NATIONAL SUSTAINABLE PAVEMENT CONSORTIUM

TPF 5 (268)

Pre-Print

Santos, J., Ferreira, A., Flintsch, G.W., Cerezo, V. (2017) "Consideration of Life Cycle Greenhouse Gas Emissions in Optimal Pavement Maintenance Programming: a Comparison Between Single-Objective and Multi-Objective Optimization Approaches," *Proceedings of the World Conference on Pavement and Asset Management*, Baveno, Italy, June 12-16, 2017.

Consideration of life cycle greenhouse gas emissions in optimal pavement maintenance programming: a comparison between single- and multi-objective optimization approaches

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The increasing awareness of the contribution of the pavement management activities to the greenhouse gas emissions (GHG) requires highway agencies to incorporate environmental considerations into the framework of their Optimization-based Pavement Management Systems (PMS). Multi-objective optimization has been identified as an effective technique to consider the economic and environmental burdens associated with the pavement management problems from a multi-criteria perspective. However, the majority of the current PMS still relies on single-objective optimization (SOO) approaches. At the same time, there has been a growing trend to implement regulatory policies that incorporate a price on GHG emissions in an effort to reduce the dangers of climate change. This new paradigm allows the environmental goals to be considered along with the traditional economic objectives in a SOO analysis. In light of this fact, one aspect worthy of scrutiny is how the pavement maintenance decision-making context might be influenced by the solutions provided by these two distinct optimization approaches. This paper aims to explore this question by applying both optimization approaches to a case study consisting of determining the optimal maintenance and rehabilitation strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA. Multiple single- and tri-objective optimization analysis considering accordingly agency costs, road user costs and GHG emissions were conducted based on a genetic algorithm.

Keywords: multi-objective optimization; single-objective optimization; life cycle assessment; life cycle costs; greenhouse gas emissions; pavement management.

Introduction

Departments of Transportation (DOTs) and decision makers in the road pavement management sector have been increasingly challenged by the need of identifying and implementing maintenance and rehabilitation (M&R) strategies that result in the advancement of the sustainability of pavement systems. In this context, decisions aiming the selection of M&R strategies amongst a large set of feasible alternatives, when made exclusively either on the basis of engineering knowledge and expertise, or on the basis of the individual application of conceptual tools, such as life cycle costs analysis (LCCA) and life cycle assessment (LCA), often result in solutions that are non-optimal, ineffective, expensive or that neglect the multidimensionality of the problem and stakeholders involved. To address these limitations, optimization models can be used to identify optimal, cost-effective and environmentally-friendly solutions (Wu et al., 2012). The implementation of effective sustainable pavement management systems requires accounting for the costs incurred by highway agencies and road users and the environmental impacts related to the pavement life cycle, by using appropriate performance metrics. Such metrics are commonly in conflict between each other in real life. Therefore, multi-objective optimization (MOO) techniques can be applied to help in dealing with the issues at hand by identifying efficient solutions. Alternatively, the damage costs associated with the environmental burdens can be integrated with the traditional LCCA components into a single- objective optimization (SOO) model by assigning monetary values to the damage caused by the substances released to the environment.

Objectives

The main objective of this paper is to investigate how the pavement maintenance decision-making context might be influenced by two distinct optimization approaches- SOO and MOO - while trying to achieve sustainable transportation systems.

Methodology

The pavement management optimization problem addressed in this paper is formulated both as a MOO and a SOO problem, in which the objective functions (OFs) representing the commonly conflicting perspectives and interests of the three main pavement management stakeholders, i.e., highway agency, road users, and environment, are considered. In the MOO approach the three OFs simultaneously minimized are as follows: (1) the present value (PV) of the total life cycle highway agency costs (LCHAC); (2) the PV of the life cycle road user costs (LCRUC); and (3) the life cycle climate change (CC) impact category, expressed in terms of CO_2-eq. On the other hand, in the SOO approach the OF corresponds to the sum of the OFs (1) and (2) of the MOO approach and the social cost (SC) of the CO_2-eq. emissions, which represents the society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2-eq. is emitted into the atmosphere in a particular year (USG, 2010). In both approaches the values of the OFs corresponding to a given M&R plan are determined by applying the MOO-based pavement management decision-support system (DSS) developed by Santos et al. (2016a). Briefly, it incorporates a comprehensive and integrated pavement LCC-LCA model, along with a decision-support module, within a MOO framework applicable to pavement management.

Optimization algorithm and technique

The optimization problem introduced in the previous section is extremely difficult to solve to an exact optimum given its marked combinatorial nature and the difficulties in verifying, when they exist, the required mathematical properties of continuity, convexity and derivability. Therefore, to solve the SOO model the DSS adopts directly the adaptive hybrid Genetic Algorithm (AHGA) developed by Santos et al. (2016b). Regarding the MOO model, it is initially transformed into a SOO model by using the augmented weighted Tchebycheff method, after which the abovementioned AGHA is employed to generate the Pareto front.

GHG emissions pricing

To estimate the marginal damage costs of pavement management-related GHG emissions, the United States Government (USG) SC-CO_2 (USG, 2010) and the SC estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) determined by Marten et al. (2015) are adopted. The SC-CH_4 and SC-N_2O estimates in Marten et al. (2015) were developed using methods consistent with those used to estimate the SC-CO_2. Both methods estimate the SC-GHG emissions over 40 years considering three distinct discount rates: 2.5%, 3% and 5%. A fourth set of values are also estimated, which represents the 95th percentile of the SC-GHG distribution at the 3% discount rate. In this paper the monetization of GHG damages are also computed for an equal number of SC-GHG estimates. Furthermore, to determine the SC of each GHG as a function of time, several points of the estimates presented by USG (2010) and Marten et al. (2015) were plotted and a function in the form of Expression (1) was fitted to the data. This procedure was performed after adjusting the original SC, expressed in 2007 USD, to year 2011 with the Bureau of Labor Statistics' Consumer Price Index. The values of the parameters *a* and *b* in Equation (1) are presented in Table 1. One important aspect worthy of highlight in this Table pertains to the fact that the 95th percentile of the SC-CO_2 distribution at the 3% discount rate originates the highest SC-GHG emissions.

$$SC - GHG_i = a\,t + b \tag{1}$$

where $SC - GHG_i$ is the social cost of the GHG_i; *t* is time (years); *a* and *b* are the regression parameters; and *i* is the GHG considered (i.e. CO_2, CH_4 and N_2O).

Table 1. Regression parameters

Env. disc. rate	CO_2			CH_4			N_2O		
	a	*b*	R^2	*a*	*b*	R^2	*a*	*b*	R^2
3% (95th Perc.)	3.42	-6781.1	0.99	119.0	-236756	0.99	1121.03	-2221330.45	1
2.50%	1.20	-2365.6	0.99	51.7	-102709	0.99	517.12	-1020464.36	1
3%	1.02	-2008.2	0.99	44.9	-89406	0.99	419.48	-830817.00	0.99
5%	0.44	-877.39	0.98	25.8	-51550	0.99	203.23	-405305.00	0.98

Case study

General description

The DSS was applied to a case study consisting of determining the optimal M&R strategy for a one-way flexible pavement section of a typical Interstate highway in Virginia, USA. Furthermore, two scenarios were considered depending on whether or not the most structurally robust M&R activity available for employment throughout the project analysis period (PAP) includes recycling-based layers. To ensure practicality of the present model, a set of constraints is defined. Among that set of constraints, the following ones are worthy of mention: (1) the Critical Condition Index (CCI) of a pavement section cannot be lower than 40 and (2) due to technical limitations which impose limits to the life of the initial pavement design and the most structurally robust M&R activities, the maximum time interval between the application of two consecutives M&R activities of that type is 30 years.

The features of the case study are shown in Table 2. The road pavement section described in Table 2 is assessed according to its economic and environmental performances in the following pavement life cycle phases: (1) materials extraction and production, (2) construction and M&R, (3) transportation of materials, (4) work-zone traffic management and (5) usage phase. The end-of-life (EOL) phase was excluded from the system boundaries because the road pavement section is expected to remain in place after reaching the end of the PAP, serving as a support for the new pavement structure. In view of this scenario, the salvage value of the pavement structure was proven to be negligible when compared to the costs incurred during the remaining pavement life cycle phases (Santos et al. 2015). With regard to the environmental impacts assigned to this phase, they are disregarded on the basis of the application of the 'cut-off' allocation method. For a deep understanding on the methodologies and formulations adopted to calculate the multiple subcategories of highway agency costs (HAC) and RUC as well as the life cycle inventory (LCI) associated with the several pavement life cycle phases, the reader is referred to Santos et al. (2015 and 2017).

Table 2. Features of the case study

Name	Parameter	
	Value	Unit
PAP	50	year
Beginning year	2011	year
Initial AADT	20000	vehicle
Percentage of PCs in the AADT	75	%
Percentage of HDVs in the AADT	25	%
Traffic growth rate	3	%/year
Initial CCI	87	-
Initial IRI	1.27	m/km
Age	5	year
Number of lanes	2	-
Lanes length	1	km
Lanes width	3.66	m
Economic discount rate	2.3 (OMB, 2013)	%

PAP- project analysis period; AADT- annual average daily traffic; PCs- passenger cars; HDVs- heavy duty vehicles; CCI- critical condition index; IRI- international roughness index; OMB- Office Management Budget.

Maintenance and rehabilitation activities

The M&R activities considered for application over the PAP are based on Chowdhury

(2011), and defined as: (1) Do Nothing (DN); (2) Preventative Maintenance (PrM); (3) Corrective Maintenance (CM); (4) Restorative Maintenance (RM); and (5) Reconstruction (RC). In the case of the PrM treatments, two types of treatments are considered: microsurfacing (McrS) and thin hot mix asphalt overlay concrete (TH). As for the RC treatment, two alternatives are also considered. They were named conventional RC (scenario I) and recycling-based RC (scenario II) and differ from each other in that the former comprises exclusively conventional asphalt layers, whereas the latter consists of a combination of conventional asphalt layers with in-place recycling layers. The recycling-based RC activity is designed in such a way that it provides equivalent structural capacity to its non-recycling-based counterpart and takes into account the Virginia Department of Transportation's (VDOT's) surface layer requirements for layers placed over recycling-based layers (VDOT, 2013). Details on the M&R actions comprising each M&R activity are presented in Santos et al. (2017).

Pavement performance prediction models

In order to determine the pavement performance over time, the VDOT pavement performance prediction models (PPPM) are used (Equation (2) and Table 3). VDOT developed a set of PPPM in units of CCI as a function of time and category of the last M&R activity applied (Stantec Consulting Services and Lochner, 2007). CCI is an aggregated indicator ranging from 0 (complete failure) to 100 (perfect pavement) that represents the worst of either load-related or non-load-related distresses.

$$CCI(t) = CCI_0 - e^{a + b \times c^{ln\left(\frac{1}{t}\right)}} \tag{2}$$

where $CCI(t)$ is the critical condition index in year *t* since the last M&R activity, i.e. CM, RM or RC; CCI_0 is the critical condition index immediately after treatment; and *a*, *b*, and *c* are load-related PPPM coefficients (Table 3).

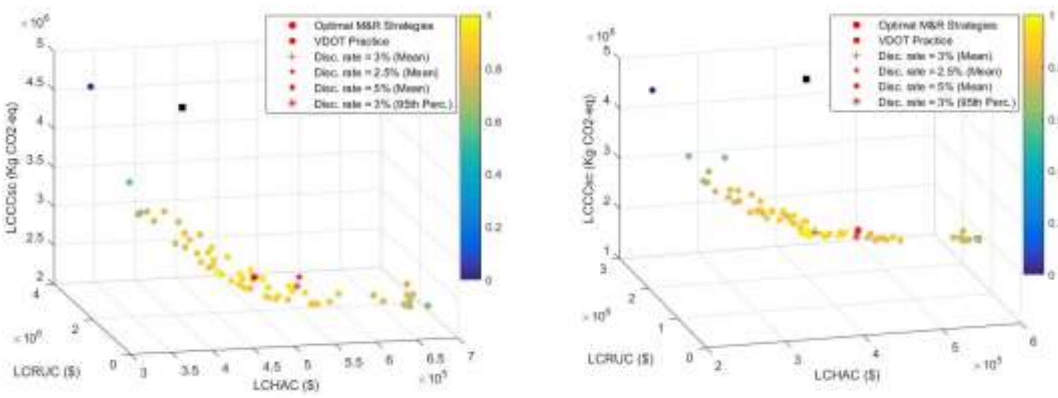
Unlike the previous M&R activity categories, VDOT did not develop individual PPPM for PrM treatments. Thus, in this case study the considered PrM treatments, i.e. McrS and TH, are respectively modelled as an 8-point and 15-point improvement in the CCI of the road segment. Once the treatment is applied, it is assumed that the pavement deteriorates according to the PPPM of a CM, but without reduction of the effective age. On the other hand, in the case of the application of CM, RM and RC treatments, the CCI is brought to the condition of a brand new pavement (CCI equal to 100) and the age is restored to 0 regardless of the CCI value prior to the M&R activity application.

Table 3. Coefficients of VDOT's load-related PPPM expressed by Equation 2 for asphalt pavements of interstate highways

M&R activity category	CCI_0	*a*	*b*	*c*
CM	100	9.176	9.18	1.27295
RM	100	9.176	9.18	1.25062
RC	100	9.176	9.18	1.22777

Results

Figures 1 plots (1) the Pareto optimal sets of solutions in the objective space, (2) the single-objective optimal solutions obtained for each SC-GHG emissions and (3) the M&R strategy defined by VDOT. Furthermore, the Pareto optimal solutions are presented with a colour scheme consistent with its fuzzy cardinal priority rating. According to this methodology, which relies on the membership function concept in the fuzzy set theory (Zimmormann, 1996), the solution in the Pareto front furthest from the most inferior solution, i.e. the one with the maximum value for all objectives, is considered as the best optimal compromise solution (BOCS). The normalized fuzzy cardinal priority ranking of this solution is equal to 1. Table 4 shows the features of the BOCS, the single-objective and multi-objective optimal solutions and the M&R strategy defined by VDOT. Table 5 displays the values of the performance metrics associated with the several M&R strategies.



(a) (b)

Figure 1. M&R strategy defined by VDOT, Pareto optimal fronts and single-objective optimal solutions: a) scenario I; b) scenario II. Legend: LCHAC - life cycle highway agency costs; LCRUC - life cycle road user costs; LCCCsc - life cycle climate change score. Note: The fuzzy cardinal priority ranking of each non-dominated solution was normalized so that it falls into the range [0;1].

For the conditions considered in both scenarios of this case study, the results presented in Figure 1 shows that the single-objective optimal solutions are also Pareto optimal, although they have not been found in the MOO approach. Furthermore, they not only belong to the Pareto front but are also amongst those of lowest distance to the BOCS, as measured by the normalized membership function value. This Figure also reveals that the single-objective optimal solutions are dependent on discount rate considered in the PV computation of the GHG damage costs. In general, discount rates that result in lower SC-GHG emissions lead to M&R strategies associated with a lower average pavement condition throughout the pavement life cycle (Tables 4 and 5). This is because a reduction in the SC-GHG emissions reduces the impact that the GHG damage costs has on the total cost. Consequently, when lower SC-GHG emissions are used, the GHG emissions arising from the most important phase of a pavement life cycle, i.e. the usage phase, are less valuable, and then the M&R strategies associated with lower average pavement condition over the pavement life cycle are more likely to be optimal.

Table 4. M&R strategies defined by VDOT, MOO approach and SOO approach

Scenario	Optimization approach	M&R activity (application year)						Avg. CCI
		CM	RM	Conv. RC	Recyc.-based RC	McrS	TH	
I	VDOT (no optimal)	7; 39	17	27	-	-	-	82.74
	MOO	13; 36; 41	-	25	-	32	46	78.18
	SOO: r = 3% (mean)	8; 20; 29; 40	-	20	-	-	1; 14; 24; 34	78.96
	SOO: r = 2.5% (mean)	6; 16; 29; 40	-	20	-	-	1; 11; 24; 34	82.66
	SOO: r = 5% (mean)	8; 20; 29; 40	-	20	-	-	1; 14; 24; 34	78.96
	SOO: r = 3% (95th percentile)	6; 16; 30; 41	-	20	-	-	1; 11; 25; 35	82.96
II	VDOT (no optimal)	7; 39	17	27	-	-	-	82.74
	MOO	4; 18; 30; 41	-	-	24	2	12; 36	80.76
	SOO: r = 3% (mean)	8; 20; 29; 40	-	-	20	-	1; 14; 24; 34	78.96
	SOO: r = 2.5% (mean)	6; 16; 29; 40	-	-	20	-	1; 11; 24; 34	82.66
	SOO: r = 5% (mean)	8; 16; 29; 40	-	-	20	-	1; 11; 24; 34	82.66
	SOO: r = 3% (95th percentile)	6; 16; 30; 41	-	-	20	-	1; 11; 25; 35	82.96

Legend: CM - corrective maintenance; RM - restorative maintenance; Conv. RC - conventional reconstruction; Recyc.-based RC - recycling-based reconstruction; McrS - microsurfacing; TH - thin hot mix asphalt overlay concrete; MOO - multi-objective optimization; SOO - single-objective optimization;

VDOT- Virginia Department of Transportation; Avg. CCI - average critical condition index; r - environmental discount rate.

Table 5. Life cycle metrics corresponding to each M&R strategy

Scenario	Optimization approach	LCHAC (€)	LCRUC (€)	$LCCC_{sc}$ (Kg)	$LCCC_{sc}$ damage costs (€)	Total LCC (€)
I	VDOT (no optimal)	425 163.98	2 665 172.68	4 512 113	-	-
	MOO	357 559.71	1 925 908.77	3 356 906	-	-
	SOO: r = 3% (mean)	475 113.78	1 033 170.22	2 670 744	69 116.28	1 577 400.29
	SOO: r = 2.5% (mean)	529 307.79	1 001 452.66	2 644 577	111 299.51	1 642 059.96
	SOO: r = 5% (mean)	475 113.78	1 033 170.22	2 670 744	13 943.10	1 522 227.10
	SOO: r = 3% (95th percentile)	527 007.91	1 007 589.38	2 535 917	198 708.71	1 733 306.00
II	VDOT (no optimal)	425 163.98	2 665 172.68	4 512 113	-	-
	MOO	369 013.26	1 083 439.83	2 499 971	-	-
	SOO: r = 3% (mean)	375 315.03	1 018 292.89	2 503 648	63 812.26	1 457 420.18
	SOO: r = 2.5% (mean)	429 509.04	986 575.33	2 477 481	102 994.00	1 519 078.37
	SOO: r = 5% (mean)	429 509.04	986 575.33	2 477 481	12 477.74	1 428 562.11
	SOO: r = 3% (95th percentile)	427 209.16	992 712.04	2 368 821	183 211.76	1 603 132.96

Legend: LCHAC - life cycle highway agency costs; LCRUC - life cycle road user costs; LCCCsc - life cycle climate change score; Total LCC – total life cycle costs; MOO - multi-objective optimization; SOO - single-objective optimization; VDOT- Virginia Department of Transportation; r - environmental discount rate.

Summary and conclusions

This paper investigated how the pavement maintenance decision-making context which embraces environmental considerations might be influenced by two distinct optimization approaches: a SOO approach and a MOO approach. The results of the case study show that the SOO approach is able to generate solutions that are not only Pareto optimal but are also amongst those of lowest distance to the BOCS in the MOO approach. In addition, the SOO approach requires less computational effort than the MOO counterpart, which results in time savings. In turn, the MOO approach requires more computational effort but the results are presented as a Pareto-optimal front. That means that the decision makers are provided with more detailed information by displaying the trade-offs between the eventual conflicting objectives considered individually. This way of presenting the results not only increases the decision maker's understanding of the search space, and consequently of the problem, but also avoids the assumption of the not widely accepted concept of perfect substitutability which is implicit in the SOO approach.

Acknowledgements

This work has been supported by the Transportation Pooled Fund TPF-5(268) National Sustainable Pavement Consortium.

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