}\right] \qquad (2)$$

Where: F = fuel consumed, T = working time, $BSFC$ = brake specific fuel consumption, P = engine power when the rotation speed provides a torque within the range including the maximum value (engine maximum efficiency point), and γ = density of the fuel (diesel density = 0.832 kg/l).

The Code of Federal Regulations in the U.S. (Code of Federal Regulations, 2005) provided the value of carbon content per gallon of diesel fuel: 2778 grams. In addition, the Intergovernmental Panel on Climate Change guidelines for calculating emissions (IPCC, 2007) required 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. EPA, 2005). Moreover, to calculate the CO_2 emissions from a liter (or gallon) of fuel, the carbon emissions are 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.

$$CO_2 \text{ from a gallon of diesel } = 2778 \text{ grams} \times 0.99 \times (44/12) = 10084 \text{ grams} = 10.1 \text{ kg/gallon} = 2.6639 \text{ kg/liter} \quad (3)$$

Finally, the fuel consumption was multiplied by the specific amount of equivalent CO_2 produced in the combustion of a liter of diesel in order to determine the total quantity of emissions related to the equipment used for a specific maintenance activity.

$$CO_2\, emissions\, [g] = F[l] \cdot \alpha \left[\frac{g}{l}\right] \quad (4)$$

Where: α = specific amount of CO_2 emitted during the combustion of a liter of diesel = 2663.9 g/liter.

PREVENTIVE MAINTENANCE: EMISSIONS CALCULATION

Emissions related to preventive maintenance treatments were computed considering the amount of materials and units of equipment adopted for the placement. Boundaries were set in order to not consider the usage phase over the life cycle and disposal at the end-of-life stage. Comparisons with other life cycle impact assessments are therefore only suggested if the same boundary conditions are considered.

The mix design and materials quantities were assessed for the PM treatments previously described as if they were applied over a lane-kilometer. Thus, emissions related to materials were simply obtained by multiplying unit values in table 2 by the respective amount. Medium-performance standard equipment was then chosen for each task. The fuel consumption for conducting a specific PM activities was then evaluated over a lane-kilometer taking into account its productivity and according to the methodology already described before. A hauling distance of 25 km was furthermore assumed from the production facility to the placement site for taking into account transportation emissions.

For comparison purposes emissions related to do nothing and then applying a major rehabilitation (i.e.; reconstruction of all the asphalt layers) were also computed. Findings are summarized in the table below.

Table 3 Emissions related to PM treatments

	Material [kg of CO_2e/(m^2)]	Transportation [kg of CO_2e/(m^2)]	Equipment [kg of CO_2e/(m^2)]	TOT. [kg of CO_2e/(lane*km)]
Ultra-thin Overlay	2.69	0.12	0.11	10950
Microsurfacing	1.95	0.10	0.05	7875
Slurry Seal	1.34	0.082	0.05	5520
Chip Seal	1.21	0.083	0.06	5074
Major rehabilitation *(milling and resurfacing ≈ 25 cm)*	24.58	1.53	0.61	100200

CONCLUSIONS

The paper presented an evaluation of preventive maintenance effectiveness on road pavements considering both the performance and the environmental impact perspectives. In particular, ultra-thin overlays, microsurfacing, slurry seal, and chip seal were studied and post-treatment deterioration models were developed using actual in service data.

Deterioration trends, besides numerically quantifying the pavement performance over a specific time span, showed that traffic was a main parameter affecting the treatments' effectiveness. Furthermore, supplemental investigations should be conducted for evaluating 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. 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.

Preventive maintenance treatments showed to be eco-effective providing equivalent carbon emissions up to twenty times lower than major rehabilitations. Since the preventive maintenance treatments reduce the rate of deterioration, applying a preventive maintenance strategy will reduce the number of major rehabilitations over the pavement life cycle.

Finally, even though there is a desire to establish what strategies are more sustainable and what is the impact of pavements on the environment, this is still a very challenging task since there are a lot of uncertainties and more research is needed. For example, limiting the analysis to some parts or to some phases may not provide a comprehensive assessment; however, it would be a step forward in the current evaluation of pavement management strategies.

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