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Road and Rail Infrastructure II

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PAVEMENT DESIGN OPTIMISATION CONSIDERING COSTS AND PREVENTIVE INTERVENTIONS

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Abstract

In Portugal, as in many other countries, due to the economic crisis, the trend of budgetary pressures on highway agencies is increasing. At the same time, road users are increasingly demanding in terms of highway quality, comfort and safety. Several highway projects have been delayed because of budget constraints. To meet these challenges highway agencies are looking for more cost–effective methodologies for pavement management at project–level. This paper presents a new pavement design optimization model, called OPTIPAV, which considers pavement performance, construction costs, maintenance and rehabilitation costs, user costs, the residual value of the pavement at the end of the project analysis period, and preventive maintenance and rehabilitation interventions. It was developed and programmed to help pavement designers to choose the best pavement structure for a road or highway. The results obtained by the application of the new pavement design optimization model clearly indicate that it is a valuable addition to the road engineer's toolbox.

Keywords: pavement design, pavement performance model; optimisation model

1 Introduction

In Portugal, as in many other countries, due to the economic crisis, the trend of budgetary pressures on highway agencies is increasing. At the same time, road users are increasingly demanding in terms of highway quality, comfort and safety. Several highway projects have been delayed because of budget constraints. To meet these challenges highway agencies are looking for more cost–effective methodologies for pavement management at project–level. Highway pavements can be designed with many possible combinations of construction and maintenance and rehabilitation (M&R) strategies. It is desirable to find the optimal pavement structure, in terms of minimum cost while satisfying the engineering constraints, by modern mathematical methods and computer technology. Thus, there is a need to develop new optimization models to provide highway agencies with a better and more efficient decision–aid tool for pavement management at project–level. This paper presents a new pavement design optimization model considering costs and preventive interventions, called OPTIPAV, developed and programmed to help pavement designers to choose the best pavement structure for a road or highway.

2 Proposed pavement design optimization system

The proposed pavement design optimization system introduces some new capabilities in the previous version of the OPTIPAV system [1], including the possibility to consider preventive M&R operations. The OPTIPAV system uses the pavement performance model of the AASHTO flexible pavement design method [2] to predict the future quality of pavements. The results of the application of the OPTIPAV system consist of the optimal pavement structure, the predicted annual pavement quality, the construction costs, the M&R plan and costs, the user costs, and the pavement residual value at the end of the project analysis period (Figure 1).

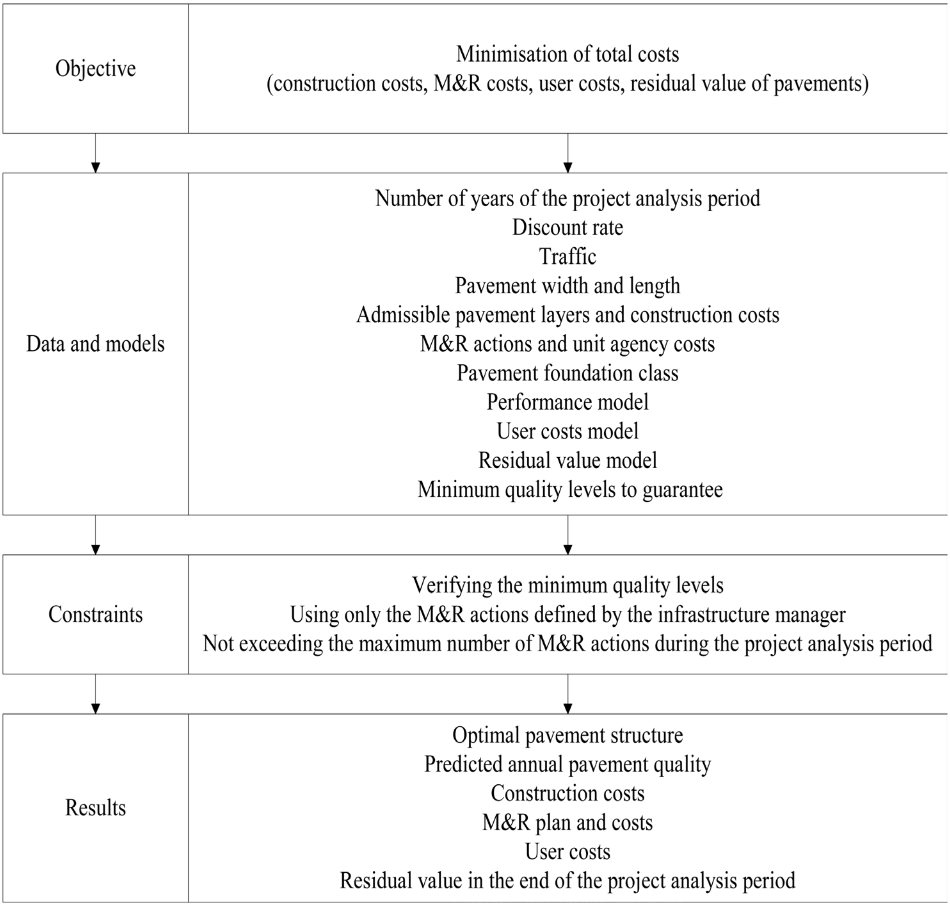


Figure 1 OPTIPAV system components

3 Case study

3.1 Introduction

The Portuguese manual [3] recommends pavement structures in relation to traffic class (from T1 to T6) and pavement foundation class (from F1 to F4). The traffic class is defined by the number of 80 kN equivalent single axle load (ESAL) applications for a design life or design period calculated depending on the annual average daily heavy–traffic (AADTh), the annual average growth rate of heavy–traffic (gh) and the average heavy–traffic damage factor or, simply, truck factor (α). On the other hand, the pavement foundation class is defined by the California Bearing Ratio (CBR) value and the design stiffness modulus (E). The Portuguese manual considers 16 different flexible pavement structures for different combinations of traffic and pavement foundation. These pavement structures were defined using the Shell pavement design method [4], with verification by using the University of Nottingham [5] and Asphalt Institute [6] pavement design methods. In order to define optimum pavement structures for national roads or highways, the OPTIPAV system was applied to 384 combinations of traffic (6 different values), foundation (4 different values of the foundation stiffness modulus), and pavement structure (16 different flexible pavement structures), using a costs optimization approach considering preventive M&R operations (Tables 1 and 2). In application of the OPTIPAV system, the following statistic design values were considered: a ZR value of -1.282 and a So value of 0.45 [2]. A discount rate equal to 3% was used in the analysis.

Table 1 Maintenance and rehabilitation actions

M&R action	Description	Cost
1	Do nothing	€0.00/m^2
2	Tack coat	€0.41/m^2
3	Surface leveling (1 cm)	€1.23/m^2
4	Surface leveling (2 cm)	€2.45/m^2
5	Membrane anti-reflection of cracks	€1.88/m^2
6	Base layer (10 cm)	€8.63/m^2
7	Binder layer (5 cm)	€6.13/m^2
8	Non structural wearing layer	€3.13/m^2
9	Wearing layer (5 cm)	€6.69/m^2

Table 2 Maintenance and rehabilitation operations

M&R operation	Description	M&R actions involved	Cost
1	No action	1	€0.00/m^2
2	Non structural surface rehabilitation	2+3+2+8	€5.18/m^2
3	Light structural rehabilitation	2+4+2+5+2+9	€12.25/m^2
4	Medium structural rehabilitation	2+4+2+5+2+7+2+9	€18.79/m^2
5	Major structural rehabilitation	2+4+2+5+2+6+2+9	€21.29/m^2

3.2 Results of the application of the OPTIPAV system

The results presented in this paper were obtained for the following data and conditions: two traffic classes (T1 and T5) characterized in Table 3; one type of pavement foundation (F3 with CBR equal to 20% and design stiffness modulus equal to 100 MPa); sixteen different pavement structures with the characteristics presented in Figure 2; a project analysis period of 40 years. Table 3 also shows the pavement structure recommended in the Portuguese manual for traffic class T5 and pavement foundation F3 (P4) and for traffic class T1 and pavement foundation F3 (P14). The characteristics of the pavement structures presented in Figure 2 (type of material, thickness, stiffness modulus; Poisson's ratio, CBR, etc.) are the characteristics considered in the pavement design process using the Shell and two other pavement design methods from which was developed the Portuguese manual of pavement structures. Figure 3 shows the construction costs of each pavement structure. As expected, the construction costs increase with the pavement structural capacity defined by the structural number (SN) considered in the AASHTO pavement design method.

Figure 4 presents the M&R costs during the entire project analysis period for the sixteen pavement structures and for traffic classes T5 and T1. As expected, the M&R costs tend to decrease with the pavement structural capacity defined by the structural number (SN), and for both traffic classes T5 and T1 the P16 is the least-M&R-costs pavement structure. The explanation for the small increase of some M&R costs with the pavement structural capacity is due to the objective of the analysis, which was the minimization of total discounted costs (construction costs, M&R costs, user costs and the residual value of a pavement) over the project analysis period and not the minimization of only M&R costs.

Table 4 presents the M&R operations to be applied to the sixteen pavement structures, during the entire project analysis period, considering traffic class T5 and T1. Figures 5 and 6 represent the predicted PSI value over the years of the project analysis period, for each pavement structure and traffic classes T5 and T1, as a consequence of the execution of the M&R operations. These Figures show, as expected, that for the lowest traffic class (T5) and for all pavement structures, the degradation of the PSI value during the project analysis period is slower than for the highest traffic class (T1).

They also show that using weak pavement structures (with a small SN value) the PSI value decreases quickly in the first years of the project analysis period. Then with the application of M&R operations (the SN increases, making these pavement structures stronger) the PSI value decreases slowly in the remaining years of the project analysis period.

Considering traffic class T5, if pavement structure P4 recommended by the Portuguese manual is adopted then two M&R operations will need to be applied during the project analysis period. Both will be M&R operation 2 (non structural surface rehabilitation) and they must be applied in the 20th and 35th years of the project analysis period (Table 4).

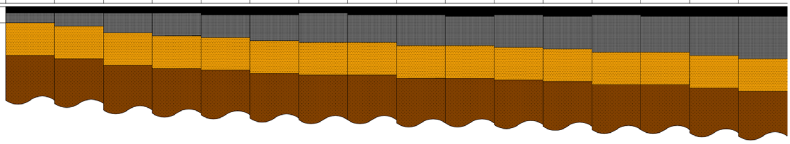
Considering traffic class T1, if pavement structure P14 recommended by the Portuguese manual is adopted then five M&R operations will need to be applied during the project analysis period. M&R operation 2 (non structural surface rehabilitation) must be applied in the 7th, 29th and 36th years of the project analysis period and M&R operation 3 (light structural rehabilitation) must be applied in the 11th and 19th years of the project analysis period (Table 4).

Table 3 Traffic classes and corresponding values

Traffic					Pavement foundation			Pavement structure
Traffic class	$AADT_h$	g_h (%)	á	ESAL (20 years)	Foundation class	E (MPa)	í	Manual
T5	300	3	3	0.88×10^7	F3	100	0.35	P4
T1	2,000	5	5.5	13.28×10^7	F3	100	0.35	P14

		Flexible Pavement Design Alternatives															
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
HMA Surface Layer	Thickness (cm)	4	4	4	4	5	5	4	5	5	6	5	6	5	6	6	6
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
HMA Base Layer	Thickness (cm)	6	8	12	14	14	16	18	17	19	18	20	20	23	22	24	26
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
Sub-base Layer	Thickness (cm)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	Stiffness Modulus (MPa)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Sub-grade	Thickness (cm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Stiffness Modulus (MPa)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CBR (%)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Total HMA Layer Thickness (cm)		10	12	16	18	19	21	22	22	24	24	25	26	28	28	30	32
Structural Number		2.36228	2.63000	3.16544	3.43316	3.60639	3.87411	3.96860	4.00797	4.27569	4.31506	4.40955	4.58278	4.81113	4.85050	5.11822	5.38594

Illustration:



Key: AC - Asphalt Concrete; G - Granular Material; CBR - California Bearing Ratio; HMA - Hot Mix Asphalt

Figure 2 Characteristics of pavement structures

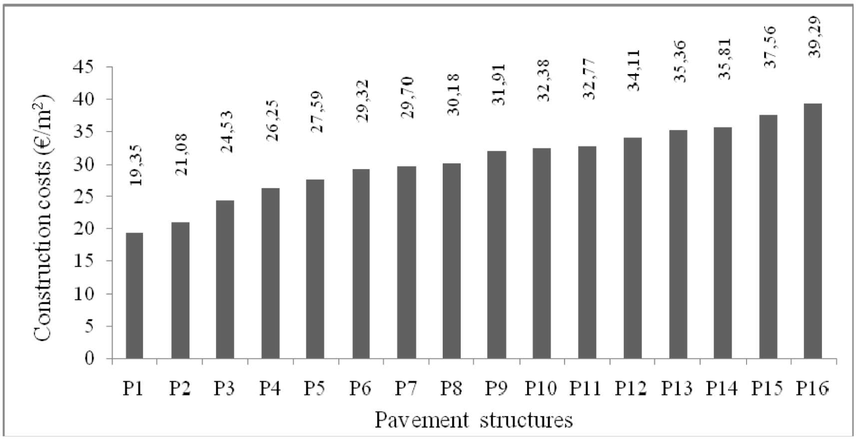


Figure 3 Construction costs of pavement structures

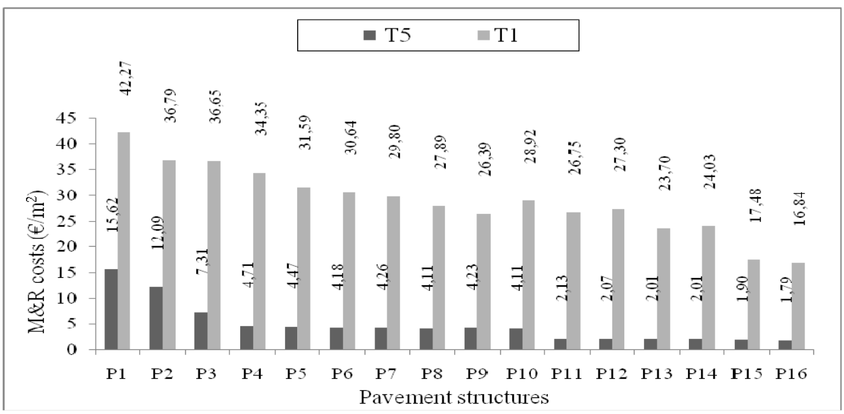


Figure 4 M&R costs throughout the project analysis period

Table 4 M&R operations to be applied in pavements

Pavement Structure	Rehabilitation operations			
	Traffic class			
	T5		T1	
	Operation (year)	Final PSI	Operation (year)	Final PSI
P1	3(3); 2(23); 2(36)	4.25	5(1); 3(8); 3(16); 2(26); 2(34)	4.28
P2	3(7); 2(30)	3.92	5(1); 2(9); 2(14); 2(22); 2(27); 2(33); 2(37)	4.31
P3	2(16); 2(26); 2(38)	4.39	5(2); 3(8); 2(20); 2(29); 2(35)	4.29
P4	2(20); 2(35)	4.16	5(4); 3(13); 2(20); 2(27); 2(34)	4.26
P5	2(21); 2(38)	4.42	5(4); 3(14); 2(23); 2(33)	4.22
P6	2(24); 2(39)	4.50	5(5); 3(14); 2(27); 2(35)	4.33
P7	2(23); 2(39)	4.50	3(5); 3(9); 2(15); 2(24); 2(32); 2(37)	4.26
P8	2(25); 2(39)	4.50	5(5); 2(16); 2(24); 2(32); 2(37)	4.39
P9	2(24); 2(38)	4.45	5(5); 2(13); 2(24); 2(33)	4.19
P10	2(25); 2(39)	4.50	4(5); 3(13); 2(25); 2(34)	4.30
P11	2(30)	4.11	2(4); 5(11); 2(21); 2(29); 2(36)	4.36
P12	2(31)	4.17	2(5); 5(9); 2(22); 2(31); 2(37)	4.41
P13	2(32)	4.24	3(5); 2(9); 2(19); 2(26); 2(31); 2(37)	4.37
P14	2(32)	4.24	2(7); 3(11); 3(19); 2(29); 2(36)	4.37
P15	2(34)	4.33	2(9); 2(17); 3(22); 2(29); 2(36)	4.30
P16	2(36)	4.41	2(10); 2(18); 3(24); 2(30); 2(36)	4.33

KEY (M&R actions): 1 – Do nothing; 2 – Non structural maintenance; 3 – Minor rehabilitation; 4 – Medium rehabilitation; 5 – Major rehabilitation.

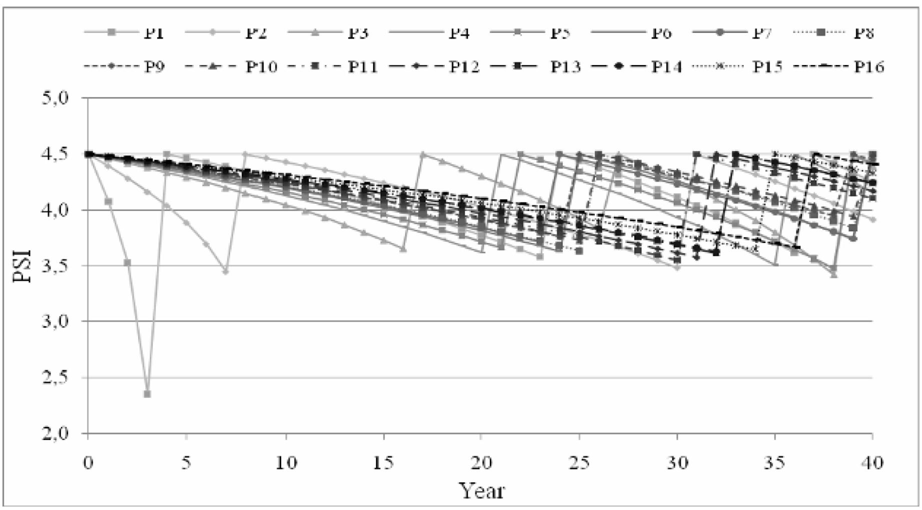


Figure 5 Evolution of PSI for each pavement structure and traffic class T5

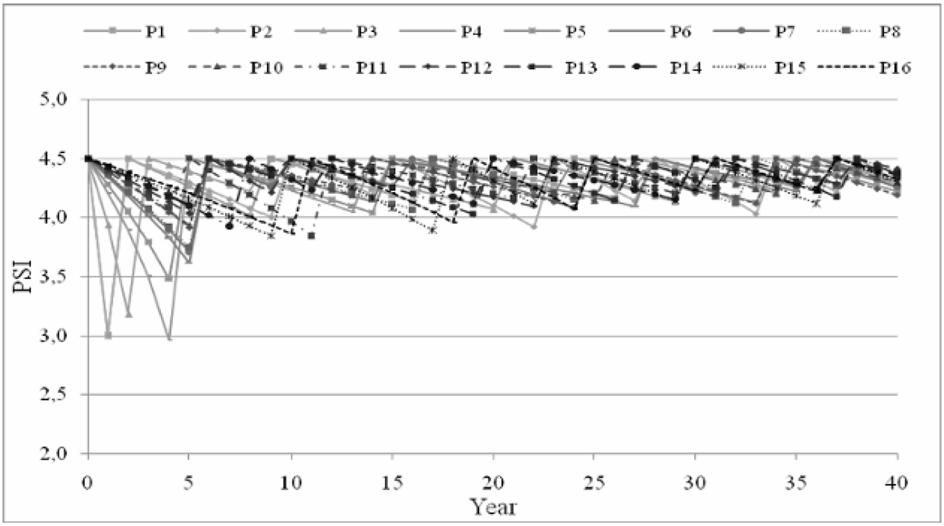


Figure 6 Evolution of PSI for each pavement structure and traffic class T1

Table 5 presents the pavement structures recommended by the Portuguese manual and the optimum pavement structures defined by using the OPTIPAV system. One can see that in eleven cases the optimum pavement structure defined by using the OPTIPAV system has more structural capacity, in five cases it has the same structural capacity, and in two cases it has less structural capacity. In most cases, pavement structures with more structural capacity allow savings in terms of life cycle costs.

Table 5 Optimum pavement structures

Traffic						Pavement foundation			Pavement structure	
Traffic class	AADT	$AADT_h$	g_h (%)	á	ESAL (20 years)	Foundation class	E (MPa)	í	Manual	OPTIPAV
T6	1,500	150	3	2	$0.29x10^7$	F1	30	0.35	NAF	P14
T5	3,000	300	3	3	$0.88x10^7$	F1	30	0.35	NAF	P16
T4	5,000	500	4	4	$2.17x10^7$	F1	30	0.35	NAF	P15
T3	8,000	800	4	4.5	$3.91x10^7$	F1	30	0.35	NAF	P16
T2	12,000	1,200	5	5	$7.24x10^7$	F1	30	0.35	NAF	P16
T1	20,000	2,000	5	5.5	$13.28x10^7$	F1	30	0.35	NAF	P15
T6	1,500	150	3	2	$0.29x10^7$	F2	60	0.35	P3	P7
T5	3,000	300	3	3	$0.88x10^7$	F2	60	0.35	P7	P13
T4	5,000	500	4	4	$2.17x10^7$	F2	60	0.35	P11	P15
T3	8,000	800	4	4.5	$3.91x10^7$	F2	60	0.35	P13	P16
T2	12,000	1,200	5	5	$7.24x10^7$	F2	60	0.35	P15	P15
T1	20,000	2,000	5	5.5	$13.28x10^7$	F2	60	0.35	P16	P15
T6	1,500	150	3	2	$0.29x10^7$	F3	100	0.35	P2	P3
T5	3,000	300	3	3	$0.88x10^7$	F3	100	0.35	P4	P4
T4	5,000	500	4	4	$2.17x10^7$	F3	100	0.35	P6	P9
T3	8,000	800	4	4.5	[illegible]	F3	100	0.35	P9	P15
T2	12,000	1,200	5	5	[illegible]	F3	100	0.35	P12	P16
T1	20,000	2,000	5	5.5	$13.28x10^7$	F3	100	0.35	P14	P16
T6	1,500	150	3	2	[illegible]	F4	150	0.35	P1	P1
T5	3,000	300	3	3	[illegible]	F4	150	0.35	P3	P3
T4	5,000	500	4	4	[illegible]	F4	150	0.35	P5	P5
T3	8,000	800	4	4.5	[illegible]	F4	150	0.35	P8	P7
T2	12,000	1,200	5	5	[illegible]	F4	150	0.35	P10	P16
T1	20,000	2,000	5	5.5	$13.28x10^7$	F4	150	0.35	P12	P13

4 Conclusions

The pavement design optimization system proposed in this paper, called OPTIPAV, can solve the problem of making LCCA for typical design periods (20 years), but also for long periods (40 years or more), in order to compare different pavement solutions in terms of global costs for the final choice of the pavement structure for a national road or highway. Additionally, the OPTIPAV system has the capability of making LCCA with or without optimization, and using only corrective rehabilitation operations or using both preventive and corrective M&R operations. The OPTIPAV system provides a good solution to the pavement design problem considering not only design criteria but also construction costs, maintenance costs, user costs and the residual value of pavement structures. The application of the OPTIPAV system to the case study permitted us to conclude that the pavement structures recommended by the Portuguese Manual are not always the optimum solutions. In most cases, pavement structures with more structural capacity allow savings in terms of life cycle costs. Although the proposed pavement design optimization model was developed using data from Portugal, it can be applicable in different countries with appropriate calibration. In addition, the proposed pavement design optimization model can easily be adapted to consider rigid pavements, other pavement performance models, other costs, as well as different types of M&R operations.

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